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# Dynamic Tuning MQP

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# Dynamically Tuning String Instrument

A Major Qualifying Project
Submitted to the Faculty of
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in partial fulfillment of the requirements for the
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in
Robotics Engineering

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# Abstract

*Cyther V3* looks to improve *Cyther V2*, a mechatronic string instrument equipped with ten strings and a set of solenoids to actuate the strings. The goal of this project was to create a next generation *Cyther* equipped with a system that can autonomously tune each string during a performance, expanding on the types of musical expressions *Cyther V2* was capable of. The tuning system senses string tension, estimates pitch, adjusts the tension, and corrects for errors in estimation using optical pickups. The frequency analysis accuracy and speed, and the tuning accuracy and speed of the new autonomous tuning system was analyzed for a single string to determine the quality of the new autonomous tuning system. Although the tuning is not precise enough for error to go undetected by human perception, this tuning system should provide a platform on which to build more interactive compositions and new kinds of musical gestures.

# Acknowledgements

Thank you to Professor Barton for designing and building *Cyther V2*, realizing the potential of an autonomous tuning system, letting me try to make it, and advising me through the entire MQP process. I recommend Professor Barton to anybody who wants to do an MQP.

Thank you to WPI's Washburn Labs, Music Perception Robotics Lab, and Robotics Lab for providing the equipment, assistance, and in some cases materials needed to complete this project.

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# Introduction

Currently, only a small portion of mechatronic string instruments can self-tune. Of the ones that can, pitch analysis is used before a performance to automatically tune themselves to presets. This type of system doesn't allow a composer or performer to adjust the tuning during the performance, which could be used to create pitch change effects. On the contrary, dynamically changing pitch allows a composer or performer to specify different tunings at any time during the performance, which adds glissando and vibrato to aspects of the piece. These techniques could be integrated into interactions between a performer and the instrument, adding depth and spontaneity to a performance.

The goal of this project is to add the ability to dynamically change the pitches of the strings of an already existing mechatronic string instrument. The instrument to be improved is WPI's Music Perception and Robotics Lab's *Cyther*: a ten-string zither that can be played by a human performer and can use solenoids to strike and dampen its strings. The goal of this project is to design and implement a tuning system controlled via software that can work while a performer plays the instrument, allowing for dynamic pitch changes. The ability to sense and control the pitch of strings while a performer plays the instrument provides the possibility to robotically create different string instrument techniques like sliding, detuning, and bending that were previously not possible.

# Background

## Pitch Changing Interactions between Musicians and String Instruments

Understanding the different techniques performers use to change the pitch of a string is important because it allows the creator of a robotic string instrument to design an instrument capable of producing these techniques and other new techniques that are derived from the instrument's robotic capabilities.

The pitch produced by a string is a function its length, weight, tension [1]. These factors change the frequency, magnitude, and shape of the waveform produced by an instrument, which is what the ear senses and the brain perceives as the instrument's sound. The pitch of a string is commonly changed by pressing the string against a surface e.g., a fret board, which changes the vibrating length of the string. *Portamento* is a technique where a performer slides his finger or another object along the string as he plays, gradually changing the vibrating length of the string to produce a smooth glide. A *trill* requires the performer to quickly alternate between pressing a string at two different positions, producing alternating pitches. *Vibrato* produces a slight alternating change in pitch, produced by the performer quickly rolling her finger back and forth around a pitch. Changing the tension in a string is another way to change the pitch of the string. Some string instruments have their strings wound around rotating pegs. By rotating the peg while the string is vibrating, the performer produces a sliding sound from one pitch to another. Another technique utilized by performers is displacing the string, which *bends* the pitch higher due to the increase in tension [2].

A performer can change the pitch of a string by lightly placing her finger at specific intervals along the vibrating section of the string, damping all but one of the frequencies that the string is vibrating at. The orchestrational term for this is harmonics. When a string vibrates, the frequency identified as the pitch is the fundamental frequency, the loudest frequency produced by the vibrating string, but the string is also vibrating at other frequencies. Figure 1 is a graph showing how different frequencies combine to form the waveform of the string.

