



Assistive Technology Individual Guitar String Plucker

A Major Qualifying Project Report

Submitted to the Faculty of WORCESTER
POLYTECHNIC INSTITUTE in Partial
Fulfillment of the Requirements for the
Degree of Bachelor of Science by:

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Submitted on March 23, 2018

This report represents the work of WPI undergraduate students. It has been submitted to the faculty as evidence of completion of a degree requirement. WPI publishes these reports on its website without editorial or peer review.

Abstract

Music has the ability to help children and adults with developmental disabilities grow cognitively and engage socially. The goal of this project is to design a device to allow people with various physical abilities to pluck individual guitar strings. For this device, custom acrylic plectrums, each attached to two electromagnetic actuators, are suspended above the sound hole or pickups of the guitar on a mounting plate. A wooden frame clamping to the body of the guitar supports the mounting plate. Two Arduino Uno microcontrollers facilitate the alternating triggering of the actuator pairs. The mechanism can successfully pluck each individual guitar string, but will require improved coding and mounting design to allow for easier component adjustments based on guitar size and type.

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1. Introduction

For many individuals, music is an important and enjoyable part of their lives. Cultures around the world have unique instruments used to celebrate, mourn, and even communicate. However, for those lacking certain cognitive and physical abilities, it becomes a significant challenge to play more complicated instruments such as string instruments. While various devices have begun to appear on the market, many only carry out the most basic functions, and often only cater to a unique individual.

Professional musician Kurt Coble has worked on assistive technology related to musical instruments as a hobby. Since 2007, he has performed using a group of “Partially Artificial Musicians” (P.A.M.) around the world, showcasing his creations. While Kurt has produced a device to play chords and strum on a guitar, he lacks a device that will allow an individual to pluck individual strings. This includes both plucking different strings individually and plucking multiple strings at once.

This project aims to create an assistive device to allow individuals with a wide variety of physical and cognitive abilities to pluck a stringed instrument. The project will look primarily at producing a device that can mimic more complex plucking patterns that involve plucking two strings at once or non-adjacent strings. The device will also combat current device issues by allowing for multiple user inputs.

2. Background

Creating a device that can pick a guitar string requires a basic understanding of how a musical note is created on a guitar. Some already existing patented and unpatented devices are capable of playing individual guitar strings like the intended device created by this project. In order to create one of these devices that can be used by the target audience, the playing capabilities of this audience must be understood as well.

2.1 Creation of a Musical Note

Sounds are created when an object vibrates the surrounding air or other medium. This oscillation creates alternating regions of high and low pressure called compressions and rarefactions. In a compression region, the molecules in the air are temporarily compressed together, whereas the areas of rarefaction contain air molecules that are more spread apart. The frequency of these alternating regions is directly related to the frequency at which the original object is vibrating. These waves, transmitted through the air, are received by the human ear and interpreted as sounds (“The Physics of Sound”, n.d.).

Guitars and other stringed instruments create this vibration through pre-tensioned strings. When plucked, the strings vibrate at a certain frequency corresponding to a musical note. However, the sound created by these strings alone is minimal as they do not disturb a large volume of air. In order to increase the volume of air affected by the vibrations, stringed instruments typically have a sound box (“Longitudinal Waves and Guitar Strings”, n.d.). In the case of an acoustic guitar, this sound box is the main body of the guitar. Guitar strings are

anchored to the main body so that any vibration in the strings causes the sound box to vibrate at the same frequency. The sound box's much larger surface area compared to the strings allows it to disturb a significantly larger quantity of air molecules resulting in a more clearly audible sound. In an electric guitar, the vibrations of the spring are sensed and changed into an electrical signal that is amplified and played back through a speaker ("How Electric Guitars Work").

2.1.1 Plectrums

Regardless of the music style or plucking method, the device used to interact with the guitar string and produce a sound is called a plectrum. The speed, angle, dimensions and material of the plectrum can all have an impact on the sound created. It is therefore necessary to understand the effects of each individual variable to choose a plectrum that will produce the most desirable sound.

The variable with the most dramatic impact on sound is the displacement of the guitar strings at the point of release due to the plectrum. String displacement is typically a result of the force applied to pluck the string. A guitar string plucked with a greater force will produce a sound wave with a larger amplitude than a note created with less force. The force is also relevant when considering the conversion of this force into displacement and the factors that affect this transfer: namely plectrum properties. Plectrums that are thinner and made of materials with high compliance tend to transmit the force of the plucking motion poorly and release the string sooner and consequently with less displacement than a thicker and less compliant plectrum (Carral and Paset, 2008).

Another factor that affects the production of sound from a guitar is the angle at which the string is plucked. In a study of stringed musical instruments, a string plucked in the traditional direction parallel the X-axis (illustrated in Figure 1) produced a quieter note than a string plucked along the Z-axis. However, the longevity of the note created along the Z-axis suffered noticeably and decayed significantly faster than the notes produced when the string was plucked in the X direction (Fletcher and Rossing, 1998). The sound wave created when a string is plucked along the X-axis results in a sound wave parallel to the face of the guitar body.

Conversely, the sound wave created when a string is plucked along the Z-axis is perpendicular to the face of the guitar body. The perpendicular plucking is perceived as louder because in addition to the forced vibration of the sound box, the sound wave created by the string is directed into the sound box resulting in an amplification of the original sound wave created by the string. In the case of the perpendicular plucking, the sound created by the string is further amplified by the acoustics of the sound box. However, the perpendicularly produced note can at times decay rapidly because the string impacts the fingerboard of the guitar and hinders the string's ability to vibrate freely.

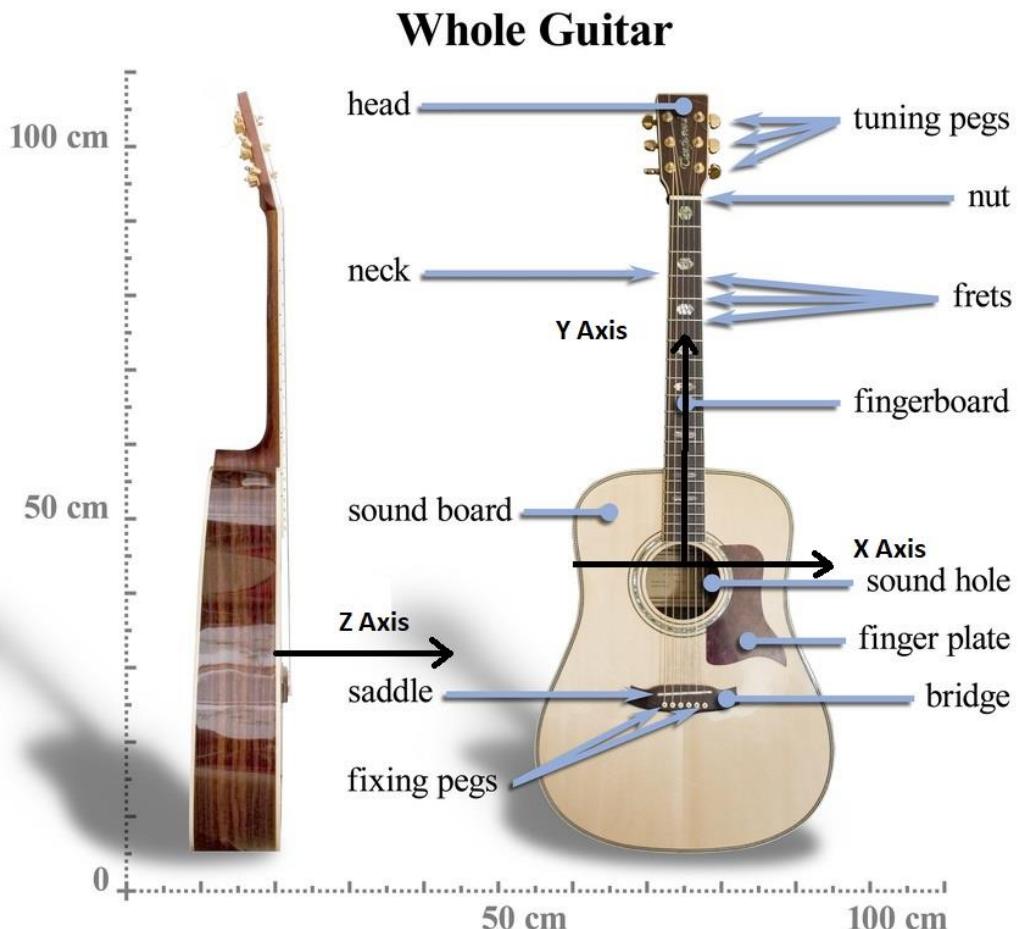


Figure 1: Representation of Plucking Directions (Adapted from Tanglewood Steel String Acoustic Guitar, 2010)

2.2 Harpsichord

The harpsichord is a stringed instrument developed in the 15th century in Europe ("Keyboard Instrument", 2017). The instrument was widely used before the 1800's, when it was largely replaced by the piano as the primary keyboard instrument used in music (Nave, n.d.). The harpsichord obtains its unique sound through the instrument plucking strings as opposed to hitting the strings with a hammer. Attached to each keyboard key is a harpsichord jack. The jack

contains a plucking mechanism, also known as a plectrum, a damper, and a tongue, as shown in Figure 2 (Beebe, 2010).

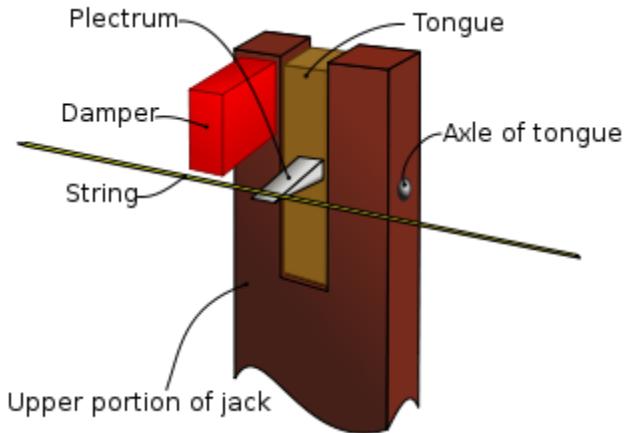


Figure 2: Representation of the Upper Portion of a Harpsichord Jack (Vladsinger, 2008)

The plectrum, while originally shaped from the bones of birds, is now often formed from various plastics such as delrin and celcon (Beebe, 2010). The plectrum is attached perpendicularly to the tongue of the jack. This tongue is constrained by an axle which allows the tongue to rotate, a spring on the back of the tongue which limits the motion of the tongue, and an angled edge which only allows the tongue to rotate in one direction. The damper is attached directly to the jack, offset slightly to the side and above the plectrum.

Figure 3 demonstrates the harpsichord plucking cycle. When a harpsichord key is depressed, the jack lifts and the plectrum make contact with the string. The plectrum flexes with the string and releases, producing a sound. When the key is released, the jack begins to lower. As the plectrum makes contact with the string, the axle pin allows the tongue to rotate slightly, enabling the plectrum to avoid displacing the string and “double triggering”. The instant the

plectrum fully moves below the string, the damper pad ensures any extraneous displacement in the string is eliminated. The spring behind the tongue returns the tongue to its original position, preparing it to be triggered again (Beebe, 2010).

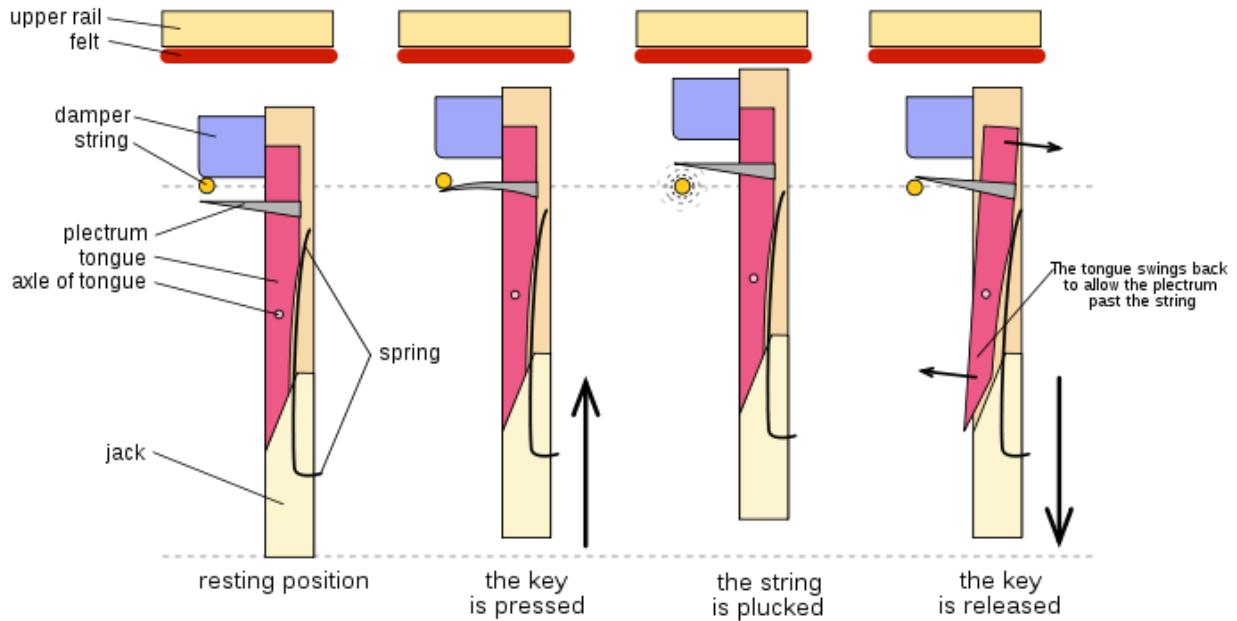


Figure 3: Representation of the Cycling of the Harpsichord Jack (Townsend, 2013)

Many harpsichord keys trigger more than one string at a time, allowing the musician to play strings that are an octave above or below normal pitch. Because the string is plucked as opposed to hit, it is difficult to alter the sound of each key being played. By using multiple jacks or keyboards, the harpsichord can play more tones and volumes (Beebe, 2010).

2.3 Mechanical Guitar-playing Devices

Patents and other existing devices can provide information about what potentially could go into a device that plays the guitar. Devices that are used or ideas presented in existing devices can provide valuable knowledge that can help guide the design process.

2.3.1 Patent Research

There are a significant number of patents that showcase devices plucking or strumming the guitar strings. Six of the patents that provided the most valuable information were the “Modular automated assistive guitar” (US7285709B2), “Automated player for stringed instruments” (US6723904B1), “Power operated guitar device” (US4037503A), “Apparatus for automating a stringed instrument” (US6166307A), “Automatic string musical instrument pick system” (US20120103163A1), and “Apparatus for playing a stringed instrument” (US 8546672 B1).

Modular automated assistive guitar (US7285709B2)

The modular automated assistive guitar is comprised of a base assembly, fretting assembly, pick assembly, and strumming mechanism. The device is modular, allowing for cross-compatibility between other stringed instruments (White, et al, 2005). This device only strums; it is unable to pluck any one or multiple individual strings. The device, shown in Figure 4, sits above the sound hole of the guitar and utilizes a slider-crank mechanism enclosed in a casing (10) to strum the guitar string with a pick.

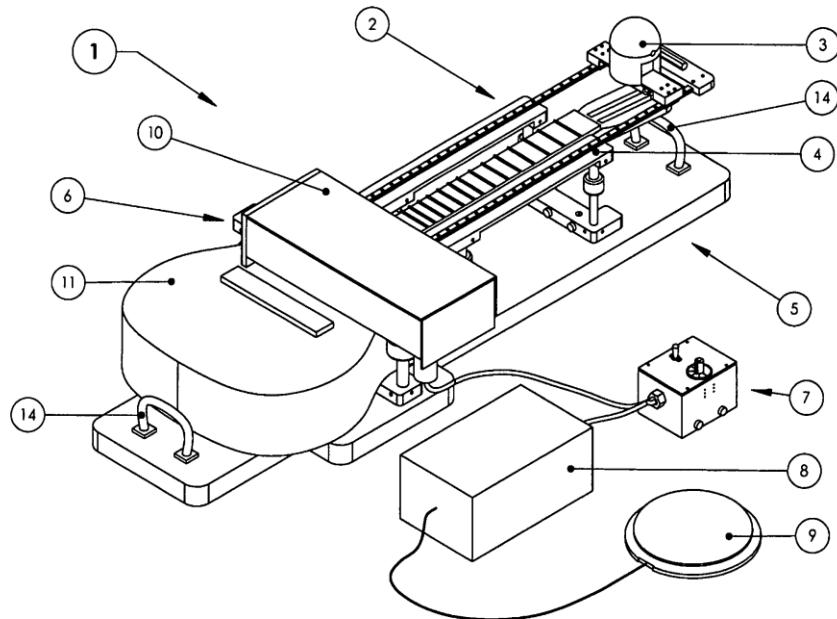


Figure 4: Image of the strumming mechanism enclosed in its casing (White, et al, 2005)

Figure 5 details the slider-crank mechanism that is protected under the casing. A crank-slider mechanism allows for the transformation of rotational movement into translational movement. The coupler (26) links the crank (29) to the whole pick assembly, which acts as a slider (20). The crank-slider mechanism is powered by a motor (13). The rotation of the crank rotates the coupler, in turn translating the slider. The six guitar strings are coplanar and parallel with the top surface of sound box. The motor-driven slider-crank allows for parallel horizontal movement of the pick across the guitar strings, while the pick is held perpendicular to the top of the sound box.

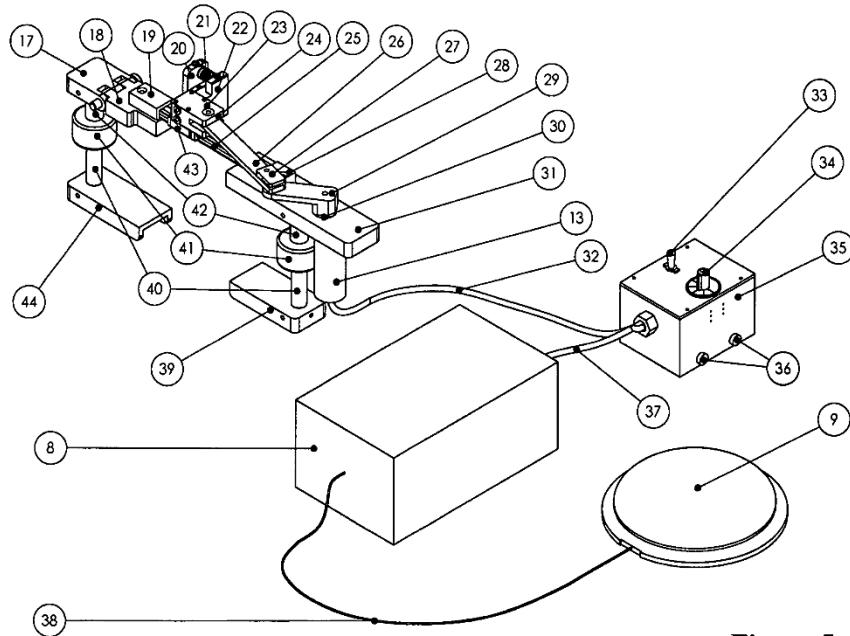


Figure 5

Figure 5: Image of the slider-crank mechanism as a guitar strummer (White, et al, 2005)

Figure 6 details the spring-lever system the pick is attached to, allowing for suitable compliance in the pick to produce the needed sounds from the strings of the guitar (White, et al, 2015). The top spring (21) and bottom spring (62) in the spring-lever assembly aids with the compliance of the pick when it strums across the strings in one direction by providing opposing spring forces. As the pick (61) strums from right to left, the top spring (21) provides a tensile spring force and the bottom spring (62) provides a compressive spring force to ensure that the pick maintains contact with the strings as it strums. The opposite occurs when the mechanism is strummed from left to right; the top spring (21) provides a compressive force and the bottom spring (62) provides a tensile force.

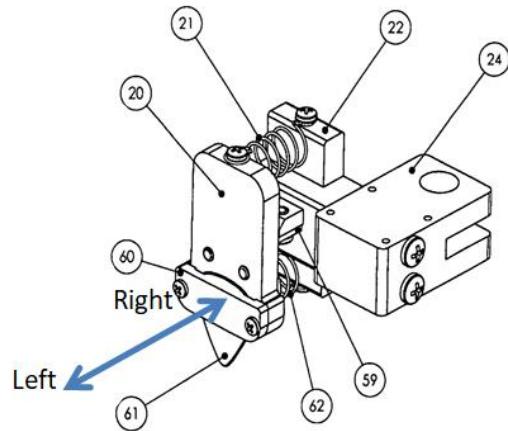


Figure 8B

Figure 6: Spring-level system on pick assembly (Adapted from White, et al, 2005)

Automated player for stringed instruments

The automated player for stringed instruments utilizes independent mechanisms for plucking and fretting the guitar. The plucking mechanism (Figure 7) consists of a multitude of plectra attached to a central hub on the output shaft of a rotary motor (Dolan and Gilmore, 2002). Axis of rotation of the rotary plectrum assembly is parallel with and above the guitar strings.

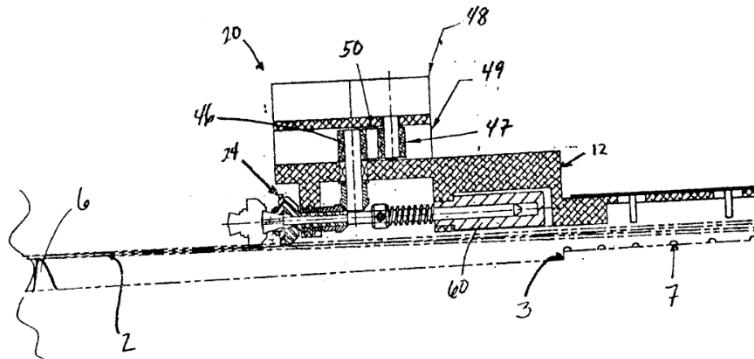


Figure 7: Cross-sectional view of the plucking mechanism parallel to guitar strings (Dolan and Gilmore, 2002)

The rotary plectrum (Figure 8) has four quills (30) that the user can adjust to have a longer reach. The conical recess (29) allow variance in the plectrum protrusion, changing how much the string is displaced and altering the amplitude of the sound wave produced (Dolan and Gilmore, 2002).

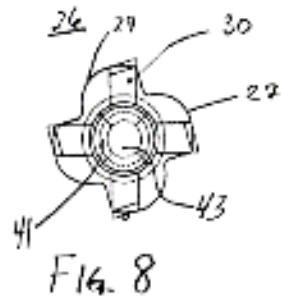


Figure 8: End view of the rotary plectrum body (Dolan and Gilmore, 2002)

Figure 9 shows the exploded view of the rotary plectrum assembly and displays how the quills (30) are radially adjustable. The amount that the quill protrudes is controlled by varying

the voltage sent to the solenoid actuator that controls the radial cam. As the cam is pushed into the conical recess (41), the plectra are pushed radially outward.

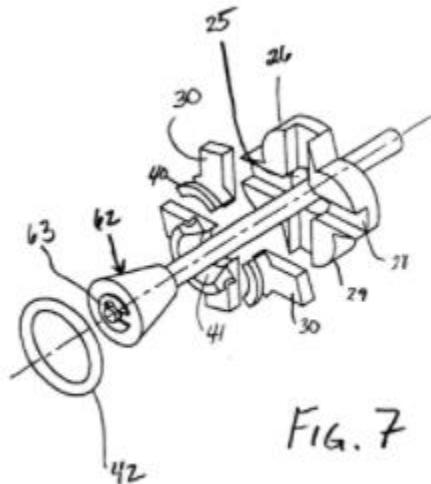


Figure 9: Exploded view of the rotary plectrum assembly (Dolan and Gilmore, 2002)

One rotary plectrum is assigned for each string, allowing for simultaneous playing of different strings. The plectra are spaced such that as the plectrum assembly makes contact with the string, there is adequate room to allow the strings to vibrate and create sound before it is struck by the next plectrum in the assembly. The difference in height between the plectrum and the plectrum hub allows the string to vibrate.

Power operated guitar device (US4037503A)

The power operated guitar device plays a guitar in an untraditional way. The device (Figure 10) moves certain cylinder assemblies (44, 46, S-1, 48) to make quick and light pressure contact with the strings, allowing the strings to vibrate after contact (Jacobson and Becker, 1974). Each cylinder strikes a single string, allowing multiple strings to be played at once. This

striking method is different from how the strings of a guitar are traditionally strummed or plucked. The cylinders are attached to a spring loaded button (36, 38) that allows the whole assembly to retract back into its starting position after making contact with the strings.

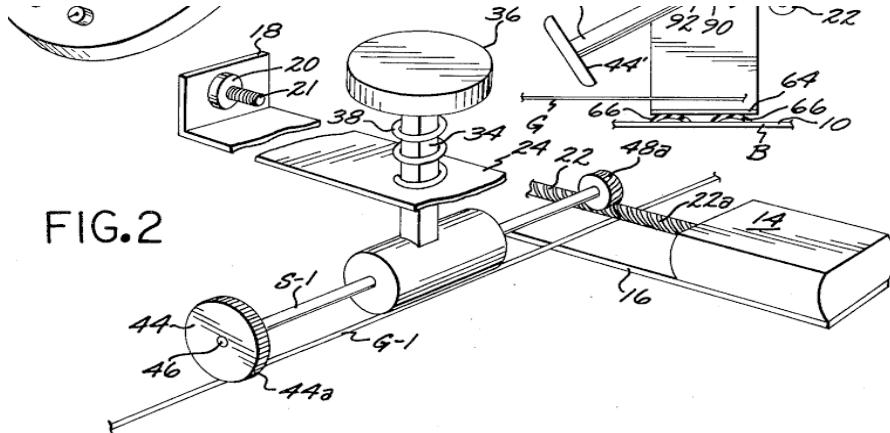


FIG.2

Figure 10: Spring loaded button (36, 38, 34) attached to cylinder assembly (44, 46, S-1, 48) (Jacobson and Becker, 1974)

Detailed in Figure 11, a worm (22) contacts the worm gears (48) of the cylinder assembly. When the worm and worm gear are meshing, they allow the extremity of the end gear (44) to make rotatable pressure contact with the guitar string.

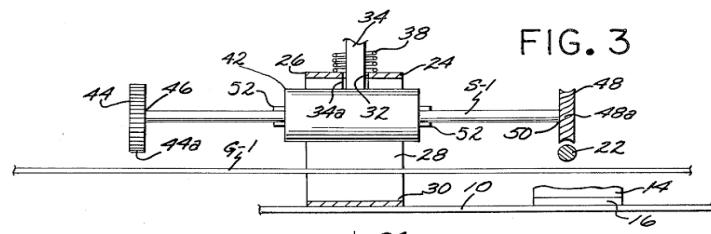


FIG.3

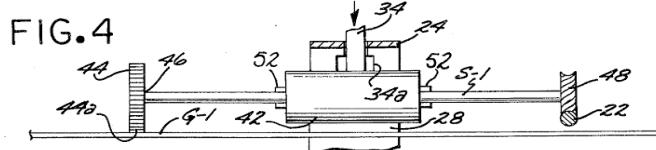


FIG.4

Figure 11: Stopping mechanism for the cylinder (Jacobson and Becker, 1974)

Apparatus for automating stringed instruments (US6166307A)

The apparatus for automating stringed instruments included a plucking mechanism for the strings, a fretting mechanism, and a linkage system that maintains tension to stay tuned (Caulkins and Caulkins, 1998). The plucking mechanism has one actuator (122) for each string, allowing for simultaneous plucking of multiple strings, shown in Figure 12.

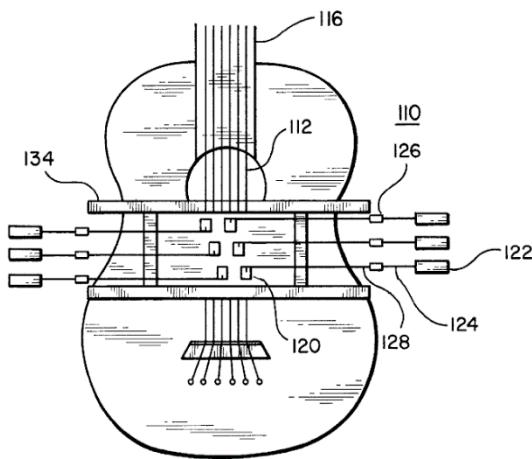


Figure 12: Figure of device ready to be used on guitar (Caulkins and Caulkins, 1998)

The portion of the device that comes into contact with the string is rotated about its axis by an actuator. This design generates reciprocating motion of a pick to vibrate the guitar strings and generate sound.

Automatic string musical instrument pick system (US20120103163A1)

The automatic string musical instrument pick system (Figure 13) utilized a solenoid-driven ratchet and pawl mechanism in combination with a rotary plectrum to pick the strings of a guitar. Ratchet and pawl mechanisms are indexing mechanisms that turn rotational movement into a series of step movements. The plectrum wheel (16) is driven by the solenoid (26). The

starting position of the solenoid is when the solenoid core (23) is at its fully extended (leftmost) position. As the solenoid core is retracted into the solenoid (moving to the right), the tip of the striker (25) contacts the tip of the plectrum (19) at (27), causing the plectrum wheel to rotate in a counterclockwise direction. A tip of the plectrum wheel makes contact with the guitar string (10) and produces a note. The solenoid converts its linear motion of the solenoid core (23) into the rotary motion of the plectrum wheel (16). The detent assembly (30) ensures that the plectrum wheel (16) only indexes once when the solenoid core (23) is retracted (DuPra, 2010).

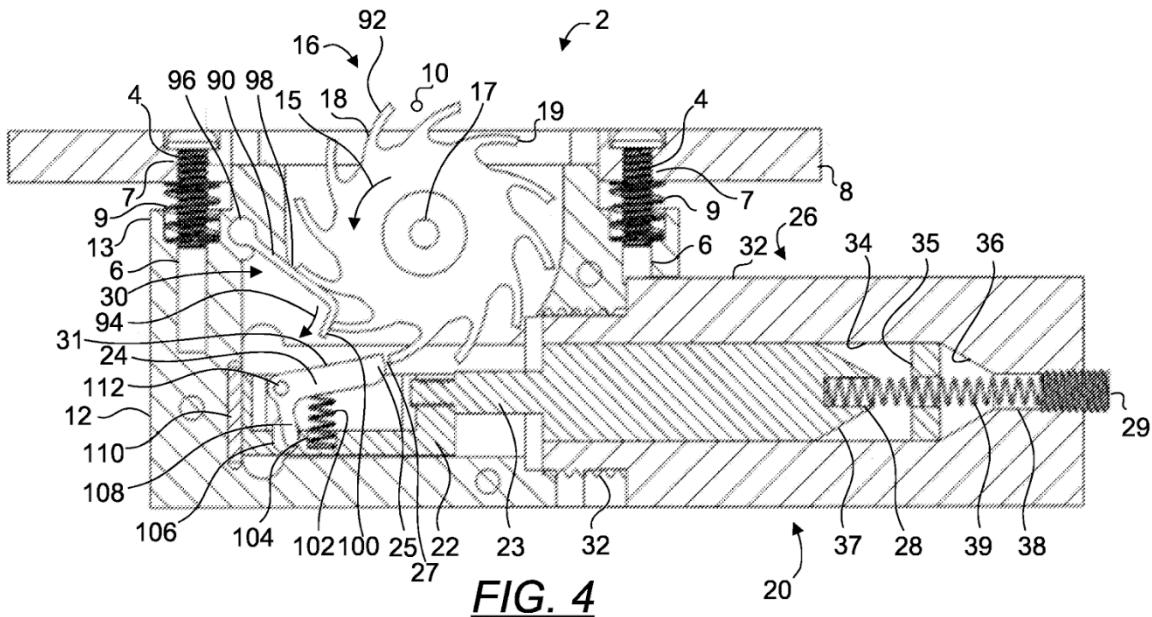


Figure 13: Cross sectional view of the device (Dupra, 2010)

When the solenoid core is extending to its leftmost position, the striker (24) pivots counterclockwise about its hinge (112), causing the striker to duck underneath the plectrum wheel tooth (18) as seen in Figure 14. Though the striker (24) maintains contact with the

plectrum wheel tooth (18), it does not cause the plectrum wheel to rotate and does not cause the tip of the plectrum wheel tooth (19) to make contact with the guitar string (10). When the striker (24) has passed by the plectrum wheel tooth (18), the striker spring (102) provides a force that causes the striker (18) to pivot about its hinge (112) in a clockwise direction. This returns the striker (24) to its starting position, where the tip of the striker (25) is in contact with the tip of the plectrum wheel tooth (19) at the contact point (27).

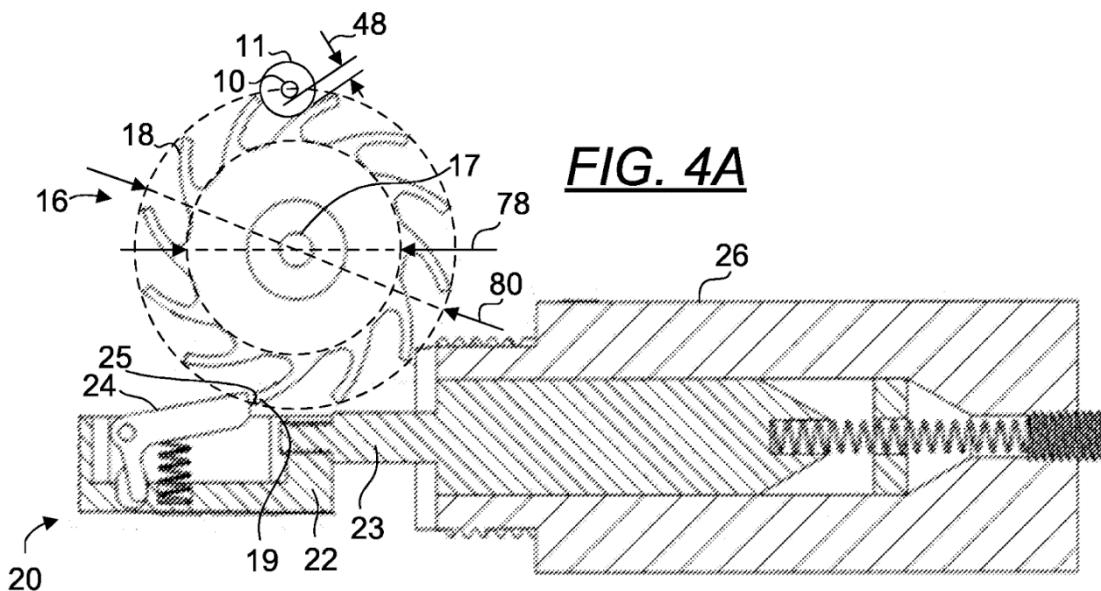


Figure 14: Cross sectional view of the solenoid, actuating assembly, and plectrum wheel (Dupra, 2010)

Apparatus for playing a stringed instrument (US 8546672 B1)

The apparatus for playing a stringed instrument utilizes solenoids to drive levers that pick guitar strings, as shown in Figures 15-17. The pick assemblies can have picks on one side or both

sides of the assembly (Pinzone, 2012). The solenoid actuators (106) transfer their linear motion through the links (146) into the plectrum assemblies (319). These links (146) are guided through the holes (343) in the shaft (316). The linear motion is then converted to rotary motion when the pick assemblies rotate about a shaft (306). When the actuator is extended and the transfer links are pushed, the plectrum assemblies (319) rotate counterclockwise about the shaft (306) causing the picks (409) to strike the guitar strings. When the actuator retracts, plectrum assembly (319) rotates clockwise around the shaft (306), causing the pick (409) to strike the guitar string and produce a note (Pinzone, 2012).

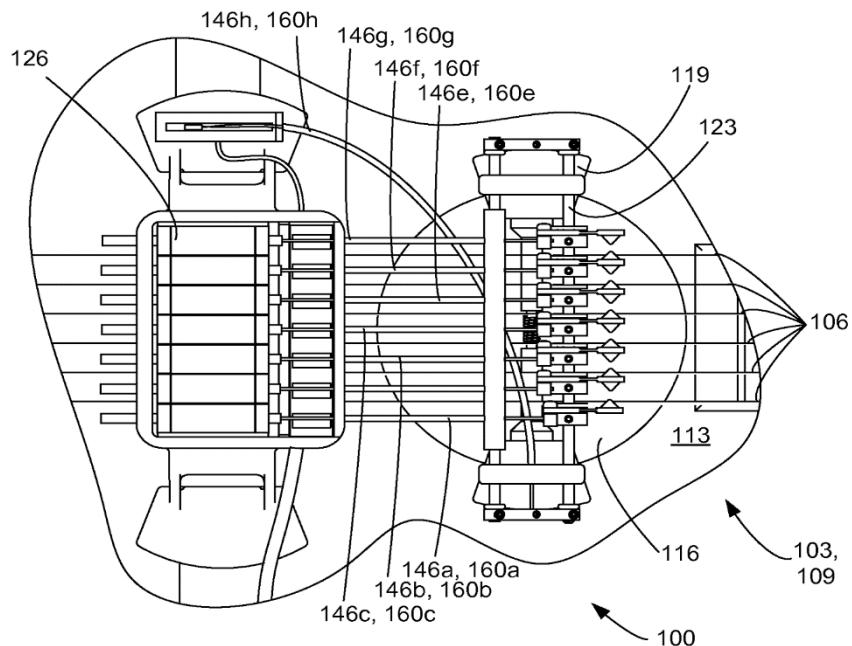


Figure 15: Top view of the device on instrument (Pinzone, 2012)

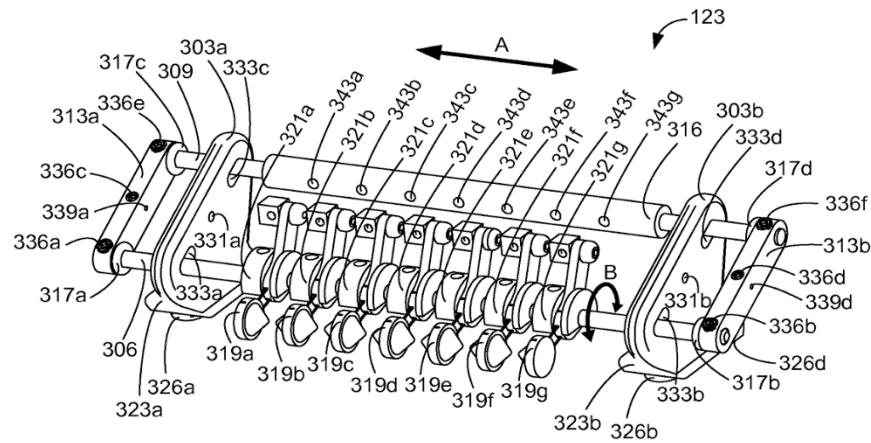


Figure 16: View of the picking assemblies aligned with link holes (Pinzone, 2012)

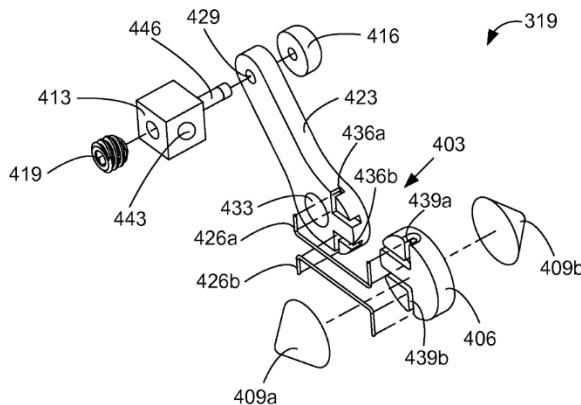


Figure 17: Exploded view of plectrum assembly (Pinzone, 2012)

Strengths and Weaknesses of Certain Design Aspects

From the research and analysis of the patents, certain desired qualities and characteristics were identified. Rotary plectrums have an advantage, as they do not need to be reset into position after picking, but also have the drawback of a higher complexity and need for custom manufactured parts. Linear picking devices have the advantage that they can utilize preexisting

picks and the designs are simpler than rotary plectrums, but they are unable to pick continuously in one direction. Picking in one direction ensures a constant pick angle each time, while picking in two directions could require a pick with a variable angle, adding to the complexity of the device. Linear picking devices pick in two directions, versus the one from a rotary plectrum, which could be seen as a drawback or a benefit depending on perspective. No one ideal way to pick a guitar string can be determined from the patents, but desirable characteristics of these patents could be utilized.

2.3.2 - Non-Patent Plucking/Strumming Mechanisms

Many non-patented devices exist for the purpose of playing stringed instruments. Several of these instruments allow for individual plucking of strings using various methods.

StrumBot

The StrumBot is an automated guitar capable of strumming and picking individual guitar strings. It has a two guitar-pick system (Figure 18). The device has a strumming, robotic arm controlled by a rotational actuator at the base of the device and a picking mechanism at the end. The arm can extend the picking mechanism along the length of the string, allowing for plucking at different points on the string. Each pick is used to strum in an individual direction and changes based on the direction of strumming. This motion is created by a rotational actuator at the end of the robotic arm, adjacent to the picks themselves. The same plectra are used for strumming and picking. The StrumBot is capable of plucking power variability through varying the angle of the

picks, and fast strumming patterns by adjustment of the speed of the rotational actuator at the base. (Carnegie and Vindris, 2016)

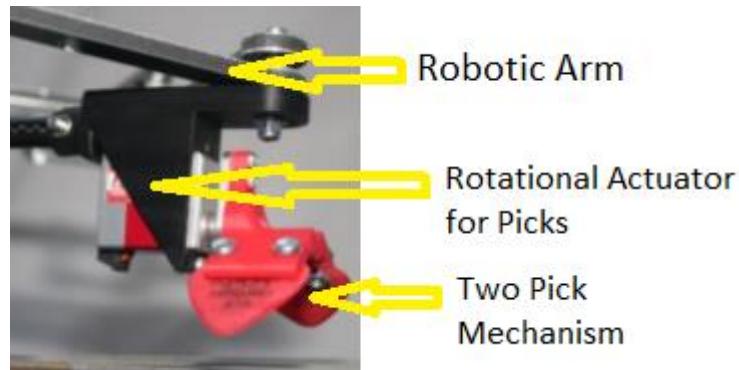


Figure 18: Two pick strumming mechanism for StrumBot (Adapted from Carnegie and Vindris, 2016)

Robotic Bass Picking

This paper compared three picking mechanisms (Figure 19) for a robotic bass to be played in a fully robotic orchestra. Two of the mechanisms were wheel type mechanisms, one large and one small, where picks attached to a wheel rotate to pluck a string. The third mechanism was a solenoid system that moves a pick back and forth, striking it perpendicularly to the length of the string. The specific instrument that the testing took place on only had one string. (Carnegie et al., 2011)

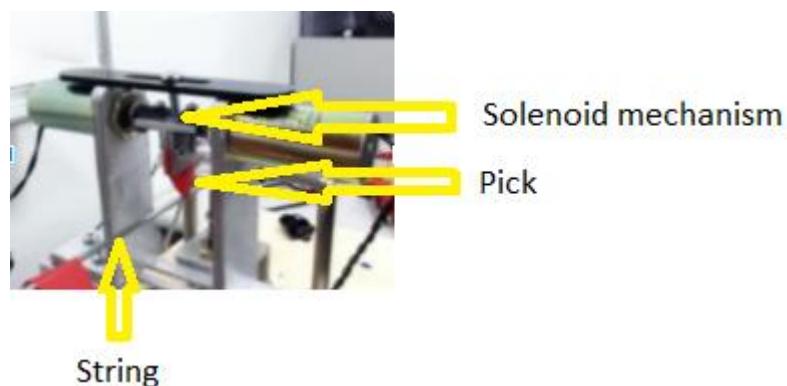
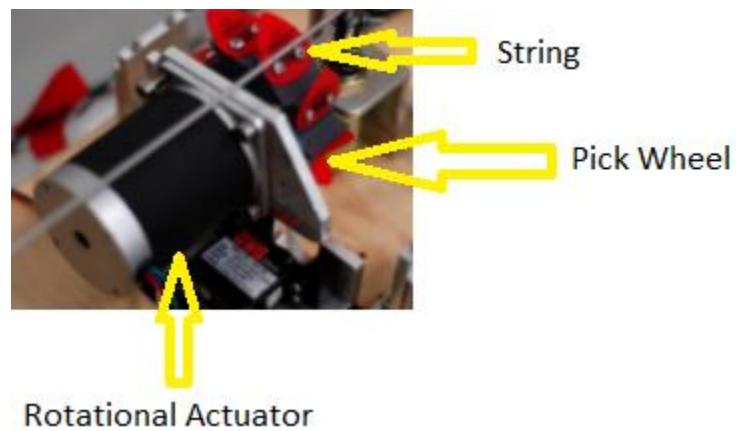
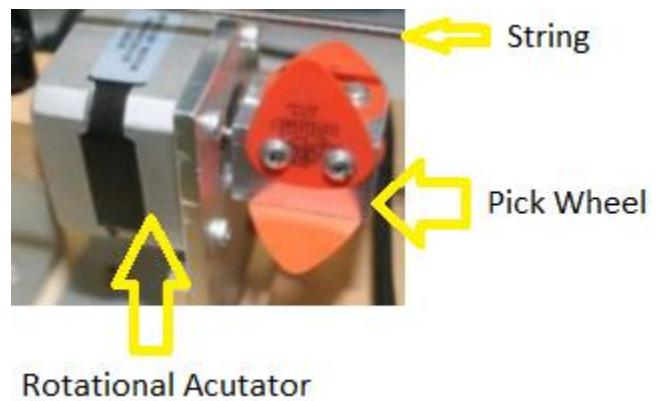


Figure 19: Small wheel, large wheel, and solenoid plucking mechanisms (All Adapted from Carnegie et al, 2011)

The mechanisms were characterized to determine the consistency of the amplitude of each note as well as picking speed. Of the two-wheel systems, the smaller mechanism produced the most consistent note amplitude, but the slowest picking speed. The large wheel mechanism was the fastest of the mechanisms, reaching up to 25 notes per second with varying consistency. The higher rate makes sense due to the greater number of picks on the wheel (8) coupled with the equivalent angular velocity. The solenoid system created highly consistent amplitudes on the same cycle strokes. The amplitudes created by the forward strokes were consistent, as were the amplitudes created by the backstrokes. This method had an overall consistency close to that of the large wheel mechanism. However, the amplitudes of these two strokes when compared together were not similar. This indicated that the solenoid was not plucking the string in exactly the same way during each half of the solenoid strokes, causing different amounts of string deflection in each direction. The solenoid was capable of a higher rate than the small wheel, but lower than that of the large wheel.

From a cost perspective, the large wheel mechanism was the most expensive, followed by the small wheel and solenoid mechanisms respectively. A relatively minor alteration in the picking mechanism that would add more control would be the addition of a servo motor to control pick elevation. Traditional guitar picks have an increasing compliance with increasing distances between the point of string contact and the location where the pick is held. Differing the elevation of the pick would alter the compliance and the point of release and by extension the amplitude of the created note.