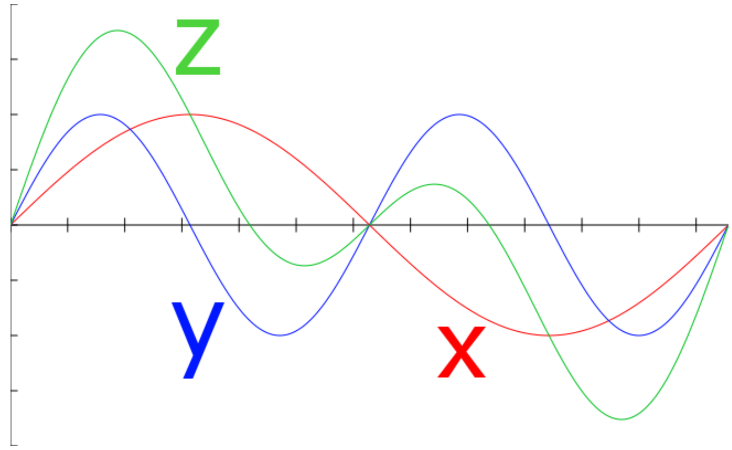

*Figure 1: Combination of Two Harmonic Waveforms into One Waveform*

When a performer's finger is placed on the string at the node of a non-fundamental partial's waveform, the fundamental frequency can be dampened, but the partial with zero amplitude will not be dampened. This creates a lighter, softer sound at a different pitch than the freely vibrating string [3]. For example, in Figure 1 the horizontal axis can be thought of as a string. Waves "x" and "y" are the waveforms that make up wave "z", which represents the vibration of the string. If a performer places his finger at the node of wave "y", wave "x" will be dampened and not heard, but wave "y", which has an amplitude of zero at the position the finger is placed, will still be heard.

## Combination of Instruments and Machines

One of the appeals of a robotic string instrument is the ability to control an acoustic instrument with the speed and precision of a computer. A motor that spins a wheel of guitar picks is capable of playing a string much faster than a performer [4], and computer clocks are capable of keeping time much more precisely than a person. Mechatronic string instruments use a variety of actuators to alter the sound of a string and use software to control the actuation [5].

### Pitch Changing Devices: Prior Work

Some mechatronic string instruments can change the pitch of their strings autonomously. One way to do this is to change the length of the vibrating sections of their strings by moving a motor-driven bridge to different positions along the string [6].

#### *Guitar Bot*

GuitarBot is an example of a mechatronic instrument that uses a sliding bridge technique. As shown in Figure 2, a motor spins a belt that is attached to a bridge which slides along the string, changing the pitch [4]. The benefit of this design is that it's possible to create bending and sliding effects using the motion of the bridge, but the downside is that the amount of time to change from one pitch to another increases the further away the pitches are from each other, so large, fast changes in pitch might not be possible. Also, without a damper this instrument produces constant portamenti.