2.4 Component Testing

2.4.1 Force Deflection Tests for Guitar Strings

Basic force testing must be completed to determine the amount of force necessary to pluck a guitar string. The testing was completed using Vernier Lab software and a pull force sensor to determine the force on a string. A distance of one eighth of an inch and one quarter of an inch from the tested guitar string were each marked. The force required to deflect the guitar string was measured with an attached force sensor. The force sensor attached to a guitar string was pulled from zero displacement to one of the measured increments perpendicular to the original string position. The string was pulled over the sound hole of the guitar, which is the target area for plucking the guitar. Five trials were performed for each measured distance with the low E (thickest) and high E (thinnest) strings. From each trial, the maximum force was determined to be the force necessary to reach the marked distance. We assumed the string would be acting as a spring. The relationship between the force applied to the string and the displacement of the string from its neutral position was therefore assumed to be linear. From the data, a linear regression was calculated to determine the force-displacement of each string. The force displacement curve with linear regression equation and R^2 value for the high E string can be seen in Figure 20 and the curve for the low E string can be seen in Figure 21.

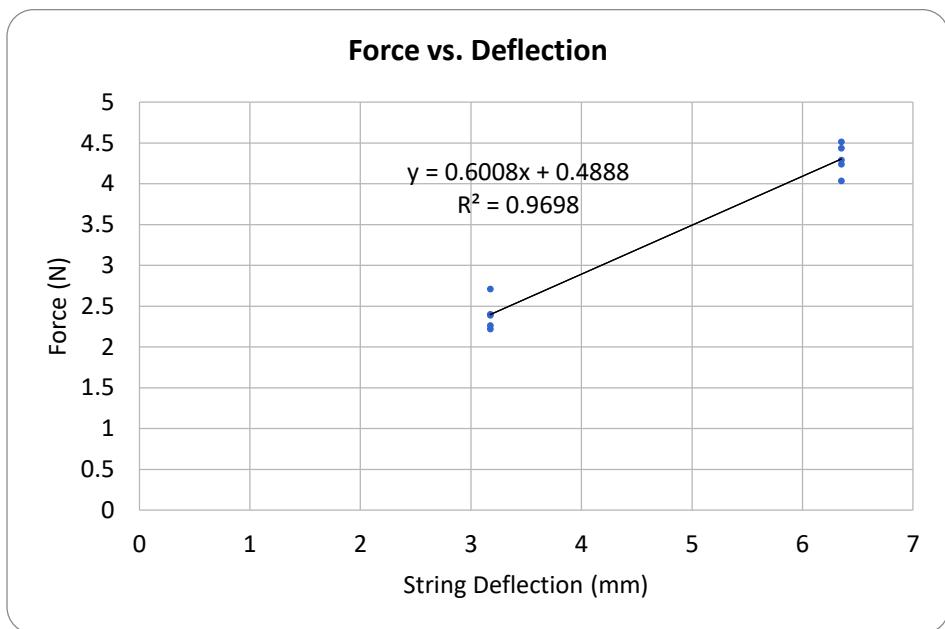


Figure 20: Force-Displacement for high E string

Based on the information, the force displacement relationship of the high E string over the sound hole of the guitar is 0.60 N/mm^2 .

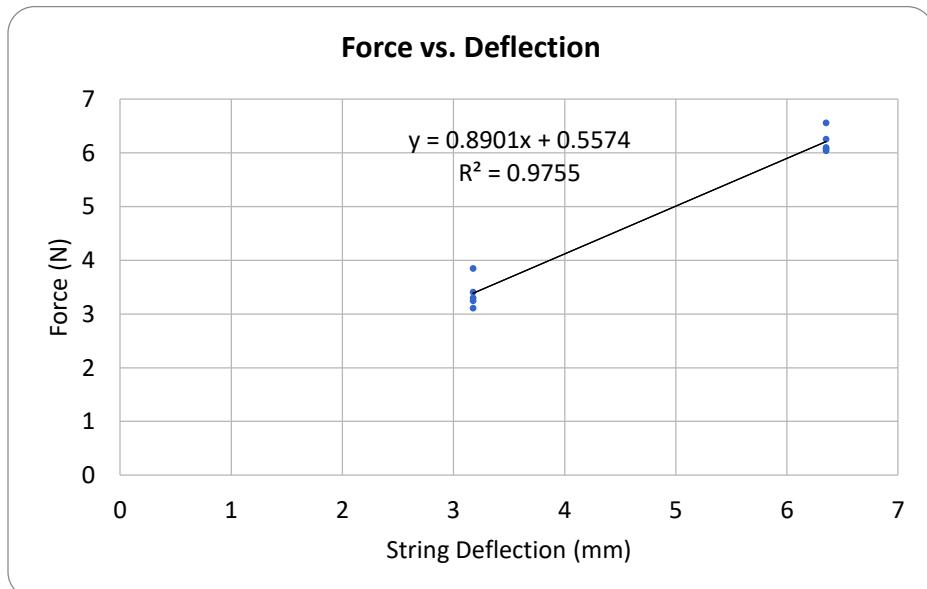


Figure 21: Force-Displacement for low E string

Based on the information, the force displacement relationship of the low E string over the sound hole of the guitar is 0.89 N/mm.

The maximum acceptable length of a plucking stroke to prevent interference of strings was determined to be an eighth of an inch, which is equal to 3.175 mm. The following calculations determine the amount of force necessary to pluck a guitar string to this level of deflection:

High E string

$$0.6008 \frac{N}{mm} * 3.175 \text{ mm} + 0.4888 N = 2.396 \text{ N}$$

Low E string

$$0.8901 \frac{N}{mm} * 3.175 \text{ mm} + 0.5574 N = 3.383 \text{ N}$$

3. Project Approach

3.1 Objectives

While Kurt currently has a device to actuate guitar strings, it has limitations. It is a single servo with a flexible plectrum that plucks the strings in a strumming pattern. Because of the sensitivity of the device, and its inability to skip over strings, the control over plucking specific strings is minimal.

The goal of this project is to design and build a versatile guitar plucking device that satisfies the variety of client needs.

3.2 Assumptions

In the design of this device, some assumptions must be made. We have assumed that the guitar and device will not be subject to operating conditions outside the norm for guitar use. In addition, we are operating under the assumption that users of the device will have had appropriate instruction and not misuse the device. Furthermore, our proposed device relies upon slippage between the guitar strings and our designed plectra. Within this system, we have assumed that the friction is negligible. Another assumption we made is that the electronic components we used are operating within the listed tolerances (I.e. a solenoid rated to give 10 kOhms \pm 1 kOhm is between 9 and 10 kOhms).

4. Needs Assessment and Design Specifications

In applying the engineering design process to this project, the first step is understanding the problem. This involves recognizing the needs of the users, defining the requirements of the solution, and identifying any constraints the project must adhere to.

4.1 Needs Assessment

In order to create a device effective for the application, it is vital to understand the capabilities of the end users. A conversation with Mr. Coble indicated that users of the assistive technology guitar will have a range of physical and mental abilities. For example, some of the users may have full dexterity of their entire body, but have limited cognitive and intellectual abilities, while other users may be highly functioning from a mental perspective, but they may have limited dexterity in their hands.

The user interface for a device is often specific to individuals based on their specific abilities. Some users interact with interfaces that sense light or motion and others might use a physical button or knob.

4.1.2 - Device Requirements

With the user capabilities in mind, there are certain specific attributes the device must contain. Through background research on how to create a musical note from a string instrument and discussions with the sponsor on user capabilities and available materials, the team has produced the following list of design requirements that must be addressed when producing the plucking instrument.

Plucking Individual Strings

Mr. Coble currently has a servo-motor powered device that can strum all 6 strings in a sequential order by an oscillating pivot arm with a plectrum attached at the end. However, this mechanism has no component that can lift the plectrum away from the face of the guitar. This does not allow the user to skip strings or only strum in one direction and not the other. The device must allow for strings to be plucked individually and remain independent from the movement of the plucking of other strings.

Background research has revealed that artificial guitar plucking mechanisms often suffer from sounding mechanical. (Carnegie and Vindris, 2016) Therefore, the new design must aim to maintain a smooth, natural tone to the notes plucked. To do so, the device will need to pluck the string with consistent deflection, in the same location on the string, and with the same contact area of the plucking apparatus each time the string is plucked. In addition to this, Mr. Coble would like the device to either work in tandem with his existing strumming mechanism or also contain a strumming mechanism, allowing one guitar to play a variety of songs.

Part Selection

The guitar plucking device is not expected to be produced for a mass market. The design is intended to be tailored to each individual's specific physical and intellectual abilities. However, Mr. Coble has requested that the device remain inexpensive. Many of the parts are typically purchased by Mr. Coble himself, and those who would be interested in purchasing an assistive guitar have indicated that cost is a large concern.

Future assembly and modification of the device will be undertaken by Mr. Coble himself, so the device and its parts must be readily available for when new projects arise. Mechanical and electrical parts must be available off the shelf or from a manufacturer, ready to use. To allow for flexible production based on different stringed instrument dimensions, the base of the device will need to be created from a stock material. While certain critical parts that will not change between different designs for different applications may remain more complex, parts that will require adjustment will need to remain simple. The device will aim to utilize parts that Mr. Coble has incorporated in previous P.A.M instruments to help ease the troubleshooting of the device in the future.

Input Method

In creating a device without the user's physical abilities specified, the device will require adaptability to a variety of different input methods. To accomplish this, the design must require a signal that can be generated through mechanical, optical or motion sensing. This will accommodate a large selection of individuals to play the instrument despite having different physical and intellectual abilities. Voltage has been used in the past as the signal that translates the user input to the device; it is not required to use this method if another is deemed more effective.

Applicable Instruments

The main focus of this project is a plucking device for a guitar primarily because Mr. Coble has found it to be one of the more popular instruments to play. However, the device must

be able to be modified to fit on a variety of different instruments. While not all parts will require quick adjustment features, the design should allow for expansion or contraction of the device based on space available on different stringed instruments. Some notable instruments that should be accounted for include the banjo and the bass guitar, and in general string instruments with a flat bridge.

4.2 - Design Specifications

Picking Cycle Timing

The device must have a maximum time of $\frac{1}{8}$ of a second to play a note and rest to be ready to play another note. This is because the device must, at a minimum, be able to play 32nd notes at 60 beats per minute.

Vertical string deflection limits

The device must only allow plucking perpendicular to the face of the guitar up to 3.175 millimeters. If the plucking were more than this, in order to create the deflection necessary for a clear note, there is a strong chance the neck of the guitar would make contact with the string, interfering with the sound.

Horizontal string deflection limits

The device must not allow string deflection parallel to the face of the guitar and perpendicular to the string greater than 3.175 millimeters. This is to be sure that the strings do not interfere with each other as they are being plucked; one at a time or both at once.

Amplitude of notes

The device must be able to play notes which have 80% or more of the amplitude of a note created on the same guitar using the same string and same string deflection, using the same plectrum, but without the device. This is to be sure that the physical device on the guitar does not compromise the audible volume of the guitar.

Power Source

The device will be battery powered. This is so the device can be used when an external power source is not available.

Mounting

The device should be mounted to the guitar in such a way that no alterations need be made to the physical body of the guitar (i.e. screwing into the body of the guitar). This is to minimize any effects on the vibrations of a guitar's sound box when a string is plucked.

Mounting Compatibility

The device must be able to mount to any acoustic guitar with a dreadnought, parlour, jumbo, round-shoulder dreadnought, auditorium, or classical body style. The device should also be able to be attached to all hollow body, semi hollow body, or full solid body electric guitars. This will ensure that most guitars donated to Mr. Coble will be compatible with our plucking device. Furthermore, the device will attach to the guitar through an external interface on the guitar. This is so that the device can be securely fixed to the guitar body and prevent movement during use.

Size

The device should not exceed the size of the convex hull of the guitar by more than 20 cm in any direction. This is to be sure the device can be easily carried by one person.

Weight

The device should weigh a maximum of 5 kg. This is so that it can be carried by almost anyone.

Multiple user interfaces

The device must accept a common input (i.e. voltage) that can be produced by multiple user interfaces. This will allow for users with different abilities who require different input methods to be able to use the guitar.

Individual String Plucking

The device should have 6 inputs: one for each individual guitar string. This is so each string can be controlled separately. This will allow for each string to be played individually and, selectively, multiple strings will be able to play together at the same time.

Cost

The device should cost no more than \$150.00 for materials and manufacturing to create a fully functional device.

Reproducibility

Power supply, fasteners, and actuators need to all be commercially available. This is so that parts are readily available to create more than one device.

5. Preliminary Designs

In beginning to explore preliminary designs, the group decided to investigate multiple concepts as the potential basis for the design. These preliminary designs focused on using different actuation mechanisms for manipulating the plectrum.

5.1 Mechanisms

5.1.1 Bidirectional Single Solenoid

Figure 22 showcases the first design, which focuses on creating a mechanism that could be used to pluck an individual string and could be replicated for each string. The design uses a solenoid with plectrum attached to the end of the plunger. The solenoid is attached to the guitar with the bracket seen in Figure 23, which allows for an added level of adjustment of the solenoid. The solenoid has an on and an off position; the on position is on one side of a string and the off position is on the other. As the solenoid moves from the on to the off position, and vice versa, the plectrum at the end of the arm plucks the string, playing a note. The string is plucked over the sound hole in the case of an acoustic guitar or over the pickups when used with an electric guitar to maximize the sound created by the instrument in both cases.

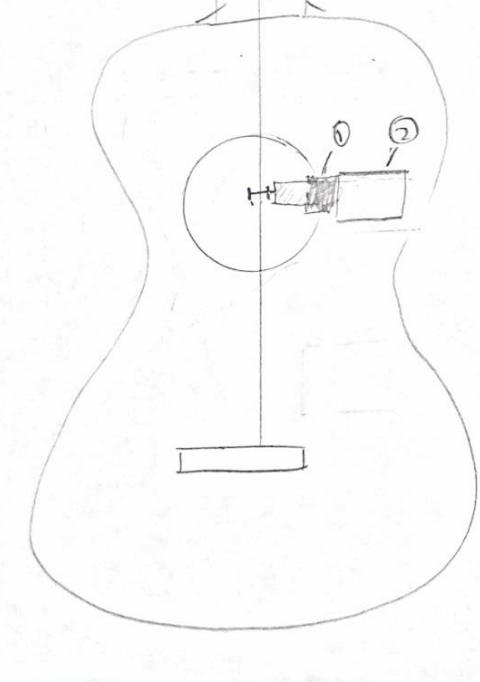
This device is permanently mounted directly onto the face of the guitar. In a design involving all six strings, three solenoids would be placed on either side of the sound hole. The actuators on either side of the sound hole would be attached to a single base plate.

MQP

Design Concept #1

October 8, 2017

- Non-Vertical Plucking
- Plucking one string
-



Design Decisions:

- Solenoids, not actuators
- Screwed into sound board
 - rubber washers
- 3 holes for mounting
- Top of sound board
- Standard pick at end of actuator
- Height adjustability
- Pluck over sound hole or pickups
- 10mm stroke

Concerns:

- Where to place/mount Arduino
 - back behind bridge?
- Sustaining requires a lot of constraining points

= Solenoid

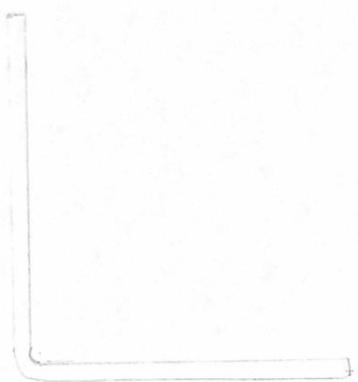
↑ = "on" position

↓ = off position

Figure 22: Design Concept 1

MQP

Design 1 Bracket



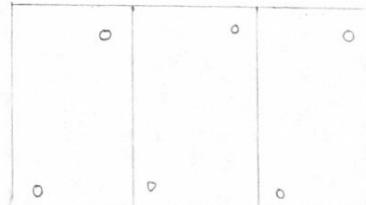
Side view



Front



Top



thickness : $\frac{3}{4}$ "

- 2 diagonal holes to ensure tight constraint
- can add more, would not suggest less

Figure 23: Design Concept 1 Solenoid Bracket



Figure 24: Zero Order Prototype of Scissor Lift Support for Design Concept 1

5.1.2 Servo Motor with Rotary Plectrum

The second design, seen in Figure 25, utilizes servo motors to pluck each individual string, as in Mr. Coble's initial design. In this set up, a custom created plectrum device would be attached to the servo motor. This plectrum device (Figure 26) would be conical to reduce the chance of breaking due to shear stress. The tip would be pointed to reduce the material in contact with the guitar string.

The servo motors would be placed on a base plate elevated above the sound hole of the guitar, with the supports equally spaced around the sound hole. Three motors would be placed equidistant from each other on the side closest to the guitar bridge, and three closest to the neck of the guitar. The centerline of each servo motor would be aligned with a string, with the servo motors closest to the neck over strings 1, 3, and 5, and the servo motors closest to the bridge over strings 2, 4, 6. The motors would be placed on the underside of the base plate, with the Arduino and power source placed on top.

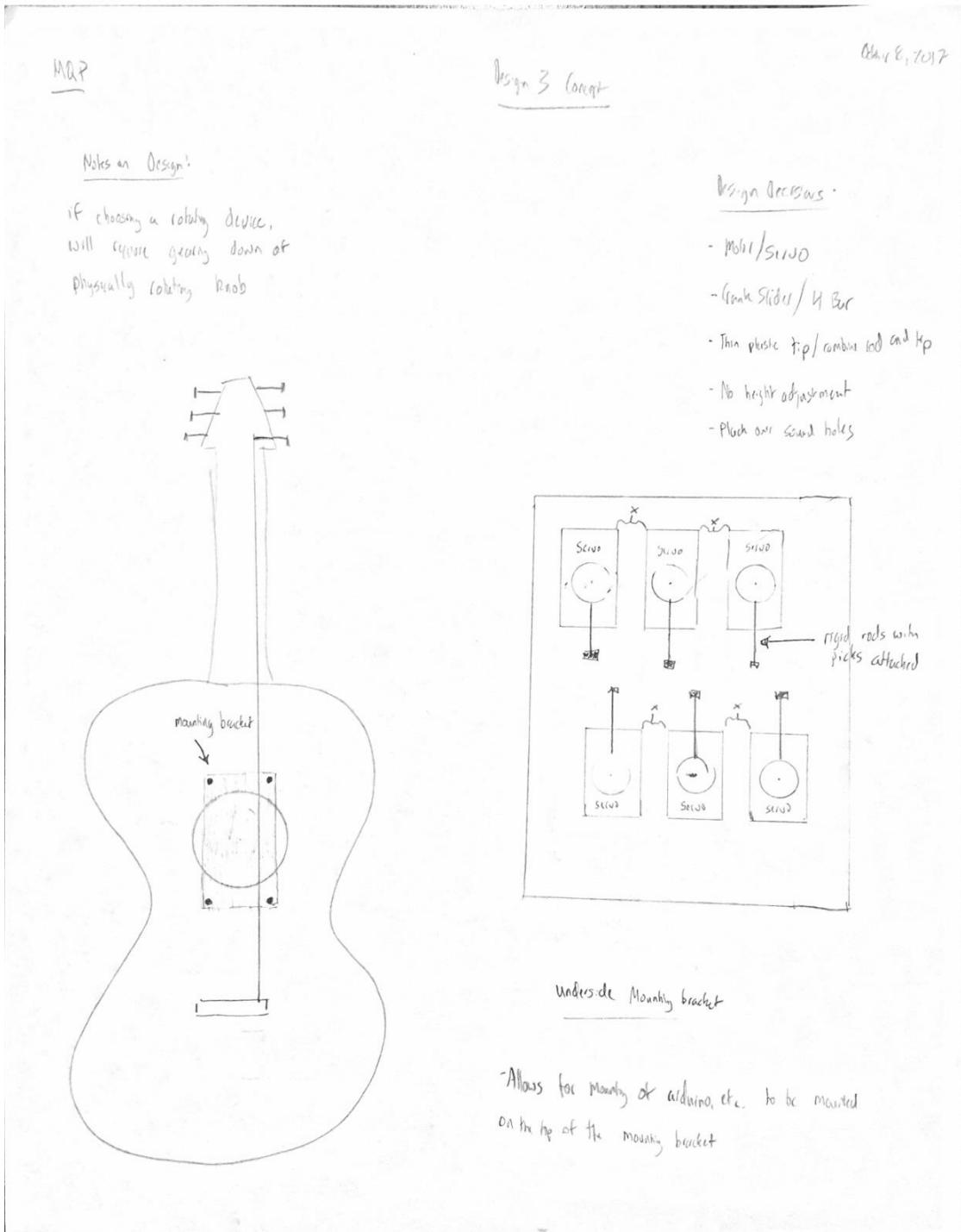


Figure 25: Design Concept 2

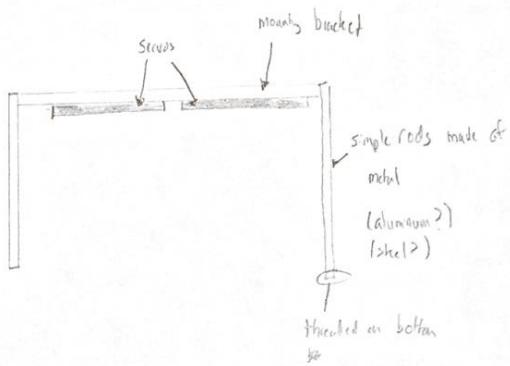
MQP

Design 3 Mounting Bracket

October 9, 2017

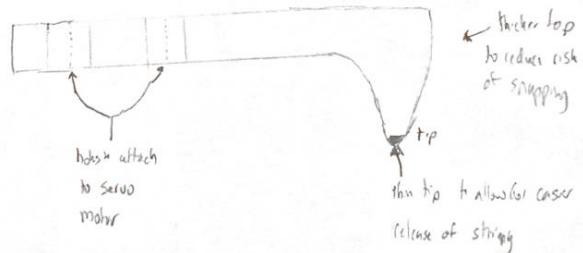
Notes (Associated with Design 3 concept):

- each servo spaced such that things are staggered in a Zppr pattern, with spacing X determined by spacing of guitar strings
- The shocker / rigid rod tension (compared to in the current Tesla Guita) should help reduce bending of the rod, which affects the range of motion needed by the servos



Plectrum Device

- narrow the tip to a cone style tip to create a smaller impact point



* ↑ signal inputs

Figure 26: Design Concept 2 Support System and Custom Plectrum

5.1.3 Solenoid with Harpsichord Jack Plectrum Attachment

The third design concept involved using a solenoid to trigger plucking device designed similarly to harpsichord jack (Figure 27). The plectrum and tongue would be 3D printed from Delrin. The jack and tongue would have one hole drilled through their sides, and have a metal pin inserted to allow the tongue to pivot. The harpsichord jack, much like in an actual harpsichord, would have a slanted edge running underneath the tongue to stop the tongue from rotating in one direction, and a leaf spring helping the tongue return to its neutral position when rotated the other direction.

The solenoid would not require Arduino coding to keep the plectrum on one side of the guitar string. Due to the jack's ability to slide over the string without plucking it, each pick cycle would involve a full extension and contraction of the solenoid. The jack would be constrained to the solenoid using screws and holes drilled in the plunger of the solenoid. The solenoid would pluck the string in a vertical manner, requiring the solenoid to be mounted directly above the sound hole of the guitar. A rigid base plate, manufactured from hardwood, acrylic, or aluminum, would be directly attached to the existing guitar holder designed by Mr. Coble. Each hole for attaching the solenoid would be a clearance fit, allowing the solenoid to slide to adjust to various guitar string locations.

MQP

Simple Harpsichord Jack

November 1, 2017

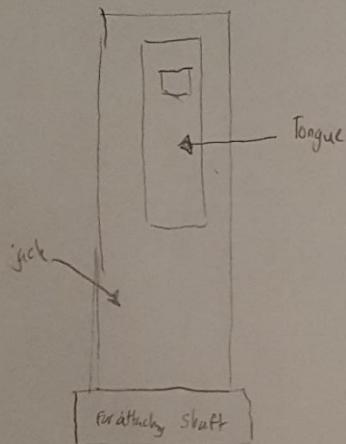
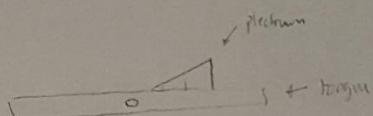
will need spring mechanism here

pivot point
in jack

11/8" leaf
spring? apparently
cheap and easy to install

Tongue

- 3D print entire plectrum + one go
 - should allow for hole to be added automatically
 - flexible plastic should allow some give
 - too brittle?
 - will require fatigue calculations

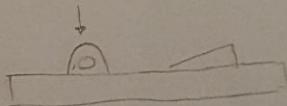


Possibility: 3D print entire thing?

↳ allows for easier holes line up

If hole is too small:

slot for shaft (also be included in jack design)



Spring selection: less than 0.5"

in compressed state

↳ spring selection may determine

size of plectrum piece

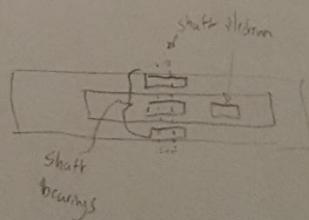


Figure 27: Simple Harpsichord Jack Design

5.1.4 DC Motor Driven Rotary Plectrum and Indexing Mechanism

The fourth design concept utilizes a rotary plectrum in combination with an indexing mechanism to achieve the goal of plucking a guitar string. There is one mechanism per string, allowing for more control with timing of strings. The driver gear of the indexing mechanism is driven by a DC motor (Figure 28). The rotary plectrum is attached to the driven gear in the indexing mechanism. The rotary plectrum has two picks that are 180 degrees apart. After the pick contacts the string, the 180 degrees of separation allows the string to vibrate freely before the plectrum contacts the string again. The indexing mechanism reduces the output of the motor to allow for multiple rotations of the motor to equate to one or half a rotation of the rotary plectrum. For example, 6 rotations of the motor would equate to a half rotation of the rotary plectrum.

Figure 29 shows that the mechanisms are mounted above the guitar strings. The supports wrap around the guitar and have a soft padding where the mounting contacts the guitar to ensure that no damage is caused to the guitar. To ensure that each mechanism has enough space and clearance, they are staggered. This gives the device adequate room for mounting and decreases the likelihood of interference between devices.

With this design, there would be no need to have a reset or home position, as the rotary plectrum can pluck in a continuous motion. The indexing mechanism and rotary plectrum allow for more flexibility in ratio of the indexing mechanism and number of picks on the rotary

plectrum. However, this design would require custom-made parts. The footprint of this device can also be large depending on the size of the motors and mounting mechanism.

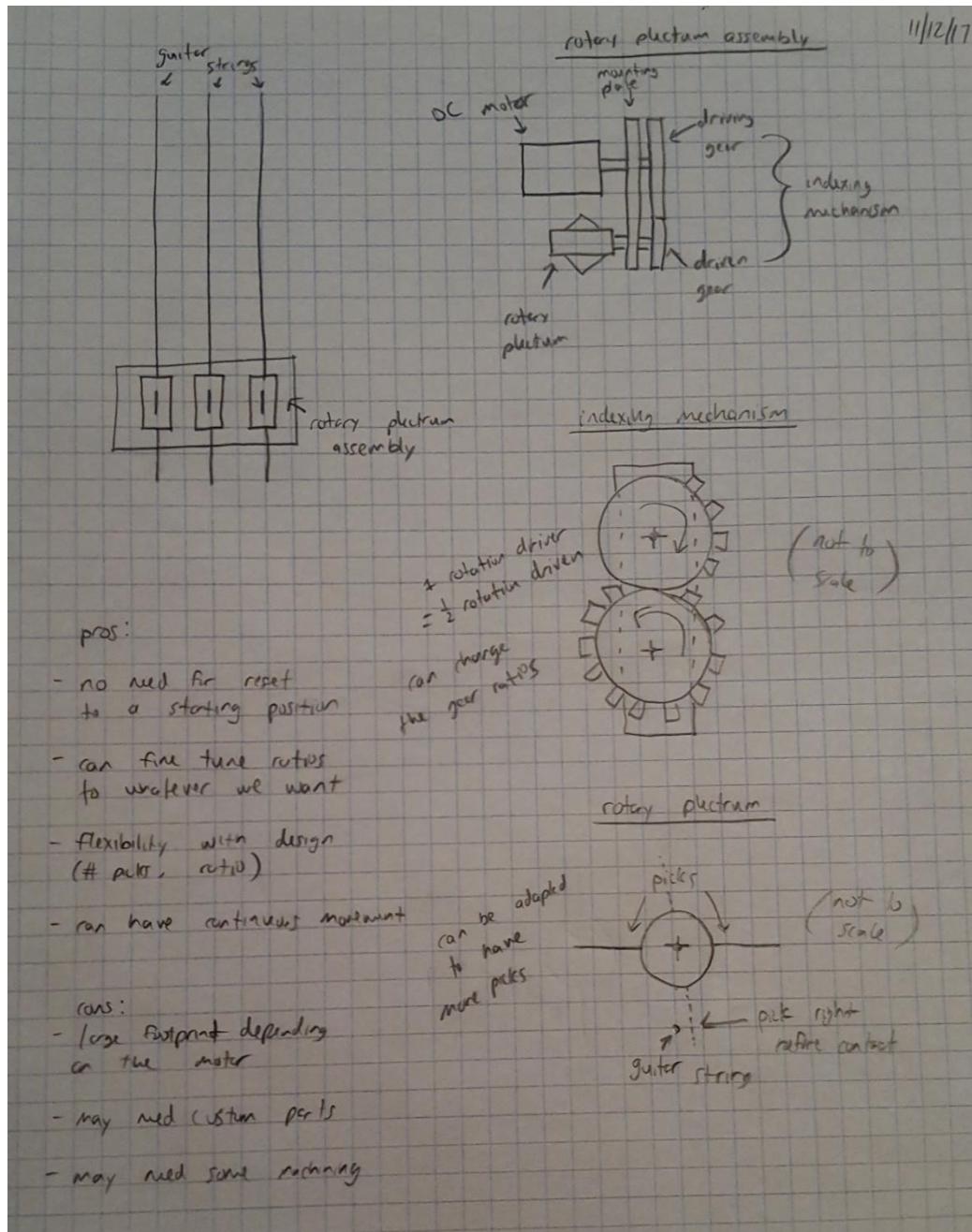


Figure 28: Sketch of the rotary plectrum and indexing mechanism

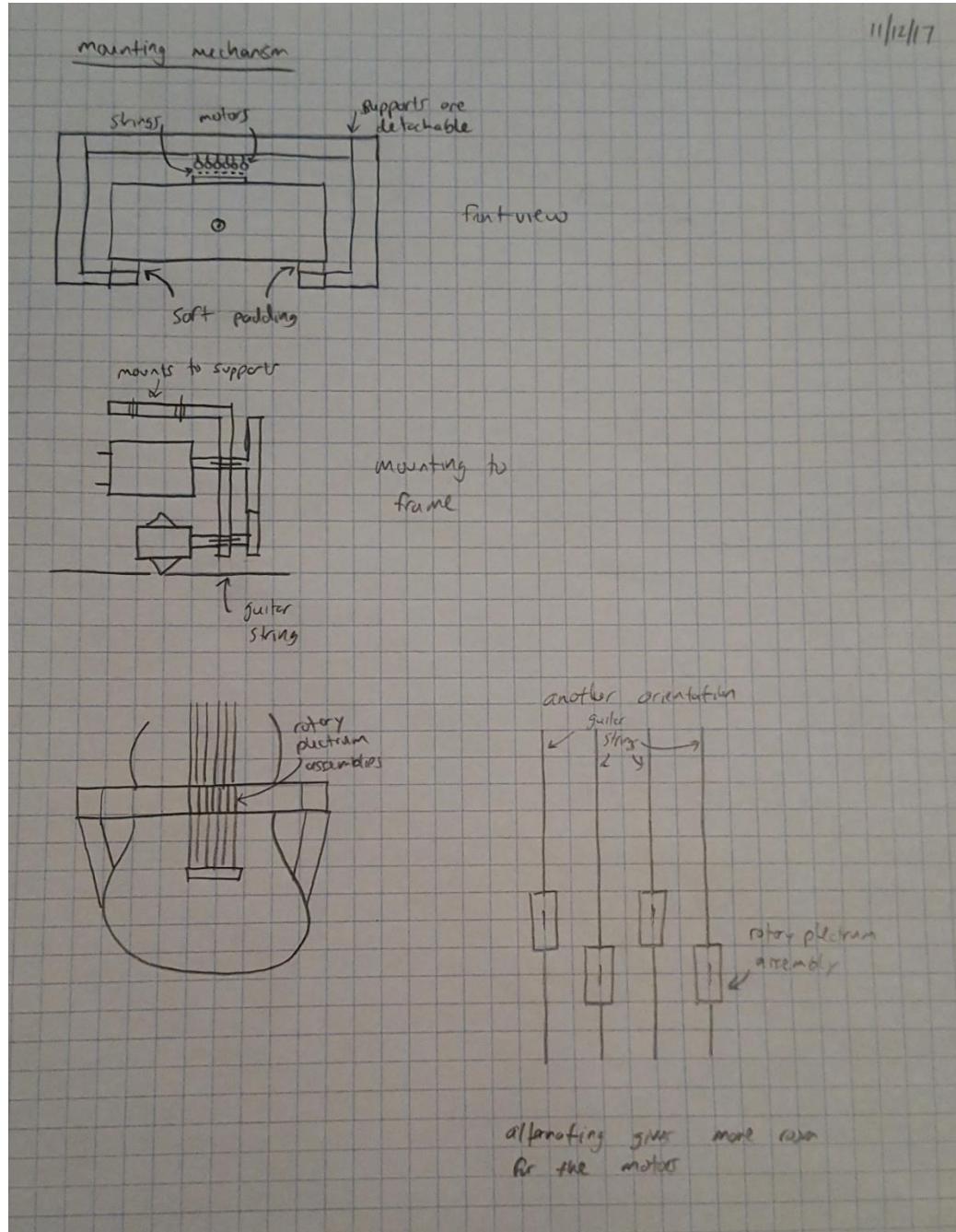


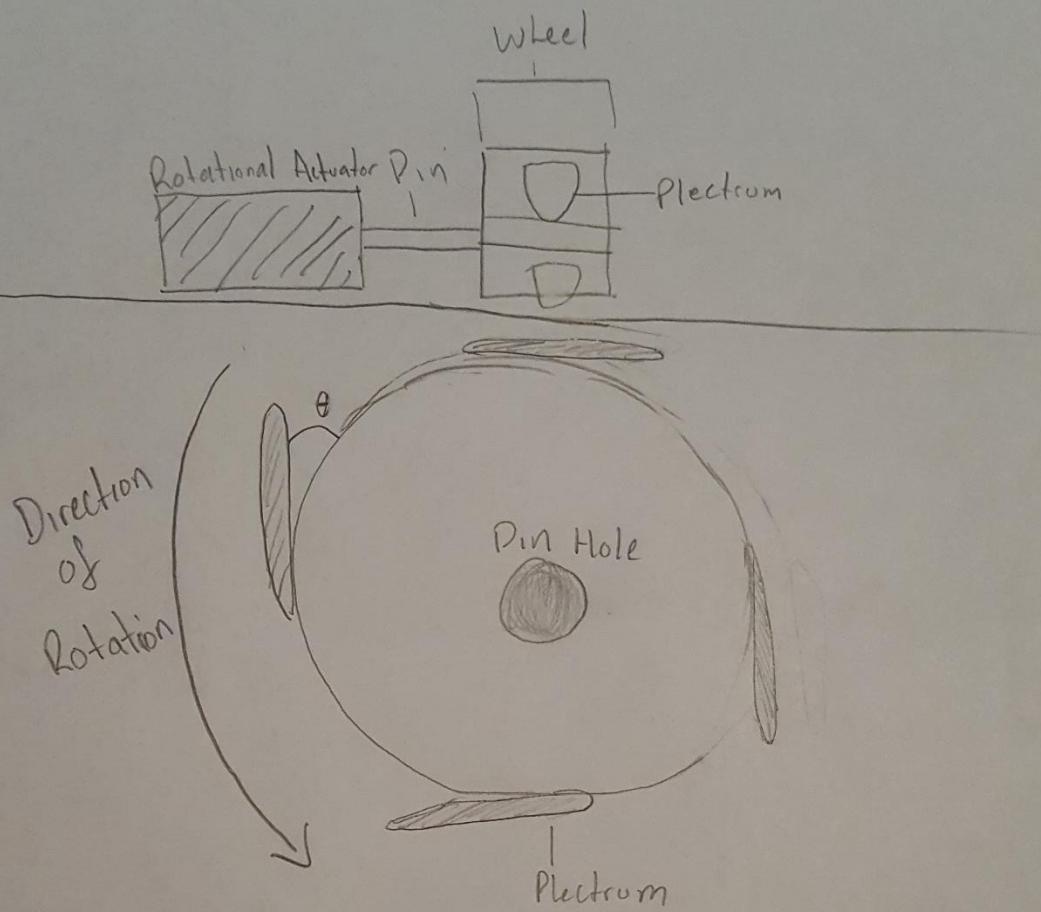
Figure 29: Mounting System for rotary plectrum and indexing mechanism

5.1.5 Four Plectrum Pick Wheel Design

The rotating plectrum wheel (Figure 30) would have any number of plectra attached at an angle to the wheel, evenly spaced. The wheel must be small enough so that the wheel only plucks one string. The number of plectra would depend on the rotating speed of the wheel and how quickly the device would need to be able to pluck the guitar strings. As the wheel spins, it would pluck the string adjacent to it. The angle of the pick would allow the pick to slip over the string at an angle as it would in the instance of a human guitar player. This device has the potential for extremely high plucking speeds dependent on the motor used, but there is concern surrounding the motor's ability to start and stop instantaneously at specific positions. The device would be either suspended over the face of the guitar or mounted on the side of the guitar (Figure 31).

4 Plectrum Pick Wheel

11/12/17



θ =angle from 'tangent line to wheel' to plectrum

Rotation speed: 120 rpm (minimum)

- Angled away from string for easy release

Figure 30: Four Plectrum Pick Wheel Design

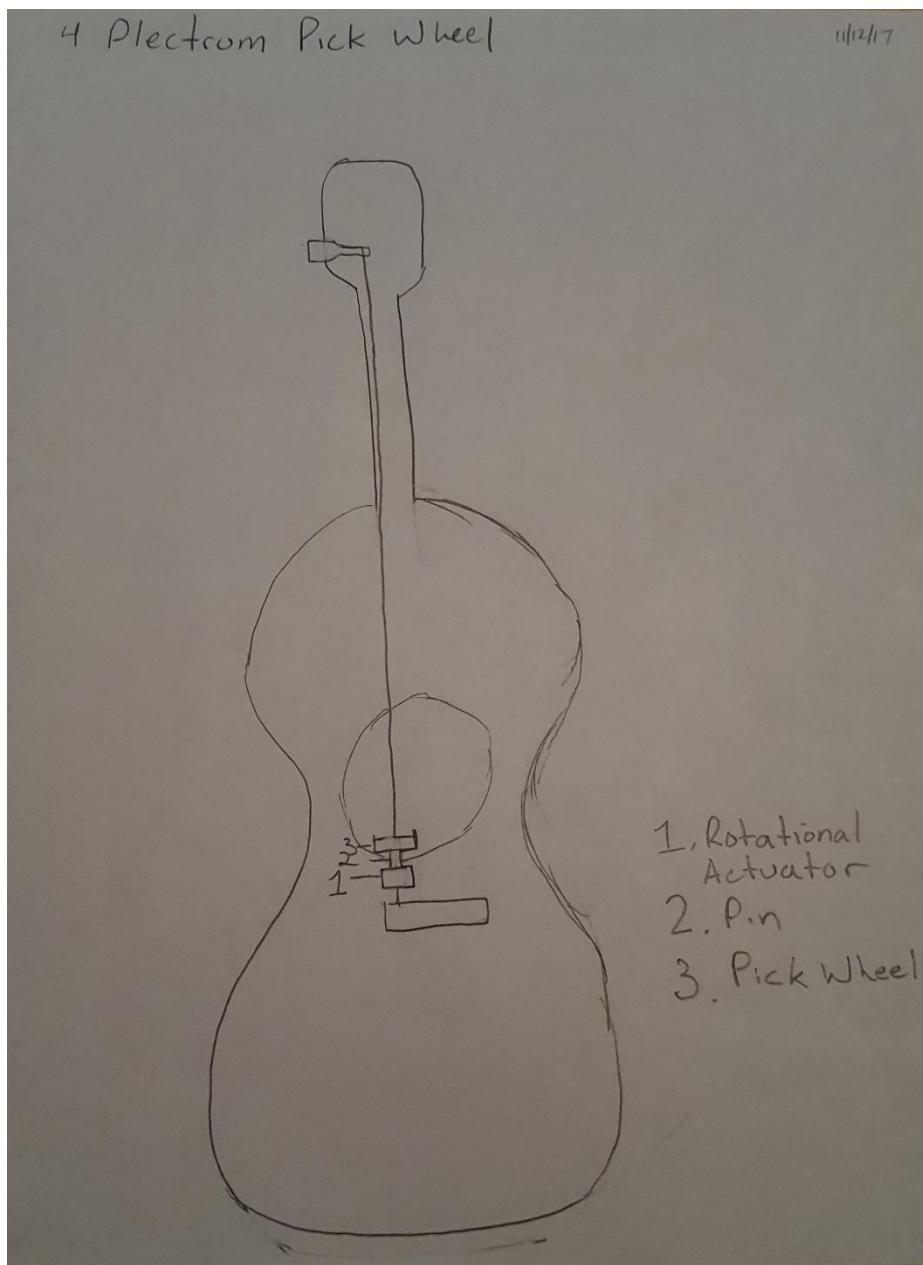


Figure 31: Mounting and Placement for the Four Pick Plectrum Wheel Design

5.1.6 Servo Driven Plucking Device

Another proposed device was also driven by a servo, however, instead of relying on a lever arm to interact with the string, this design utilized a set of gears (Figure 32). Two gears

were to be used to translate the rotational motion of the servo in the vertical plane to rotation in the horizontal plane (with respect to the guitar face). The final gear in the assembly, the one rotating horizontally, would have a protrusion that acts as a plectrum to pluck the string. In order to give an approximate actuation similar to how a guitar is usually plucked, the diameter of the second gear would be large enough to approximate linear motion within the range of string deflection.

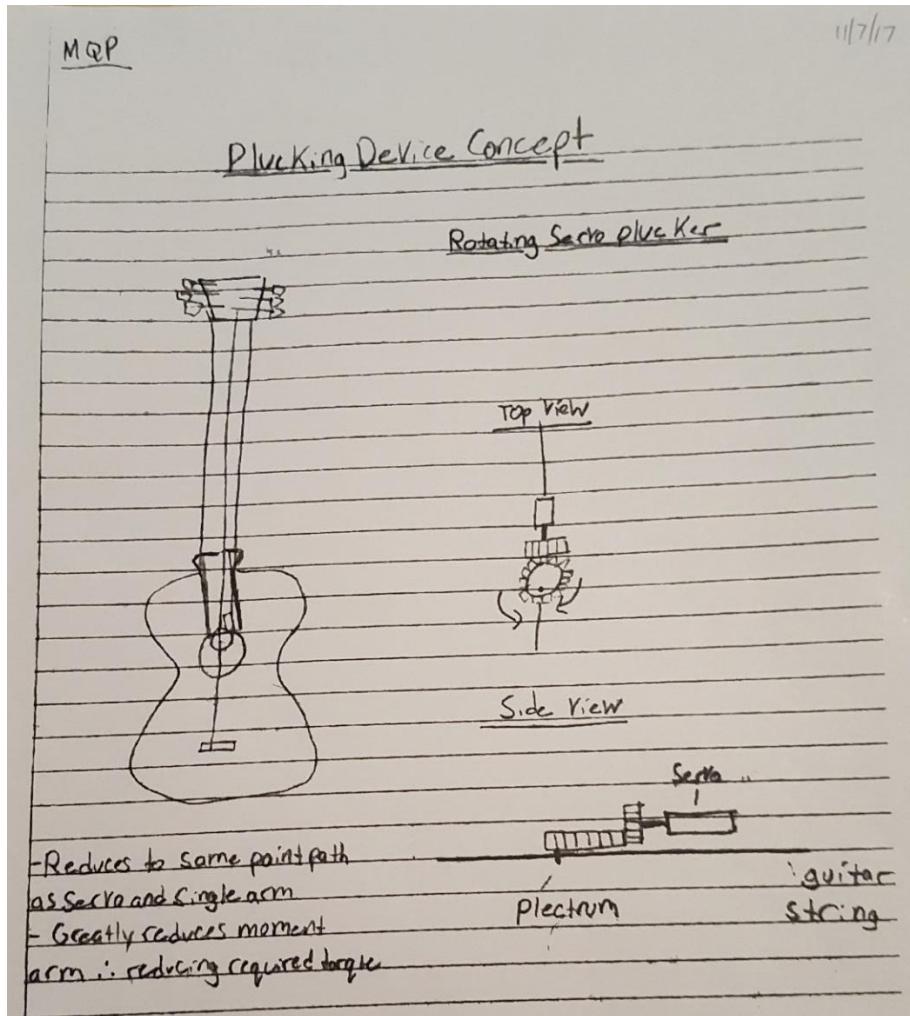


Figure 32: Servo Driven Plucking Device Concept Sketch

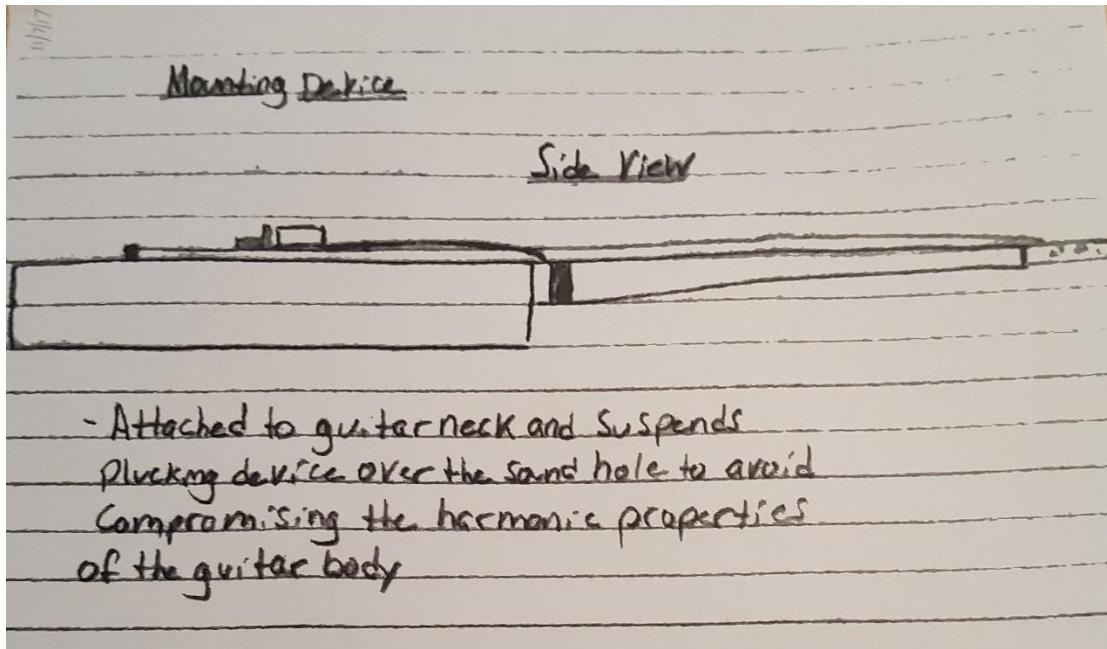


Figure 33: Mounting for the Servo Driven Plucking Design Concept

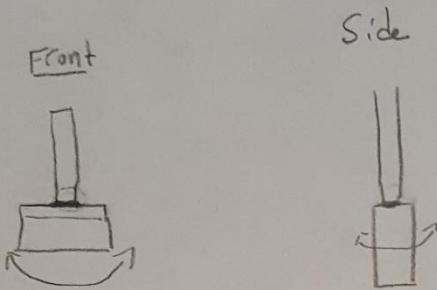
5.2 Mounting

5.2.1 Rotating Clamp Surface Mounting Design

One of the difficulties with mounting a device to a guitar is the variance of body contours from guitar to guitar. To achieve the tightest mounting with a minimal chance of damage to the guitar or sliding of the mounting device, the force applied by the clamp needs to be perpendicular to the surface it is placed on. The surface mounting design shown in Figure 34 utilizes a rubber pad attached to a ball joint which comes in contact with the guitar body. The ball joint allows the rubber pad to rotate with three degrees of rotational freedom to fit to the contour of the guitar body and is attached to the mounting device

11/12/17

Rotating Clamp Surface



Clamp attachment site is on a rotating joint with one degree of freedom. When the surface of the clamp comes in contact with the guitar body it rotates to be perpendicular to the contour

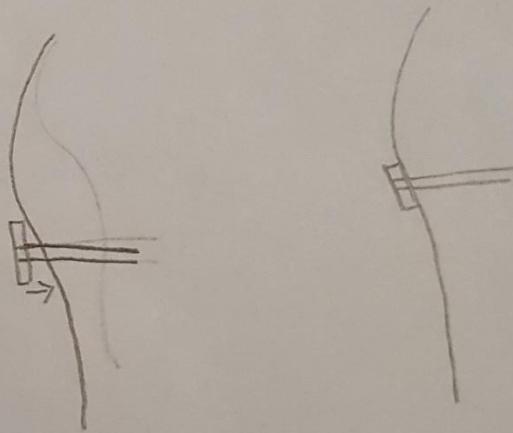


Figure 34: Rotating Clamp Surface Mounting Design Concept

5.2.2 Preliminary Full Mounting System Designs

A mounting system for the solenoids and electronics is required, as interference with the guitar body is not desired. The mounting system would attach onto and detach from the guitar in

a way that would not alter or damage any part of the guitar. It must also hold all of the electronics that are required to pluck the guitar strings. The mounting system would ideally be adjustable to fit a variety of sizes of guitars.

5.2.3 First Mounting Design

The first mounting design (Figure 35) utilized multiple telescoping sections to accommodate most guitar sizes that are available. The mounting system was intended to fit guitars that ranged from 36" to 48" in length, from 9" to 16" in width (at the concave curve of the guitar body) and from 4" to 8" in height. Telescoping supports (1)(2)(6)(7) allow for the change in dimensions.

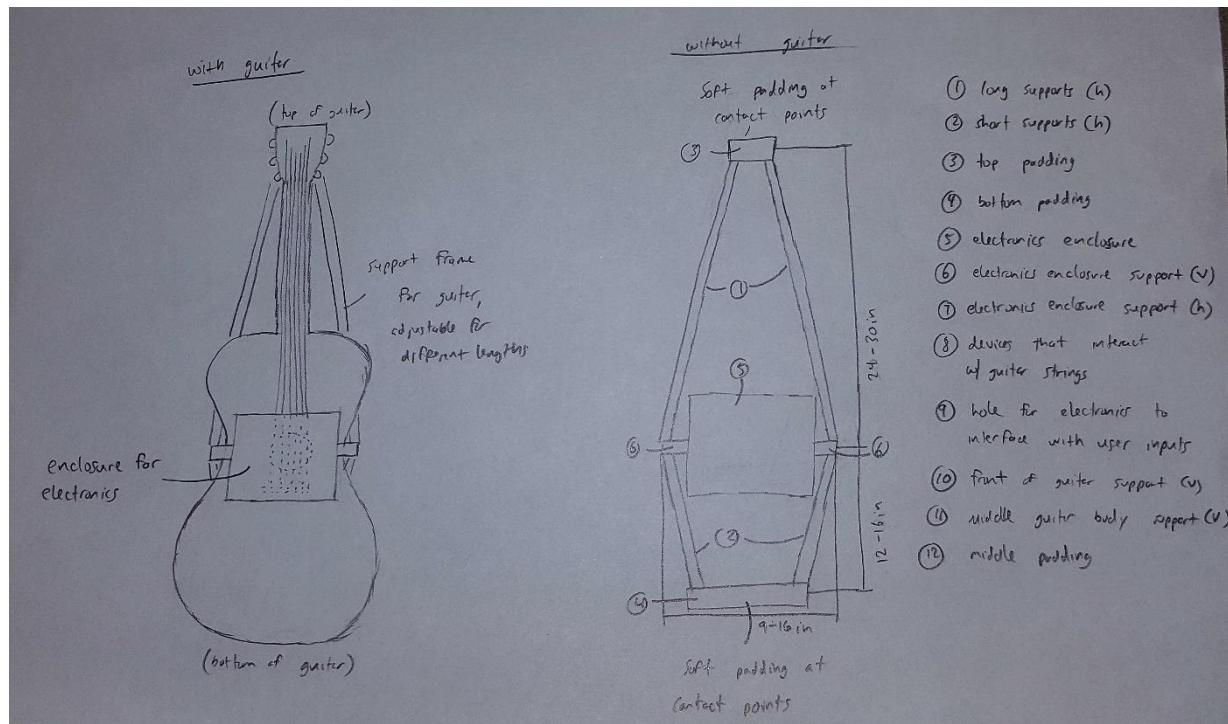


Figure 35. Top view of the mounting system

These telescoping sections each had a set screw in the body, to lock them into place when the user has adjusted the mounting system to its desired dimensions. The mounting design does not interfere with or damage the guitar in any way. This is accomplished by rubber padding at each of the contact points (3)(4)(12) with the guitar (Figure 36). The contact points provide support for the different heights of the guitar at different points.

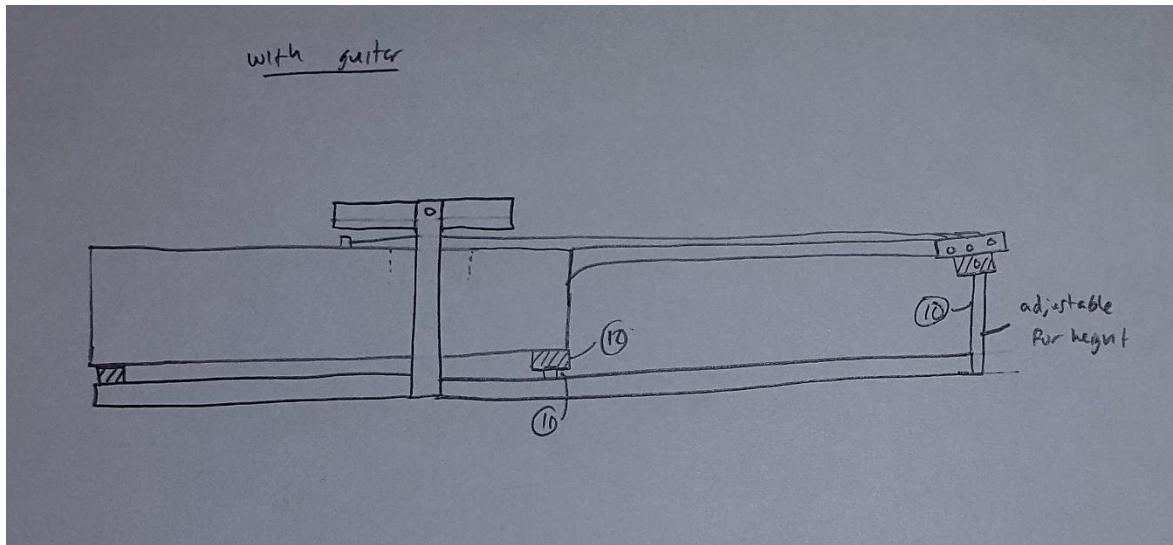


Figure 36. Side view of mounting system with guitar.

A drawing of the electronics box on the mounting system is shown below in Figure 37. The electronics enclosure (5) houses all of the electronic components of the devices, e.g. the actuators, power source, and logic board. The electronics box rotates about its supports (7), as not all guitars are perfectly flat. The devices that interact with the guitar strings (8) protrude from a cavity in the underside of the electronics box (5). A hole in the electronics enclosure (9) allows for any wires or inputs from the user interface.

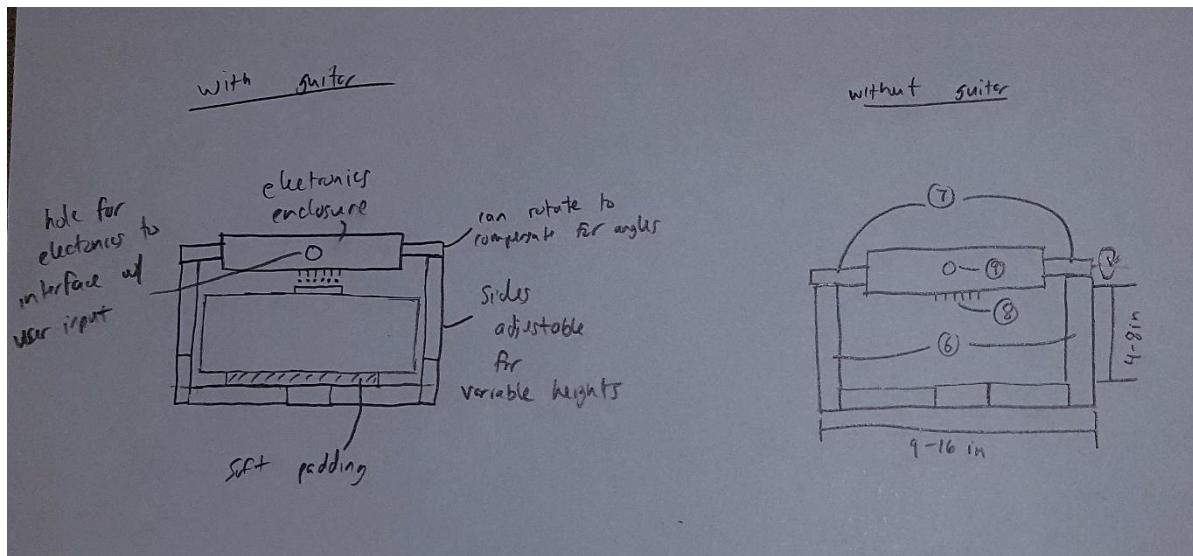


Figure 37. Drawing of the electronics box on the mounting system

A 3D model of this design was created in SolidWorks to test the feasibility of the design and how the parts would interact with each other and with a guitar. An image of the full assembly without a guitar is shown in Figure 38.

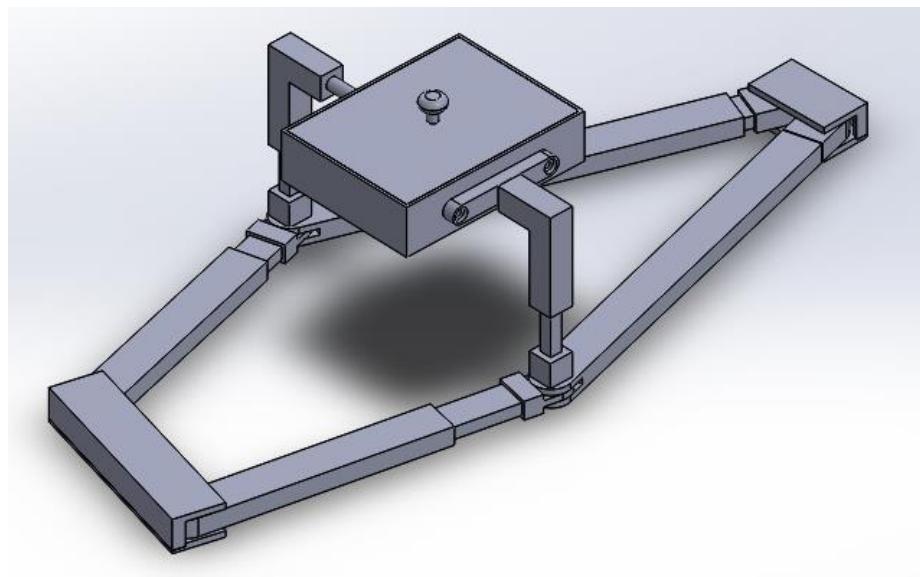


Figure 38. 3D Model of mounting system made in SolidWorks

The main advantage of a telescoping design like this is that it has many degrees of freedom and is very customizable for the user's specific guitar size. The mounting system would be able to fit a wide variety of guitar sizes. The biggest drawback of this design was the fact that a design that fits that many guitars is very complex and would require many custom machined or 3D printed parts. This increases the cost of the mounting system and decreases the feasibility and reproducibility of the design for the user.

5.3.3 Second Mounting Design

The second mounting design (Figure 36) was conceptualized at the same time as the previous system. It was similarly designed so that it could accommodate guitars with dimensions up to 36" to 48" in length, from 9" to 16" in width and from 4" to 8" in height. The intended contact points of the system were to be fixed to the guitar with adjustments taking place within the telescoping tubing.

The telescoping tubes are only adjustable in one direction. This limits the degrees of freedom that each structure piece is responsible for, in turn simplifying the ability to adapt the device to each individual guitar. In other words, the two support structures along the y-axis adjusted only the length of the mounting system, while the two tubes parallel to the x-axis altered only the width.

Snap buttons, commonly utilized in adjustable tools like crutches, were the intended fastener for the telescoping tubes. These buttons allow minimal unwanted travel in the structure, while at the same time making adjustments uncomplicated.

Despite the advantages that this system, it was not chosen as the final mounting system.

In order to determine any issues and disadvantages the system might have, a preliminary model was also constructed in Solidworks. This model revealed that despite the system's ability to mount to a variety of different sized guitars, mounting the electronics would be troublesome. If the electronics were permanently mounted to the two x-axis beams, transferring the device to a different guitar meant the plucking device itself would not necessarily be positioned over the sound hole. Adding the correct number of beams to allow this adjustment would have proved cumbersome and overly complicated.

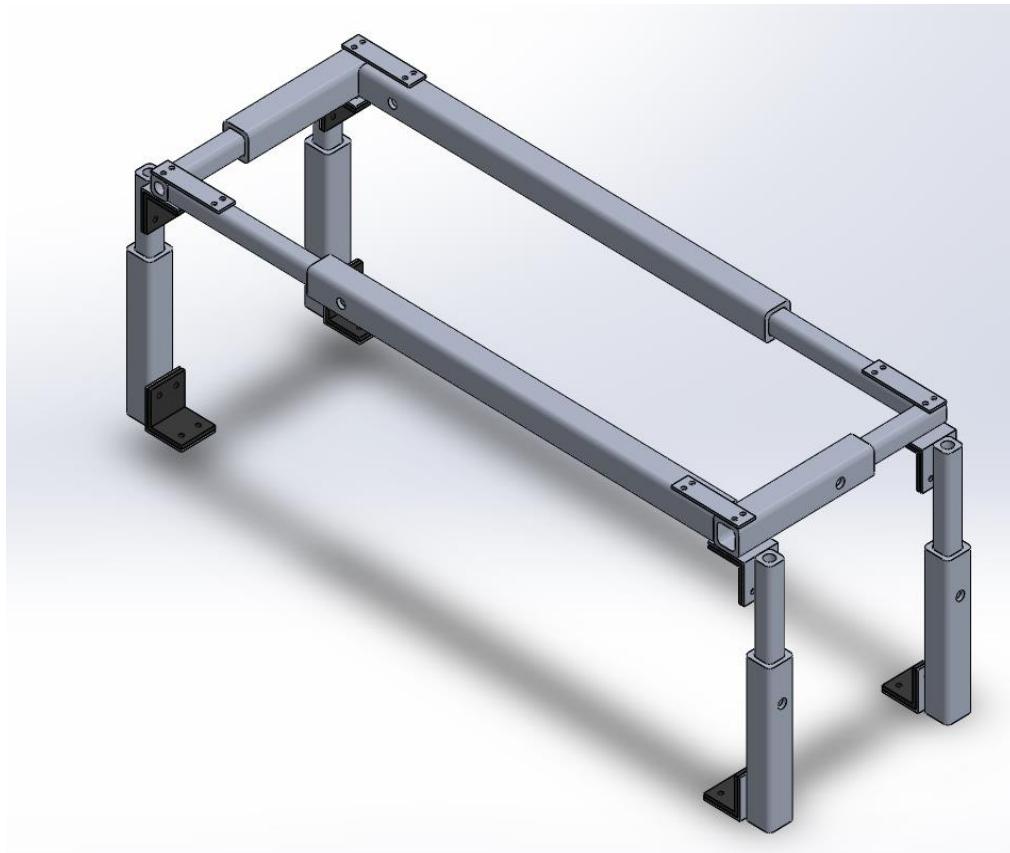


Figure 36: Second Mounting Design

5.3 Controls and Circuit Design

Initially, an Arduino was proposed as the control unit of the device. Though using an Arduino allows more customization, the question was raised if eliminating the microprocessor in favor of direct electronic connection might simplify the design and make it more easily reproduced. In order to evaluate this suggestion, it is necessary to establish the requirements of the device's circuit. The main electronic requirements of the circuit controlling the device are as follows.

- In the case that either a servo or an electric linear actuator are used, the circuit must be able to limit the actuator motion to the desired range
- The circuit must be capable of allowing the device to both play the instrument strings individually as well as strum them in unison
- The circuit must be able to create a delay of at least 15ms between user input and device reaction in order to avoid interrupting a previous command (prevents an input from being given but not executed)

The first requirement can be accomplished using mechanical means. However, if the design did not allow the limiting of the range of motion through mechanical means, it is possible to do so electrically. The circuit solution would use a pulse voltage regulator in order to regulate the voltage supplied to the chosen actuator so that the range of motion of the device remained within the desired limits. This solution works only for actuators with a variable range of motion.

Allowing the device to play strings both individually and in unison is somewhat simpler. The circuit required would incorporate a set of switches that could be closed to complete the circuit

and allow actuation of the device for individual strings. In addition, an over-riding master switch would be required that closes all of the individual circuits. This would require a separate input from the six inputs for each individual string, but would accomplish the goal.

Finally, in order to meet the required time delay within the circuit, a timing circuit would be necessary. This uses a system of capacitors and resistors in order to delay voltage transmission through the circuit.

Although all of these circuits can separately provide their desired effects, integrating them together without interference would be difficult without an Arduino. In addition, the physical space occupied by the combination of these circuits would be far greater than that of an individual microprocessor. Based on the necessity and complexity of the above circuits, the team decided to pursue using an Arduino to control the device.

It is evident that the picking mechanism must be activated by an input such as a switch. An Arduino can support a limited amount of voltage before it is damaged (5V). Because the types of motors we have been considering typically run on 6-12V, the Arduino must be protected from these larger voltages. To solve both of these problems, a transistor is the best option. Transistors read smaller voltages as a switch and activate a circuit with a larger voltage that could potentially damage the signaling device, which in this case is the Arduino. (“Transistors”, n.d.)

6. Decision Matrix

To choose a design concept to move forward with, it was necessary to evaluate the degree to which each design met the individual design specifications. A design matrix was utilized to help make this decision.

6.1 Initial Pairwise Comparison Chart

A pairwise comparison chart successively compares one criterion against all of the others. Categories deemed more important receive more points. The total number of points for each design specification is then used to create a weighting system for the decision matrix. Table 1 is the preliminary pairwise comparison constructed using all of the previously stated design specifications.

Table 1: Initial Pairwise Comparison

Pairwise Comparison: Is Top Row More Favorable than Side Column?											
	Device Response Time	Pick Cycling Time	Vertical string deflection limits	Horizontal string deflection limits	Amplitude of notes	Mounting	Mounting Compatability	Size	Multiple user interfaces	Cost	Reproducability
Device Response Time	x	0.5	1	1	0	1	0	0	0.5	0.5	0.5
Pick Cycling Time	0.5	x	1	1	1	1	0.5	1	0.5	1	1
Vertical String Deflection	0	0	x	0.5	0	0.5	0	0.5	0	0	0.5
Horizontal string deflection limits	0	0	0.5	x	0	0.5	0	0.5	0	0	0.5
Amplitude of notes	1	1	1	1	x	1	1	1	1	1	1
Mounting	0	0	0.5	0.5	0	x	0	0	0	0	0.5
Mounting Compatability	1	0.5	1	1	0	1	x	1	1	1	0.5
Size	1	0	0.5	0.5	0	1	0	x	0.5	0	1
Multiple user interfaces	0.5	0.5	1	1	0	1	0	0.5	x	0	1
Cost	0.5	0	1	1	0	1	0	1	1	x	0.5
Reproducability	0.5	0	0.5	0.5	0	0.5	0.5	1	0	0.5	x
Total	5	2.5	8	8	1	8.5	2	6.5	4.5	4	7
Weighting	8.77%	4.39%	14.04%	14.04%	1.75%	14.91%	3.51%	11.40%	7.89%	7.02%	12.28%

6.2 Revised Pairwise Comparison Chart

Although using the design specifications for criteria was conceptually sound, many categories addressed the same design criteria. This led to an overly complex decision matrix with categories that were not necessary to evaluate to choose a design to prototype. Upon a second revision, the pairwise comparison chart was reduced. Categories such as Vertical String Deflection and Horizontal String Deflection were simplified into a single criterion. Other specifications, like Multiple User Interfaces, were identified as factors independent of the concept designs therefore adding no actual value from evaluation. A pairwise comparison does not actually determine the overall importance of a particular factor, and so the calculated weightings were used only to rank each factor in order of importance.

Table 2: Revised Pairwise Comparison Chart

Pairwise Comparison V2									
	Pick Cycling Time	String Deflection	Amplitude of notes	Mounting	Mounting Compatability	Size	Cost	Reproducability	Spacing
Pick Cycling Time	x	1	1	1	0.5	1	1	1	1
String Deflection	0	x	0	0.5	0	0.5	0	0.5	0
Amplitude of notes	1	1	x	1	1	1	1	1	0.5
Mounting	0	0.5	0	x	0	0	0	0.5	0.5
Mounting Compatability	0.5	1	0	1	x	1	1	0.5	1
Size	0	0.5	0	1	0	x	0	1	1
Cost	0	1	0	1	0	1	x	0.5	1
Reproducability	0	0.5	0	0.5	0.5	1	0.5	x	0
Spacing	0	1	0.5	0.5	0	0	0	1	x
Total	1.5	6.5	1.5	6.5	2	5.5	3.5	6	5
Weighting	3.95%	17.11%	3.95%	17.11%	5.26%	14.47%	9.21%	15.79%	13.16%

6.3 Decision Matrix

The final decision matrix reflects the revised Pairwise Comparison chart. The percent values out of the total score values were calculated for each category. These percentages were subsequently carried over to the decision matrix as the specification weighting. Our team examined each specification individually and assessed how well the design would meet the

specification based on the established rubric as seen in Appendix B. Based on the assessed criteria, we determined that the design we would pursue was the horizontal solenoid actuated concept.

Table 3: Decision Matrix for the Five Major Designs

Criteria	Weighting	Rotary with Indexing		Rotary without Indexing		Solenoid Horizontal		Harpsichord		Servo Horizontal	
		Rating (1-3)	Total Weighting x Rating	Rating (1-3)	Total Weighting x Rating	Rating (1-3)	Total Weighting x Rating	Rating (1-3)	Total Weighting x Rating	Rating (1-3)	Total Weighting x Rating
Pick Cycling Time	3.95%		0		0		0		0		0
String Deflection	17.11%	3	0.5131578947	3	0.5131578947	3	0.5131578947	2	0.3421052632	3	0.5131578947
Amplitude of notes	3.95%	2	0.07894736842	2	0.07894736842	2	0.07894736842	3	0.1184210526	2	0.07894736842
Mounting	17.11%	2	0.3421052632	2	0.3421052632	3	0.5131578947	1	0.1710526316	3	0.5131578947
Mounting Compatability	5.26%	1	0.05263157895	1	0.05263157895	3	0.1578947368	1	0.05263157895	3	0.1578947368
Size	14.47%	2	0.2894736842	2	0.2894736842	3	0.4342105263	1	0.1447368421	2	0.2894736842
Cost	9.21%	1	0.09210526316	1	0.09210526316	3	0.2763157895	1	0.09210526316	3	0.2763157895
Reproducability	15.79%	1	0.1578947368	1	0.1578947368	3	0.4736842105	1	0.1578947368	3	0.4736842105
Spacing	13.16%	3	0.3947368421	3	0.3947368421	2	0.2631578947	2	0.2631578947	2	0.2631578947
Total Rating Scores	100.00%		1.921052632		1.921052632		2.710526316		1.342105263		2.565789474

7. First Prototype

From the decision matrix, the horizontal solenoid design had the highest score. The first prototype of the design began with research on different types of solenoids with different stroke lengths, force output and voltage requirements. The solenoid that best fits our design specifications is the Robot Geek "small solenoid"¹. It is capable of a 5mm stroke length and produces 700g (1.54lbs) of force at 12V and 1.4A. With the solenoid choice finalized, the building of the first prototype began.

7.1 First Prototype Design

Our first prototype (Figure 37) utilized an Arduino Uno (1) with an on-board breadboard, a momentary switch (2), the Robot Geek “small solenoid” (3), a 9V battery (4), two 1.5V batteries (5), and a .3mm acetal polymer guitar pick (6). A solenoid was fixed to the baseplate (7) with mounting screws while the baseplate itself was attached to the guitar with duct tape. This was created as a temporary mounting solution to show that the solenoid mechanism could pluck a single guitar string. The final design for the mounting system was designed to incorporate six solenoids.

¹ Source: Robotgeek.com Part Number: ASM-SOL-SM

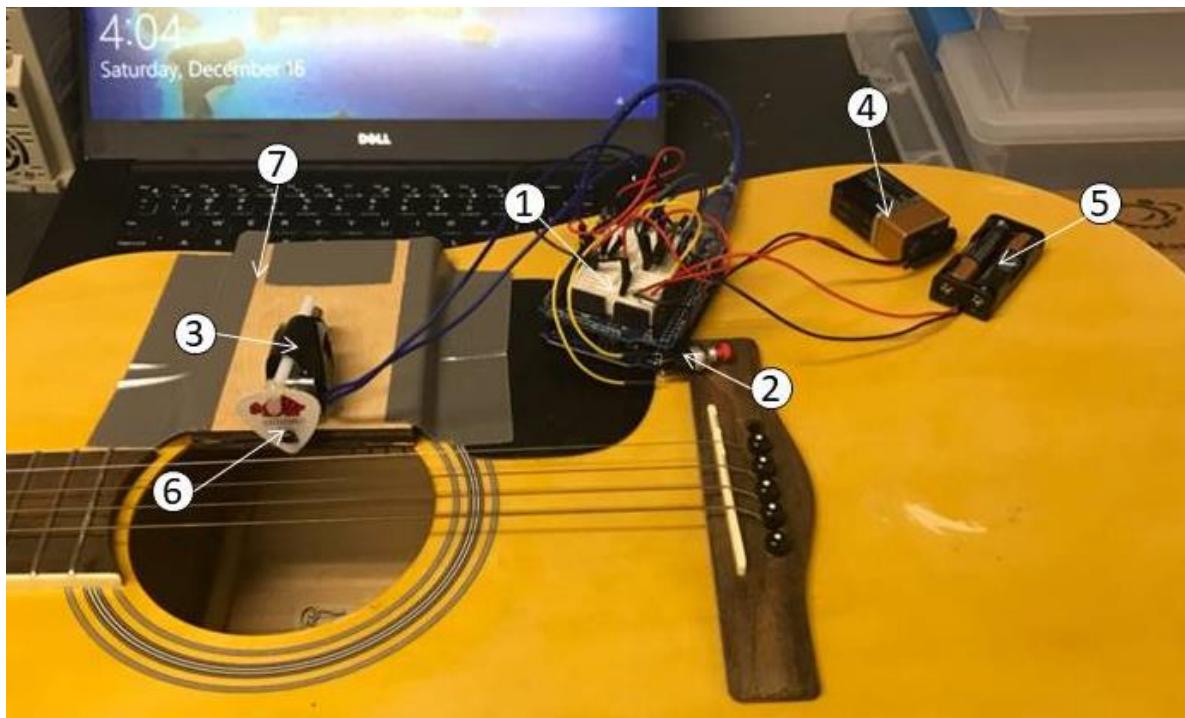


Figure 37: First Prototype

The pick mounting and placement relative to the guitar strings is shown in Figure 38.

The solenoid included a threaded plunger and screws which were used to fix the guitar pick in place such that the tip of the pick (9) was just below the guitar strings, allowing the pick to pluck the guitar string when the solenoid is actuated. A hole (8) was drilled through the pick along the middle axis and roughly $\frac{3}{4}$ of the way down from the wide side of the pick. Because the pick was so thin (.3 millimeters in thickness) a shim between the pick and the screw was required to eliminate undesired degrees of freedom.

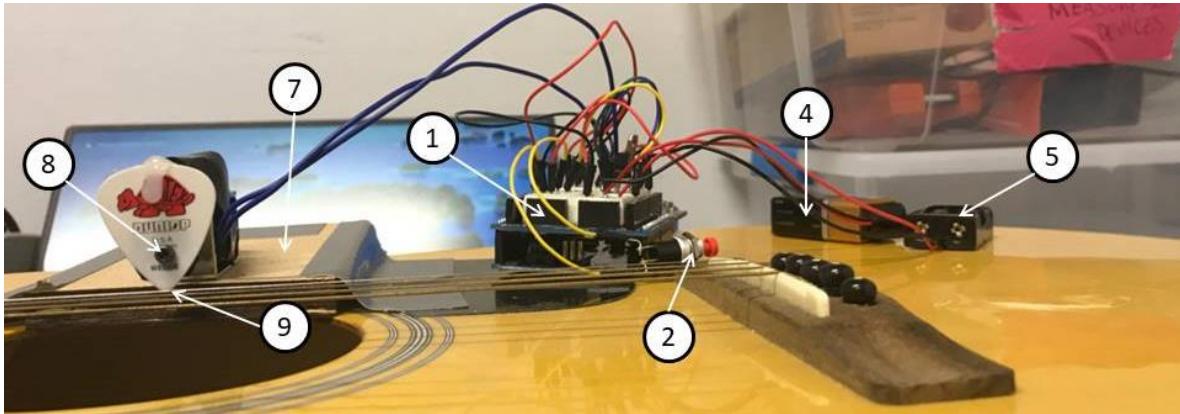


Figure 38: Front View of the First Prototype

The track assembly on the solenoid is shown in Figure 39. While testing the assembly to see if the device could successfully pluck a guitar string, more issues arose. Because the solenoid head was able to rotate in the solenoid coil, the pick itself was able to rotate, causing the tip of the pick (9) to become misaligned with the string resulting in a failure to pluck. A track and guide rod (10) were created to help remedy this problem by preventing the pick from rotating. The track was made from a piece of stock plastic (11) that was glued to the pick (6) and ran through a hex nut (12) held in place with duct tape (Figure 40).

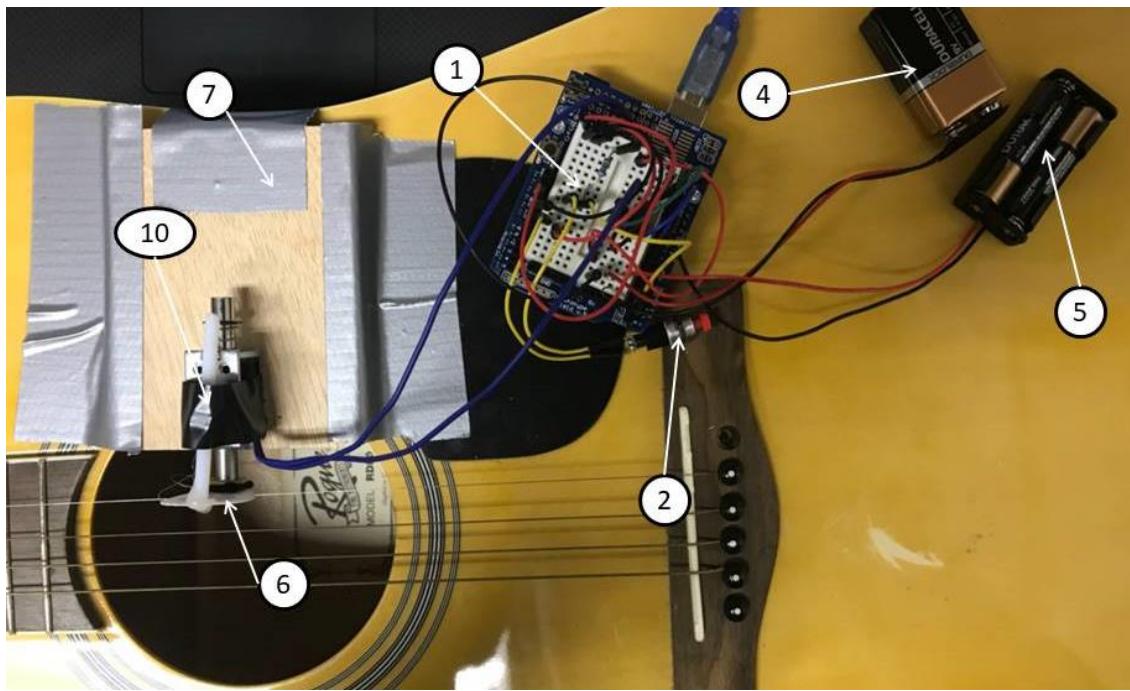


Figure 39: Top View of the First Prototype

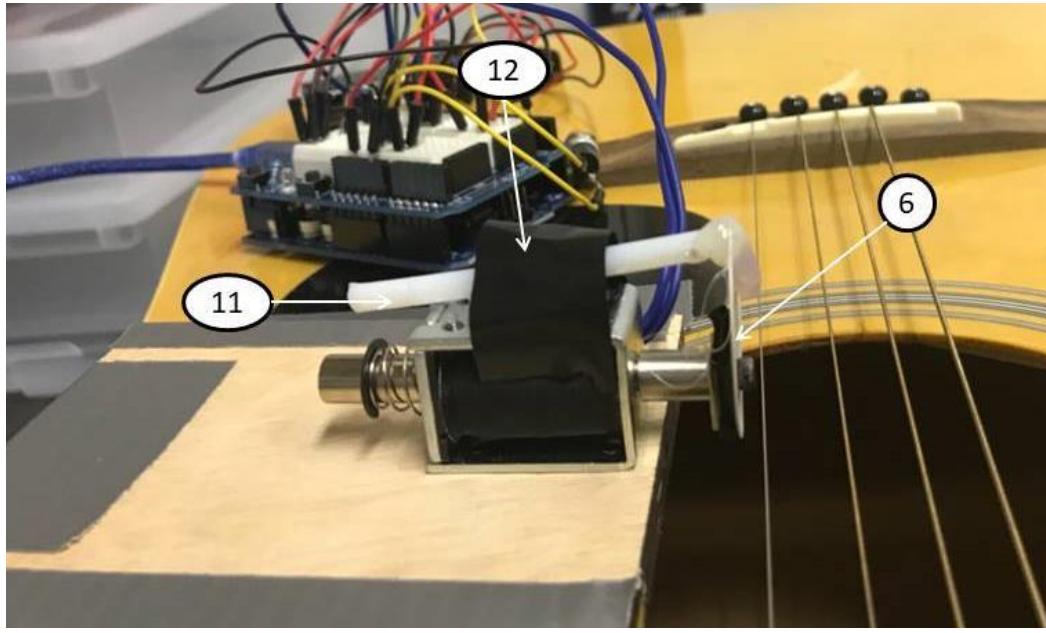


Figure 35: Right View of the First Prototype

Our first prototype presented with many problems. The guide built to correct for the rotation of the pick about the solenoid head was imprecise and allowed some parts to still move and rotate slightly. As a result, the tip of the pick often missed the guitar strings and failed to pluck. Another issue with the first prototype was caused by the return spring present in the solenoid design. After an initial trigger and plucking, this spring returned the solenoid plunger to its initial position which caused a second pluck to occur in the opposite direction. Because the final design required precise control over individual plucks; this issue was resolved in the final design.

7.2 First Prototype Circuit and Controls

Arduinos are controlled by a code that receives digital inputs and outputs digital signals based on those inputs. In the case of our plucking device, the user must give an input to the Arduino through some interface which leads to an output and a string being plucked. The first prototype developed included an Arduino with two basic circuits. One of these circuits was completed by a user input (Switch Button S1), which triggered the second circuit to actuate the solenoid L1. The diagram for the full Arduino set up is in Figure 41.

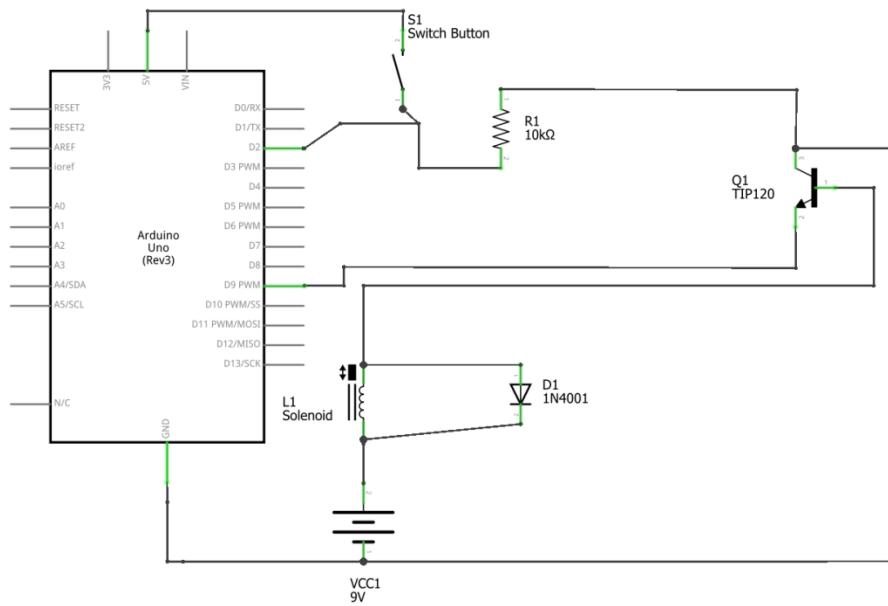


Figure 41: First Prototype Circuit Diagram

The first circuit is a 5V signal connected to a momentary switch (S1). This determines whether the signal reaches digital input 2 on the Arduino (D2). When this digital input is received by the Arduino, digital output 9 on the Arduino (D9) is triggered as an output to TIP120 transistor Q1. The resistor (R1) before the transistor is used as a pull down signal to limit the signal in order to prevent a false triggering of the solenoid circuit. The Arduino board can only safely receive 5V of power, however the solenoid (L1) requires at least 6V to properly function. To solve this problem, two circuits were created. A transistor in the Arduino circuit signals the solenoid circuit which is powered by a 9V battery. In addition, an 1N4001 diode (D1) was added across the solenoid to ensure the current only flows one direction around the solenoid actuating loop.

The full Arduino setup illustration can be seen in Figure 42 and the actual wiring setup can be seen in Figure 43.

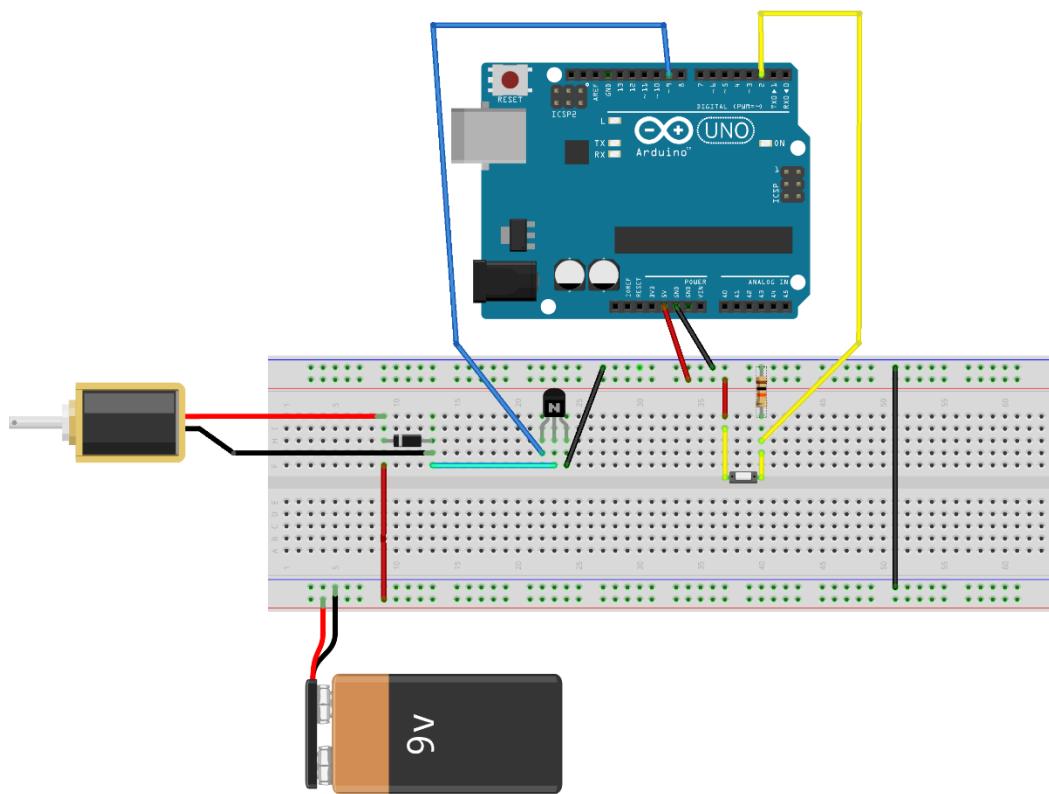


Figure 362: Illustration of single solenoid Arduino wiring setup

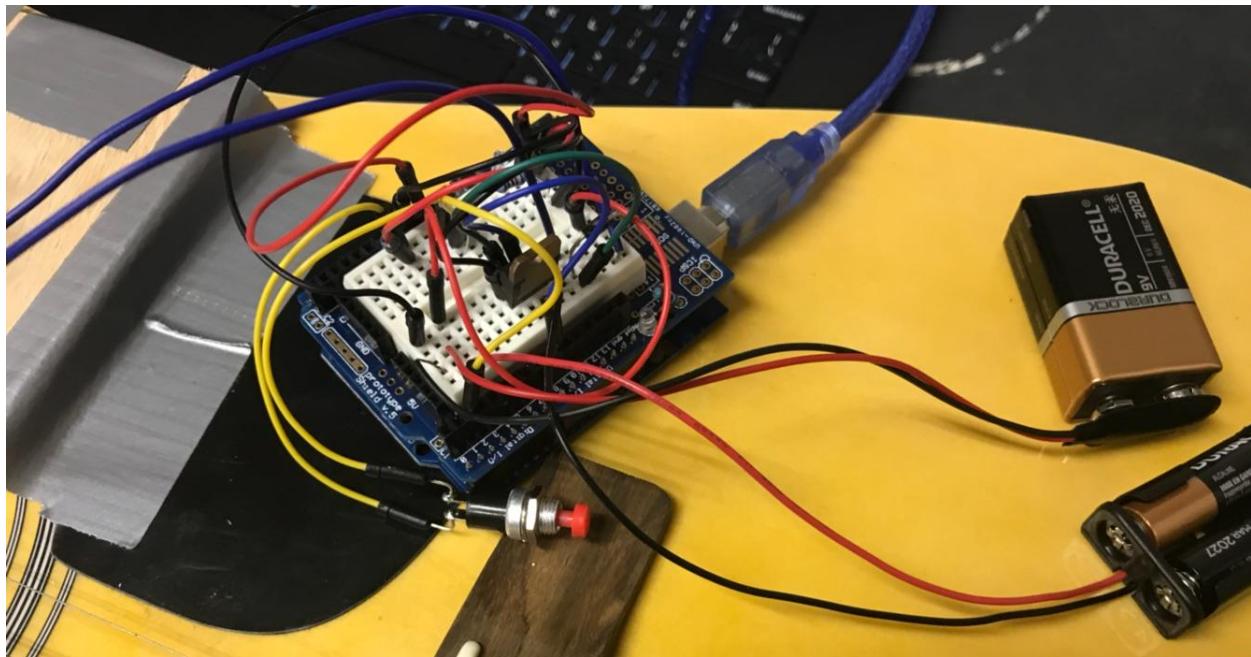


Figure 43: Picture of the Arduino and circuit

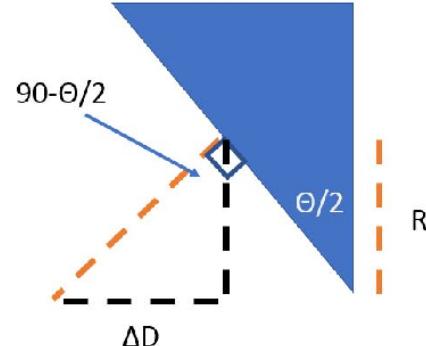
From a controls aspect, the code for the Arduino (Appendix A) assigns the function of individual digital inputs and outputs based on their desired role. These stay constant after they are set at the beginning of the code. The next part of the code identifies whether these digital pins are output or inputs. Following this is a continuous loop that checks whether the switch is turned on or off and whether to trigger the solenoid. Finally, the code contains a delay to ensure the code runs correctly with every iteration.

8. Testing

The primary testing that occurred for the design of the project was the testing of different plectrum internal angles in order to determine what would be best for the design. This testing was done in MathCAD and was used to determine the amount of displacement in the vertical deflection, based on the displacement of the plectrum in the horizontal direction. This was done with the understanding that if the plectrum was displaced vertically past the initial starting point from the end of the plectrum, the string would slip and a note would be played.

The calculations that occurred in MathCAD are as follows:

<u>Pick Deflection Calculations</u>	
$\Theta = 0$	Full angle of plectrum
$\Theta_{calculations} = \frac{\Theta}{2}$	Angle used for calculations
$\Theta_{angle} = 90 - \Theta_{calculations}$	
$\Delta D := 0.125\text{in}$	Maximum Horizontal Deflection
$R := 3\text{mm}$	Distance from desired impact point to tip of plectrum
$+$	
$\Theta_{angle} := \text{atan}\left(\frac{\Delta D}{R}\right)$	
$\Theta_{calculations} := 90\text{deg} - \Theta_{angle}$	
$\Theta := 2 \cdot \Theta_{calculations}$	
$\Theta = 86.753\text{-deg}$	



This analysis indicated that an internal angle of the plectrum of 85 degrees, based on an initial vertical impact height of 3 mm, would be ideal for the release of the string from the plectrum based on the solenoid stroke length we had selected.

9. Final Design

9.1 Final Mechanism Design

The final design was an alternating solenoid system with two solenoids per string. The design is such that there is a unidirectional solenoid with no return spring on each side of every string with a plectrum held between the solenoids. The code for the device (Appendix A) is written such that the solenoids will be activated in an alternating pattern. This ensures that the correct solenoid fires which returns the plectrum to the opposite side of the string with each cycle. The breadboard and Arduinos are mounted to the solenoid plate by Velcro strips. The full system design can be seen in Figure 43.

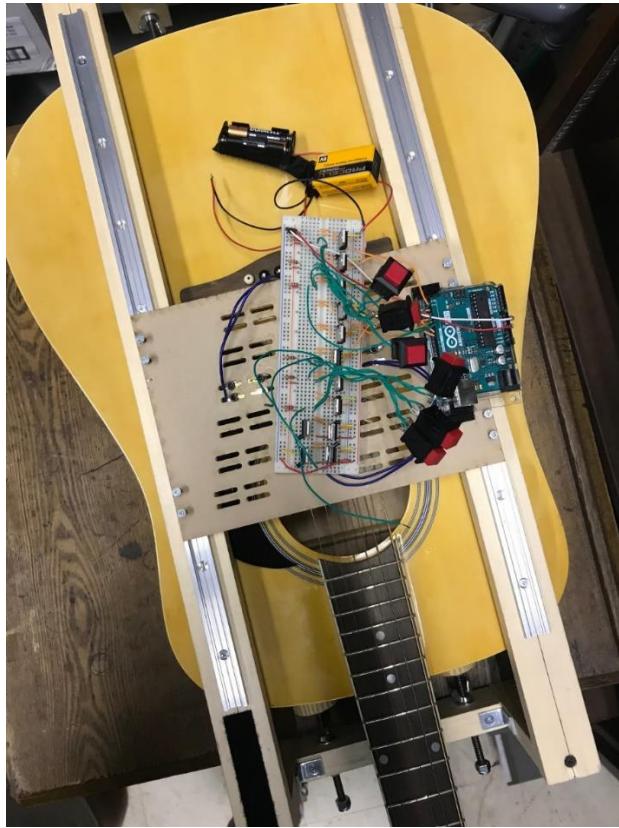


Figure 43: Final Prototype

The solenoid sub-systems are mounted to an acrylic, laser cut plate shown in Figure 44 (Orthographic Drawing in Appendix C), on the mounting mechanism. 10 mm M3 screws fix the solenoids through slots on the acrylic plate, allowing for adjustment of the solenoids to be sure they are centered on the string. The plates are elevated by a spacer (Orthographic Drawing in Appendix C).



Figure 44: Mounting Plate Top View with Solenoid Pair

The plectrum (1) (Orthographic Drawing in Appendix C) as seen in Figure 51 below is also laser cut acrylic and is connected to the solenoids by a 3D printed hub adapter (2) (Orthographic Drawing in Appendix C). The plectrum was cut with an 85 degree internal angle. This angle was chosen based on the stroke length of the solenoids so that geometrically it could be assumed the string would move down and release as the plectrum moves across the string. A mathematical model for the plucking of this plectrum was used to make these calculations. The hub adapter has the solenoid plunger shape on one end and the plectrum end shape on the other. Also seen in Figure 45, the connector is designed with two bottom extrusions that extend over the bottom of the solenoid in order to prevent the plectrum from rotating and missing a string.

The guiding attachment for each plectrum sufficiently prevented each plectrum from rotating but was not tested to determine if it was sufficiently robust for long-term use.

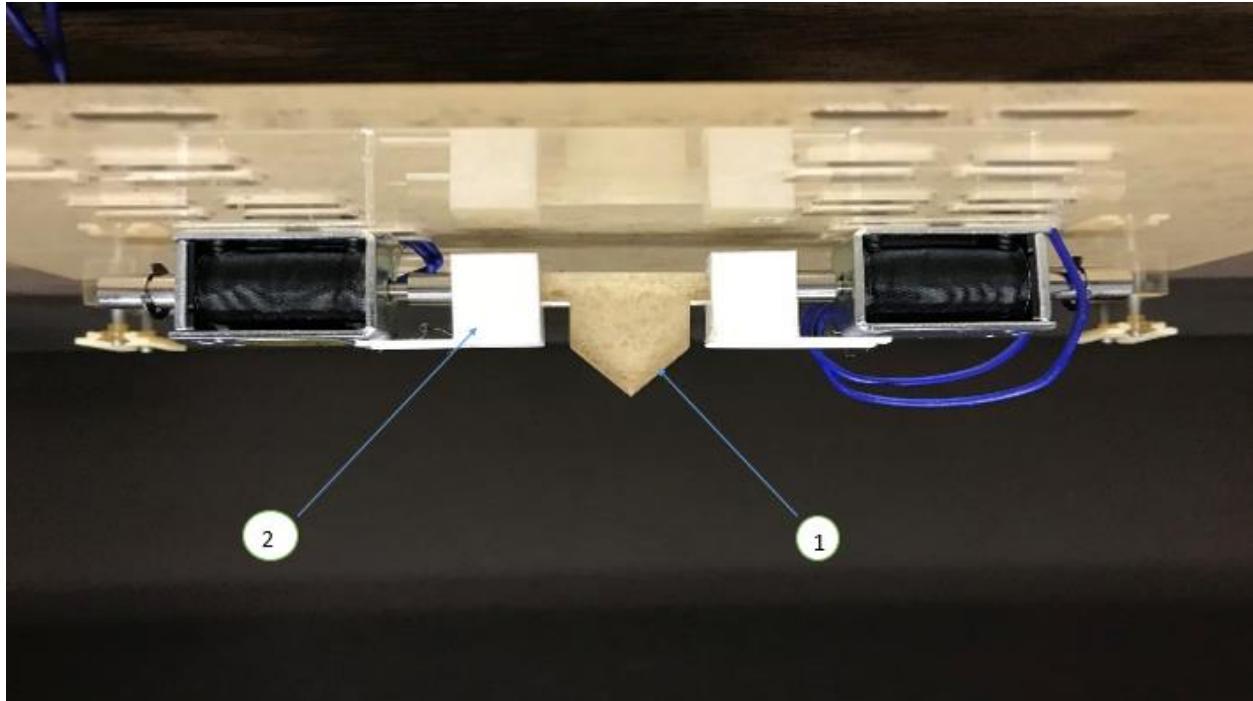


Figure 45: Solenoid-Plectrum Assembly with Connector

The device worked to pluck individual strings. The only observed issues with the device were that two strings cannot be plucked at the same time and if one of the pushbuttons were held for an extended amount of time, a double pluck occasionally occurred.

9.2 Final Mounting Design

Taking into considerations the advantages and disadvantages of the mounting designs in sections 5.2.2 and 5.2.3, a final mounting design was created that tried to encompass take the

advantages of both designs while limiting the pitfalls of the other designs. This design focused around using a track and carriage system to allow for flexibility in guitar types and sizes. The assembly drawing with bill of materials for that design can be found in Appendix C.

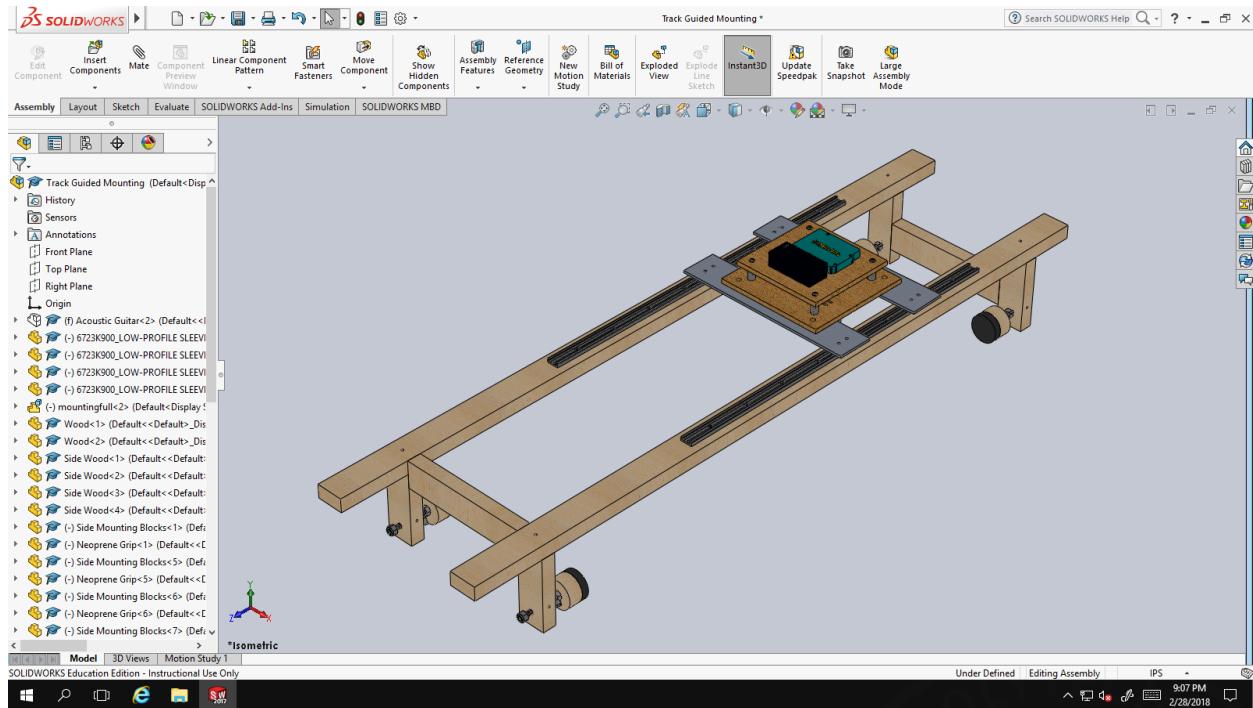


Figure 46: Final Mounting System Design CAD Model

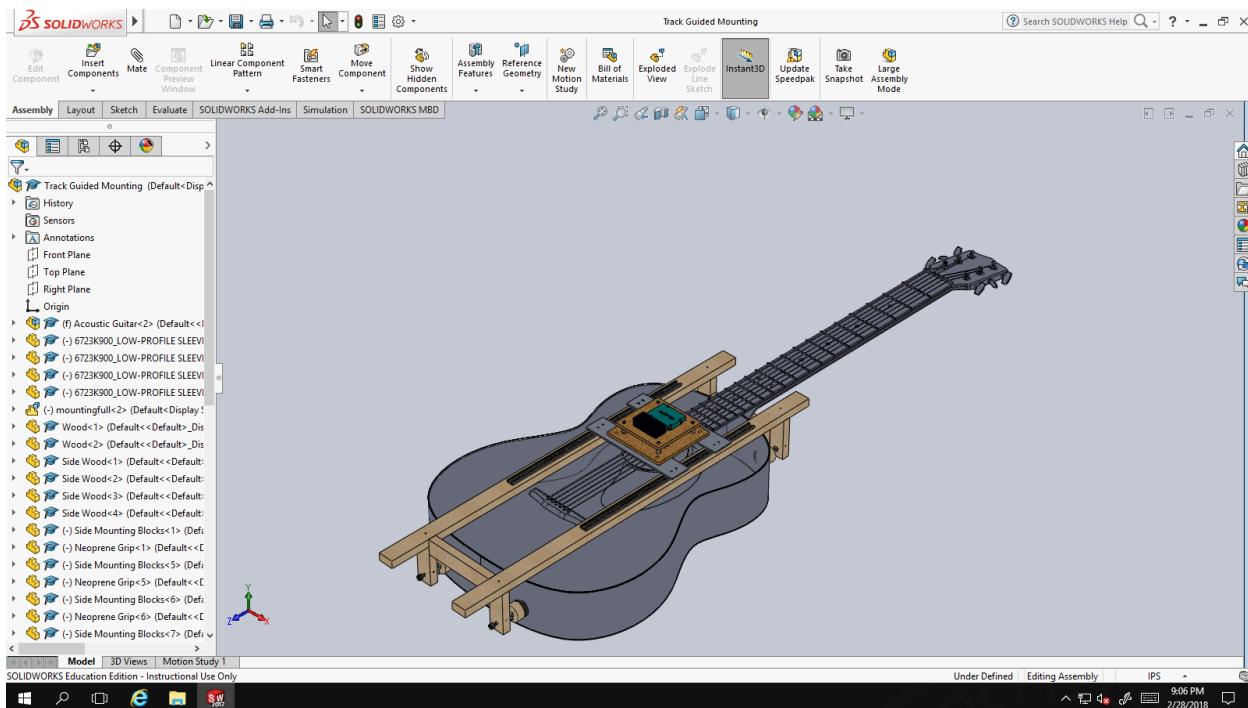


Figure 47: Final Mounting System Design CAD Model with Guitar

9.3 Final Controls Design

The circuit board works the same way as the preliminary circuit design. It uses the same transistors and resistor setup for both the pushbuttons and the solenoids. The solenoids are wired to be in parallel with the battery so that the voltage is the same through each solenoid, ensuring they all have the same power when activated. The Arduino code coordinated the pairing system for the solenoids. For the design, two Arduinos were necessary. This is because each Arduino has only 13 digital input/output pins and three were necessary for each string. One input button and two output solenoids per string were necessary, for a total of 18 digital pins necessary; more than the amount of digital pins available on one Arduino Uno.

To control the device, 6 inputs and 12 outputs were used. Momentary pushbutton switches were used for the 6 inputs, one for each string. The 12 outputs were 12 solenoids. The solenoids worked in pairs that, as stated before, were alternatively activated by the pushbuttons. This design also limits the solenoids actuation time to the time it takes to complete one stroke. After a stroke occurs, the solenoid lies dormant until its pair pushes it back into the original position and it is reactivated to pluck the string once again. This limits the energy use so that 12 volts of battery power can power the device for an extended period of time.

10. Results

After building the device and using it with 6 strings, the team made observations as to the performance of the device. These observations are as follows

10.1 Code

Individual strings can be plucked reliably. However, as the code is currently set up, two strings cannot be plucked at the same time. This is due to the nature of Arduino code which runs its primary function in a continuous loop. So at any one time going through the loop it can only read one string input. This is visually displayed if the triggers for the solenoids are held down all together. When this occurs, the solenoids are activated one after the other in a row as the loop is iterated.

10.2 Timing

The code in the device required time delays to prevent double triggering of the solenoids to allow the Arduino time between reading signals. The project timeline did not allow for optimization of the delays within the code. Therefore, some of the delays could potentially be longer than they really need to be. If testing was done to optimize the length of the delays, the Arduino could potentially spend less time between reading signals and react faster to the user input.

10.3 Solenoid Connector

The connector piece for the plectrum to the solenoid is functional in the current design, but weak. The two parts that stick out of the bottom to prevent the rotation of the plectrum can be broken off easily when made with the low resolution FDM 3D printer we used. The tolerances of the parts also created a problem in that the two ends, one fitting to the plectrum and the other to the solenoid didn't always fit and stay smoothly, even though they were designed to be press fit.

10.4 Breadboard and Electrical Circuits

With the basic circuitry kit that was used to create our device, manual wiring of the circuitry was required and this allowed for wires to come out of the breadboard and prevent the device from working normally.

10.5 Arduinos and Breadboard Attachment

The Arduinos and breadboard are attached to the solenoid plate using Velcro. This leaves them exposed to potential damage or for the wiring to come loose.

10.6 Pricing

The cost of creating one device was around \$250, much higher than the originally intended price of \$125. By ordering parts in bulk, the unit price could be reduced. The current Bill of Materials with pricing can be found in Appendix D.

11. Conclusion and Recommendations

The goal of this project was to design and manufacture a device that attached to a guitar and allowed users to play a guitar through a variety of interfaces. To accomplish this goal, a battery-powered device was designed, manufactured, and tested. The device successfully plucked the individual strings on an acoustic guitar and attached to the guitar without any modifications or alterations made to the guitar.

11.1 Recommendations

11.1.1 Optimization of Time Delays

Testing should be done to optimize the length of the time delays in the code. If the time delays were to be optimized, the time it takes for the Arduino to read consecutive signals could be reduced. This could help to minimize the response time of the device to the user input.

11.1.2 Plucking Multiple Individual Strings at Once

The code should be adjusted to allow for multiple individual strings to be plucked at once. This increases the amount of complexity with which the user would be able to express themselves while using the device.

11.1.3 Printed Circuitry

If the circuits were professionally printed, this would stop any problems with wiring coming undone, allowing for the device to work more reliably.

11.1.4 Electronics Case

Developing a case for the electronic components of the device would keep them protected from any problems that could occur due to their exposure. These problems include moisture, metals that could short circuit the system, or people knocking out the wiring.

12. References

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13. Appendices

13.1 Appendix A: Arduino Code

```
//Assigning values to buttons and solenoids for assignment to digital pins
```

```
int pushButton1 = 1;  
int solenoid1_1 = 2;  
int solenoid1_2 = 3;
```

```
int pushButton2 = 4;  
int solenoid2_1 = 5;  
int solenoid2_2 = 6;
```

```
int pushButton3 = 7;  
int solenoid3_1 = 8;  
int solenoid3_2 = 9;
```

```
//Setting up counter variables for alternation of solenoids
```

```
int count1 = 2;  
int count2 = 2;  
int count3 = 2;
```

```
int x = 255;  
int y = 0;
```

```

void setup() {
    // Assigning buttons and solenoids as inputs and outputs to pins

    pinMode(pushButton1, INPUT);
    pinMode(solenoid1_1, OUTPUT);
    pinMode(solenoid1_2, OUTPUT);

    pinMode(pushButton2, INPUT);
    pinMode(solenoid2_1, OUTPUT);
    pinMode(solenoid2_2, OUTPUT);

    pinMode(pushButton3, INPUT);
    pinMode(solenoid3_1, OUTPUT);
    pinMode(solenoid3_2, OUTPUT);

}

void loop() {
    //checks state of pushbutton, activates solenoid if on, alternates solenoid based on counter
    variables

    //if statements are used so that the activation of solenoid is instantaneous

    if((count1 % 2) == 0){ //checks if the counter is even or odd
        if(digitalRead(pushButton1) == LOW){ //check to see if button is on or off
            digitalWrite(solenoid1_1, y); // put solenoid to off position
            delay(150);
        }
    }
}

```

```

if(digitalRead(pushButton1) == HIGH){
    { digitalWrite(solenoid1_1, x); // solenoid to on position
    delay(50); //time delay fo full solenoid activation
    digitalWrite (solenoid1_1, y);//deactivate solenoid
    count1 = count1+1; //change counter variable at activation
    delay(150);}
}

if((count1 % 2) != 0){
    if(digitalRead(pushButton1) == LOW){
        { digitalWrite(solenoid1_2, y);
        delay(150);}
    }

    if(digitalRead(pushButton1) == HIGH){
        { digitalWrite(solenoid1_2, x);
        delay(50);
        digitalWrite(solenoid1_2, y);
        count1 = count1+1;
        delay(150);}
    }
}

if((count2 % 2) == 0){ //checks if the counter is even or odd
    if(digitalRead(pushButton2) == LOW){ //check to see if button is on or off
    { digitalWrite(solenoid2_1, y); // put solenoid to off position
    delay(150);}
}

```

```

}

if(digitalRead(pushButton2) == HIGH){

    { digitalWrite(solenoid2_1, x); // solenoid to on position
    delay(50); //time delay fo full solenoid activation
    digitalWrite (solenoid2_1, y);//deactivate solenoid
    count2 = count2+1; //change counter variable at activation
    delay(150);}

}

}

if((count2 % 2) != 0){

    if(digitalRead(pushButton2) == LOW){

        { digitalWrite(solenoid2_2, y);
        delay(150);}

    }

    if(digitalRead(pushButton2) == HIGH){

        {digitalWrite(solenoid2_2, x);
        delay(50);
        digitalWrite(solenoid2_2, y);
        count2 = count2+1;
        delay(150);}

    }

}

if((count3 % 2) == 0){ //checks if the counter is even or odd
    if(digitalRead(pushButton3) == LOW){ //check to see if button is on or off
    { digitalWrite(solenoid3_1, y); // put solenoid to off position
}
}
}

```

```

    delay(150);}

}

if(digitalRead(pushButton3) == HIGH){

{ digitalWrite(solenoid3_1, x); // solenoid to on position
delay(50); //time delay fo full solenoid activation
digitalWrite (solenoid3_1, y);//deactivate solenoid
count3 = count3+1; //change counter variable at activation
delay(150);}

}

}

if((count3 % 2) != 0){

if(digitalRead(pushButton3) == LOW){

{ digitalWrite(solenoid3_2, y);
delay(150);}

}

if(digitalRead(pushButton3) == HIGH){

{ digitalWrite(solenoid3_2, x);
delay(50);
digitalWrite(solenoid3_2, y);
count3 = count3+1;
delay(150);}

}

}

delay(1); }

```

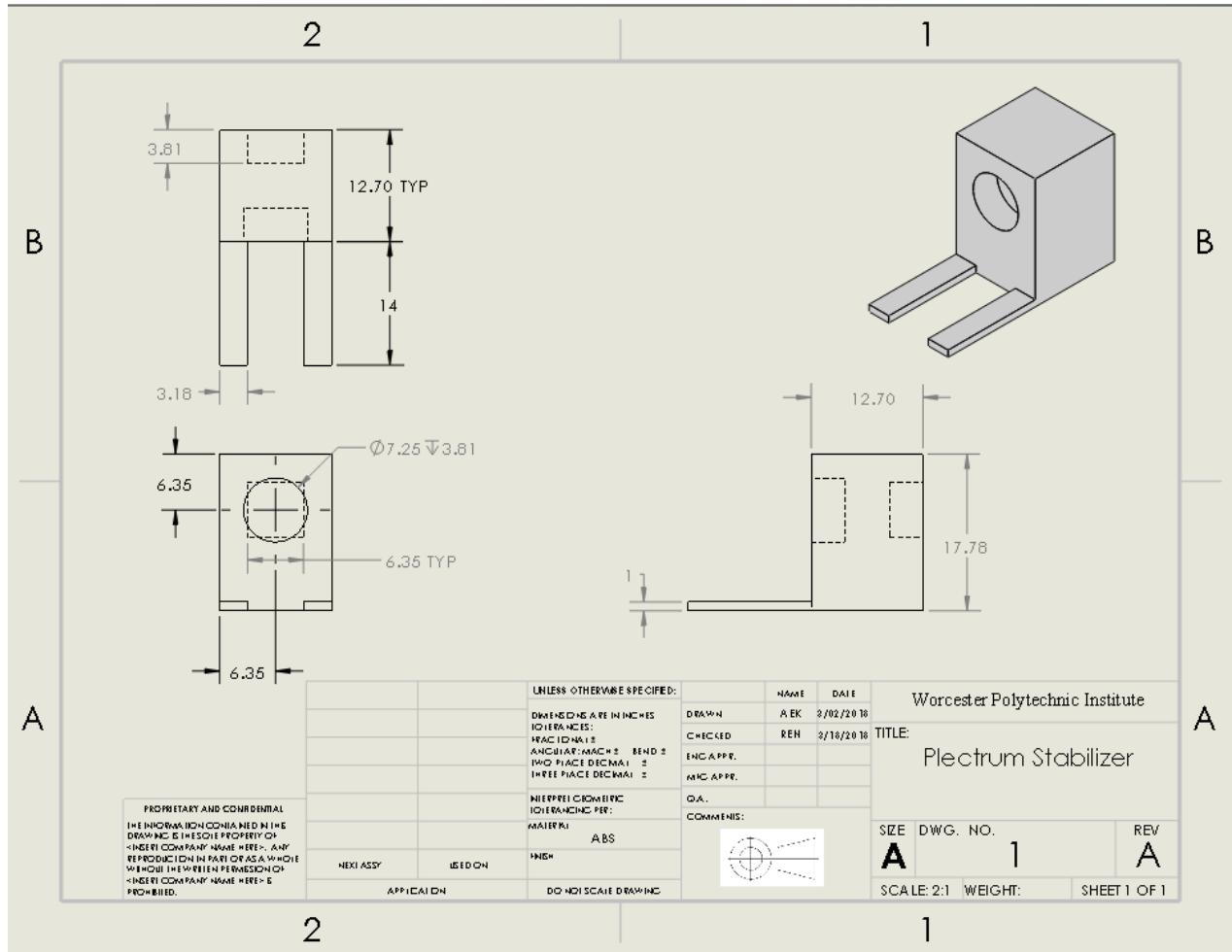
13.2 Appendix B: Rubric for Evaluating the Decision Matrix

	1	2	3
Device Response Time	The device response time exceeds 200% of 15 milliseconds (originally specified design). Lag is very noticeable and severely hinders ability to play guitar.	The device responds within 150% of 15 milliseconds (originally specified design). Some lag may be noticeable but guitar can still be played adequately.	The device responds within 15 milliseconds (originally specified design) allowing for the guitar to be played without lag
Pick Cycling Time	Pick cycle completed in greater than 1/4 of a second	Pick cycle completed within 1/4 of a second.	Pick cycle completed in 1/8 of a second.
Vertical String Deflection	String impacts guitar fretboard severely altering the quality of the note produced.	String impacts the fretboard but does not severely alter the quality of the note produced.	String does not impact the fret board.
Horizontal string deflection limits	Horizontal deflection of the strings results in substantial string interference. Note quality is severely altered.	Horizontal deflection of the strings results in some string interference, but the note produced is not significantly altered.	Horizontal deflection of the strings does not cause interference among the strings.
Amplitude of notes	Amplitude of the produced note is less than 50% of the amplitude produced with a guitar without the device.	Amplitude of the produced note is greater than 50% of the amplitude produced with a guitar without the device.	Amplitude of the produced note is greater than 80% of the amplitude produced with a guitar without the device.
Power Source	Device must be plugged into a wall socket	Device performs sub-optimally when not plugged into a wall socket	Device is battery powered.

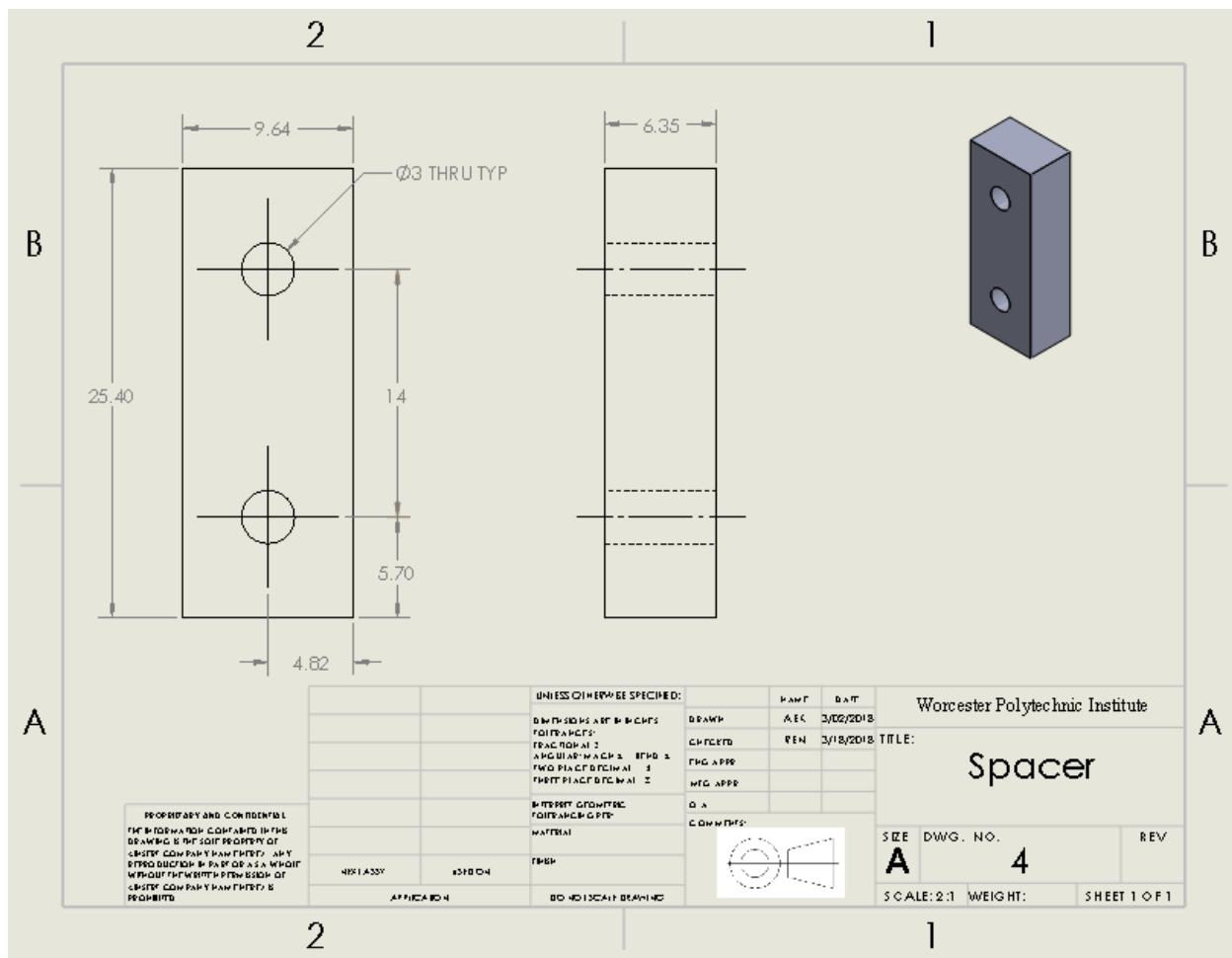
Mounting	Major alterations to the guitar are necessary to mount the device.	Minor alterations to the guitar are necessary to mount the device.	No alterations are necessary to mount the device
Mounting Compatibility	Device is capable only of being mounted on the initial guitar.	Device is capable of mounting on most guitars and similar string instruments of varying dimensions.	Device is capable of mounting on all guitars and similar string instruments of varying dimensions.
Size	Device dimensions exceed 68.5 cm, 53.3 cm, 35.5 cm by more than 5%. As the typical plane luggage size limit for international travel.	Device dimensions are within 5% greater than 68.5 cm, 53.3 cm, 35.5 cm.	Device dimensions do not exceed 68.5 cm, 53.3 cm, 35.5 cm.
Multiple user interfaces	Device is capable only of receiving input from a single interface.	Device is capable of accepting input from two user interfaces supplying the correct input.	Device is capable of accepting input from at least three user interfaces supplying the correct input.
Individual string plucking	Device is incapable of plucking individual strings	Device is capable of plucking select individual strings	Device is capable of plucking any individual string.
Cost	Device cost exceeds \$125.00 by more than 20%	Device cost does not exceed \$125.00 by more than 20%	Device cost is less than \$125.00
Reproducibility	Power supply, fasteners and actuators are all unavailable commercially.	One of the following is not commercially available: Power supply, fasteners and actuators.	Power supply, fasteners and actuators are all commercially available.

13.3 Appendix C:Drawings

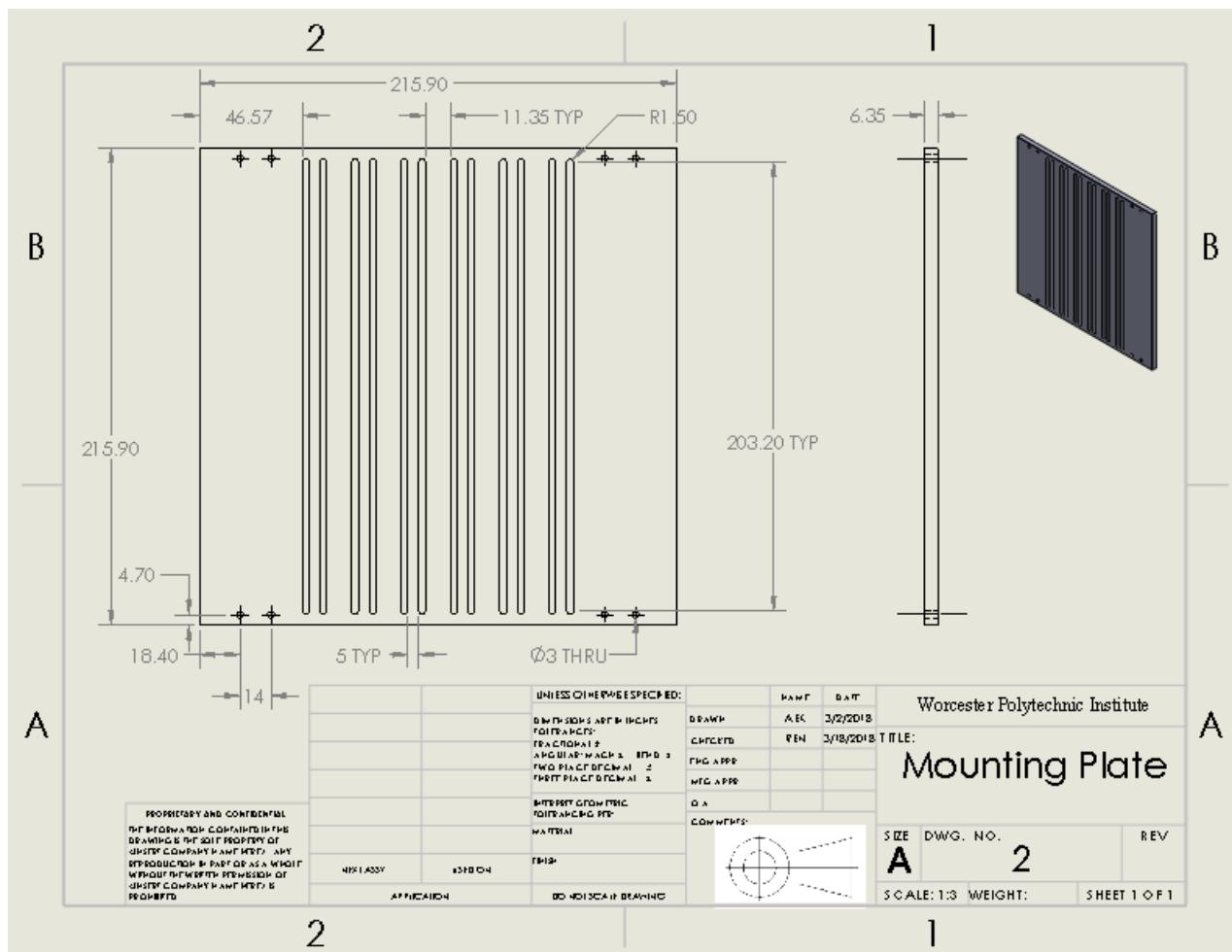
Plectrum-Solenoid Connector



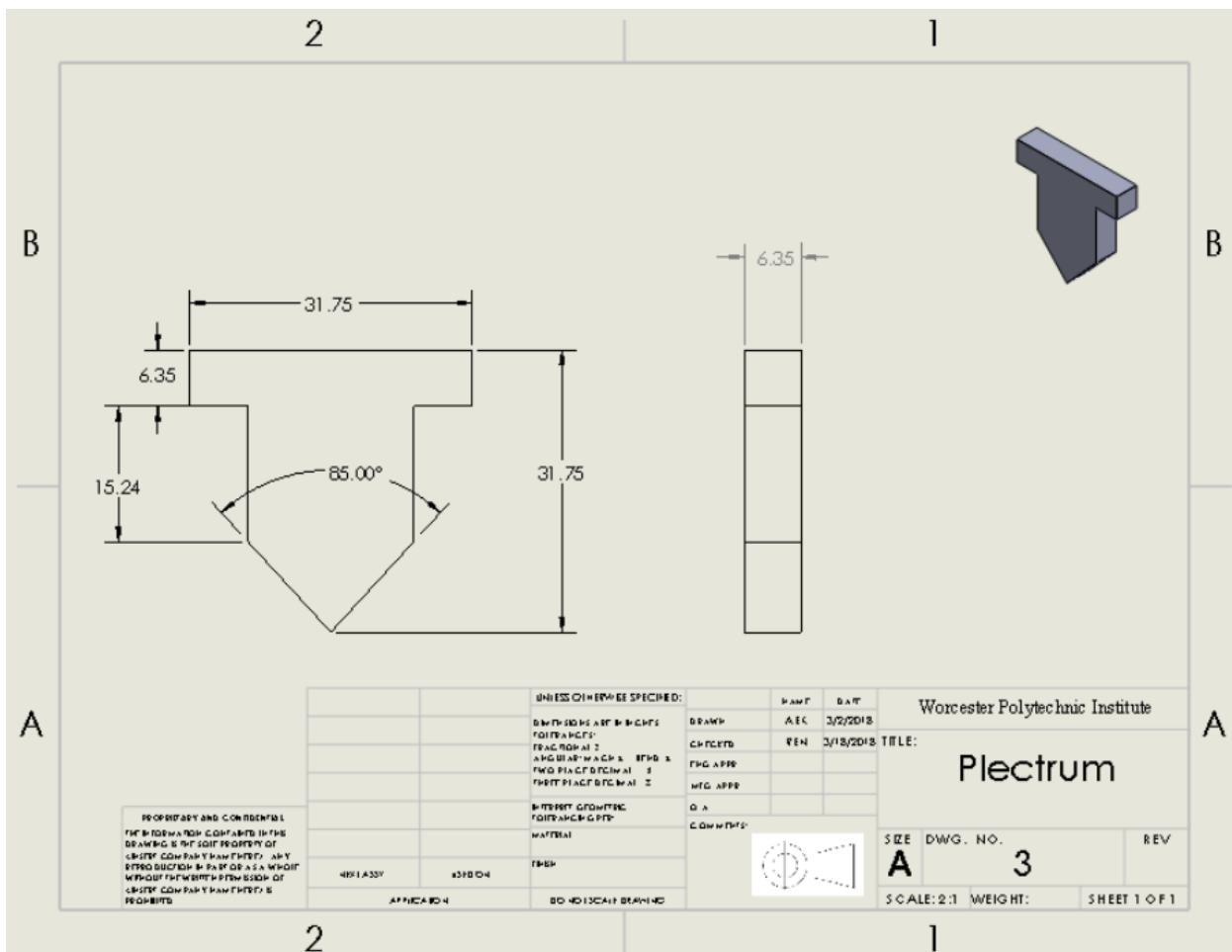
Height Spacer



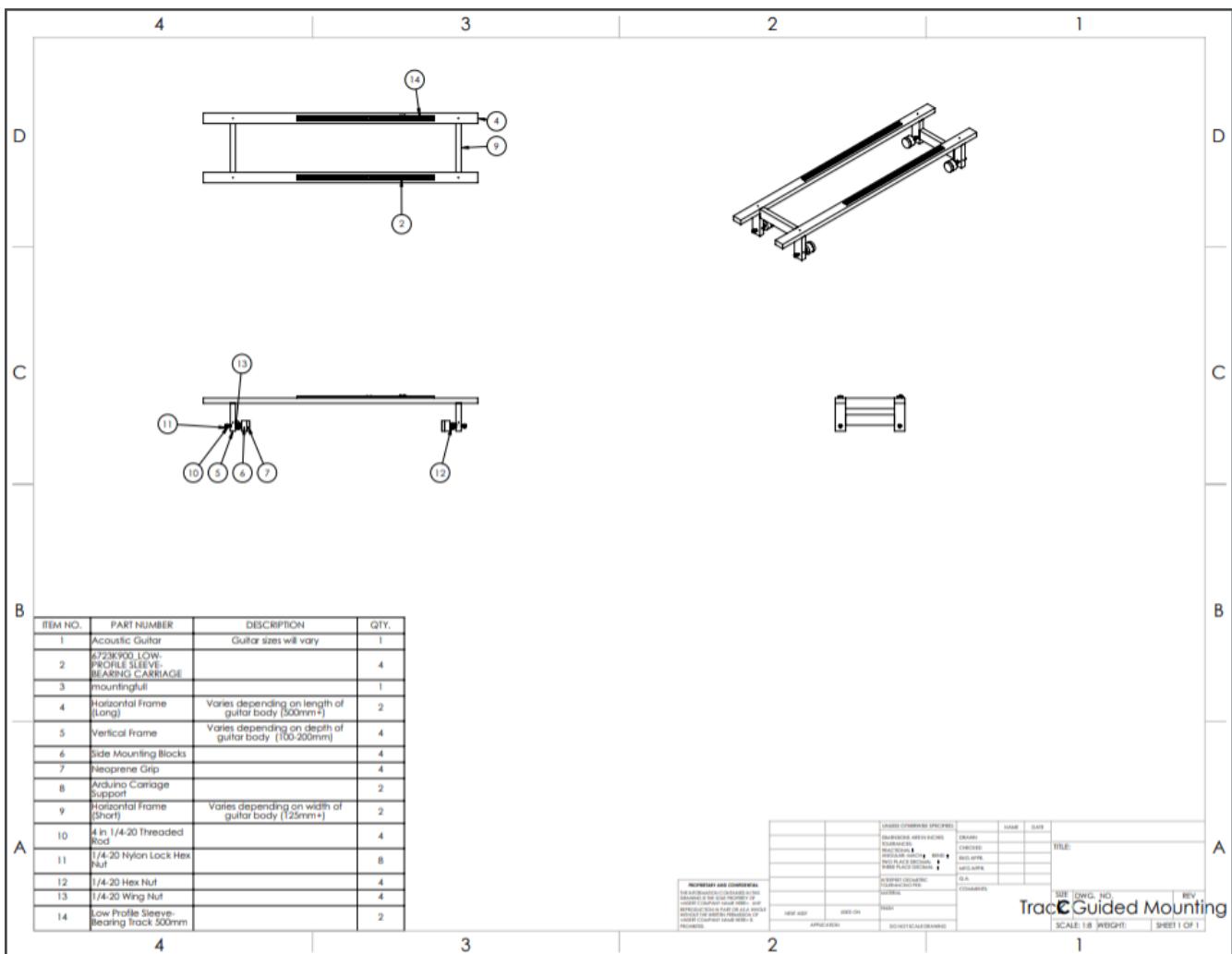
Solenoid Plate



Plectrum



Track Guided Mounting Assembly



13.4 Appendix D: Bill of Materials and Prices

Item	Number	Price	Link
1 in. x 2 in. x 8 ft. Select Kiln-Dried Square Edge Whitewood Board	1	\$5.59	https://www.homedepot.com/p/1-in-x-2-in-x-8-ft-Select-Kiln-Dried-Square-Edge-Whitewood-Board-418532/203450502?keyword=098945053304&semanticToken=20030+++%3E++++st%3A%7B098945053304%7D%3Ast++cn%3A%7B0%3A0%7D++98945053304%7Bproductkey%7D
WM232 1-5/8 in. x 1-5/8 in. Douglas Fir Full Round Moulding	1	\$3.50	https://www.homedepot.com/p/American-Wood-Moulding-WM232-1-5-8-in-x-1-5-8-in-Douglas-Fir-Full-Round-Moulding-232-LF/100029053
#6 x 2 in. Philips Bugle-Head Coarse Thread Sharp Point Drywall Screws (1 lb. - Pack)	1	\$6.47	https://www.homedepot.com/p/Grip-Rite-6-x-2-in-Philips-Bugle-Head-Coarse-Thread-Sharp-Point-Drywall-Screws-1-lb-Pack-2CDWS1/100128601?keyword=764666103375%3E++++st%3A%7B764666103375%7D%3Ast++cn%3A%7B0%3A0%7D++764666103375%7Bproductkey%7D
E/O 3/4 in. x 5/16 in. x 10 ft. Black High Density Rubber Foam Weatherstrip Tape	1	\$3.98	https://www.homedepot.com/p/Frost-King-E-O-3-4-in-x-5-16-in-x-10-ft-Black-High-Density-Rubber-Foam-Weatherstrip-Tape-R534H/202262324?keyword=077578012223%3E++++st%3A%7B077578012223%7D%3Ast++cn%3A%7B0%3A0%7D++77578012223%7Bproductkey%7D
Low-Profile Sleeve Bearing Carriage for 17mm Wide Rail	4	\$21.44	https://www.mcmaster.com/#6723k9/=1bbs29c

17mm Wide Guide Rail for Low-Profile Sleeve Bearing Carriage (500mm)	2	\$50.00	https://www.mcmaster.com/#6723k5/=/1bdq3iv
Medium-Strength Steel Nylon-Insert Locknut Grade 5, Zinc-Plated, 1/4"-20 Thread Size	1	\$4.39	https://www.mcmaster.com/#95615a120/=/1bdqrc2
Steel Phillips Flat Head Screws M3 x 0.5 mm Thread, 25 mm Long	1	\$4.00	https://www.mcmaster.com/#91420a130/=/1bdqscp
Medium-Strength Steel Hex Nut Grade 5, 1/4"-20 Thread Size	1	\$3.26	https://www.mcmaster.com/#95505a601/=/1bdq5sr
Grade B7 Medium-Strength Steel Threaded Rod 1/4"-20 Thread Size, 4" Long	4	\$7.44	https://www.mcmaster.com/#98750a025/=/1bdq6b1
Medium-Strength Steel Nylon-Insert Locknut Class 8, Zinc-Plated, M3 x 0.5 mm Thread	1	\$3.36	https://www.mcmaster.com/#90576a102/=/1bdq6wl
18-8 Stainless Steel Wing Nut 1/4"-20 Thread Size	1	\$7.32	https://www.mcmaster.com/#92001a321/=/1bdq917
1-1/2 in. Self-Adhesive Anti-Skid Surface Pads (8-Pack)	1	\$2.48	https://www.homedepot.com/p/Everbilt-1-1-2-in-Self-Adhesive-Anti-Skid-Surface-Pads-8-Pack-49970/203661152
5 in. x 48 in. K-Style Foam Gutter Filter	1	\$5.99	https://www.homedepot.com/p/GUTTERSTUFF-5-in-x-48-in-K-Style-Foam-Gutter-Filter-GS-K5-SPAN/203318223
TIP 120 Transistor	12	\$7.32	https://www.digikey.com/product-detail/en/stmicroelectronics/TIP120/497-2539-5-ND/603564
Diode	12	\$1.32	https://www.digikey.com/product-detail/en/micro-commercial-co/1N4007-TP/1N4007-TPMSCT-ND/773694
10 kOhm Resistor	6	\$0.60	https://www.digikey.com/product-detail/en/stackpole-electronics-inc/CF14JT10K0/CF14JT10K0CT-ND/1830374
Momentary Switch Button	6	\$8.10	https://www.digikey.com/product-detail/en/e-switch/PS1057ARED/EG2045-ND/46295

Arduino UNO Rev3	2	\$46.76	https://www.digikey.com/product-detail/en/arduino/A000066/1050-1024-ND/2784006
AAA Battery	2	N/A	N/A
9V Battery	1	N/A	N/A
9V Battery Connector	1	\$5.00	WPI ECE Department
2x AAA Battery Connector	1	\$4.00	WPI ECE Department