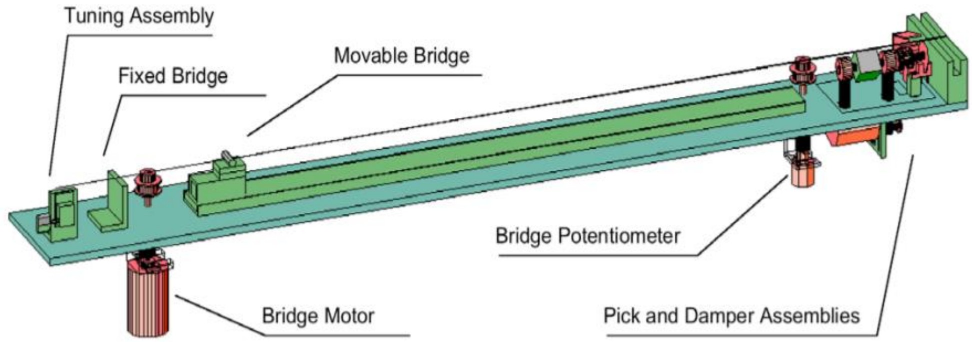


*Figure 2: GuitarBot Motorized Sliding Bridge CAD Model[4]*

### Crazy J's Guitar Player

Another way to mechanically change a string's pitch is to position solenoids above every fret on a fret board. The solenoids can push down on the string at the fret, which changes the length of the string, causing the pitch of the string to change. Crazy J's Guitar Player, shown in Figure 3, uses this technique and places an array of "fingers" all activated by solenoids along the frets of a guitar. The fingers press on the frets and change the pitch of the strings as a guitar player would [7]. The benefit of this design is that reaching any pitch will be equally fast because each pitch has a dedicated solenoid. This allows for large pitch intervals to be played just as fast as small intervals. Also, by using solenoids to press the strings, a varying amount of force can be used to create harmonic effects. The downside of this design is that no bending or sliding effects can be created, which limits the expressive capabilities of this instrument. Also, using a solenoid for every pitch is expensive.

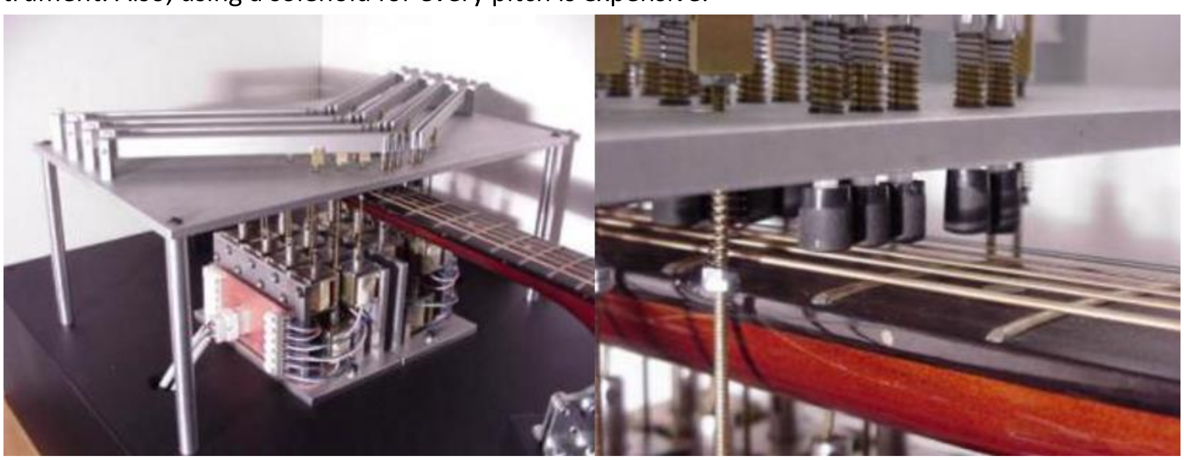

*Figure 3: Crazy J's Guitar Player Solenoid Actuated Pitch Changing Mechanism[7]*

### Shibuya Labs Violin Playing Robot

A combination of sliding actuators along the strings and pressing the strings with solenoids has been used by Shibuya Labs in their violin playing robot. They developed a system for pressing on violin strings, shown in Figure 4, which slides four solenoids, one for each string of the violin, along the length of the violin fingerboard. This technique is the most similar to how a performer naturally adjusts the pitch by moving their hand along the finger board [8]. A benefit of this system is that it is capable of performing pitch bends and slides by pressing a solenoid onto a string and then sliding along the string, allowing for more expressive techniques. Using solenoids to press down on the strings allows the instrument to play the harmonics of the strings, like a performer would. By mimicking how a person plays the violin, the Shibuya Labs violin playing robot must move its "hand" to change pitch, which might not allow for the instrument to play complex pieces with many large pitch changes that are too difficult for a person to play.

*Figure 4: Shibuya Labs Prototype for Pitch Changing in a Violin Playing Robot[8]*

### *The Violobot*

The Violobot created by the Canada Council for the Arts, shown in Figure 5, is another example of pitch changing using a sliding finger. This mechatronic string instrument uses four different sliding actuators, each with their own finger pressing on a string. A benefit of this system is that it allows for pitches to slide in opposite directions, which the Shibuya Labs Violin can't do because, every actuator slides together [8]. This allows for the Violobot to play songs that a person could not play. On the other hand, using only one actuator per string means that like the other instruments with sliding actuators, a large change in pitch will take more time than if there were actuators for every note.

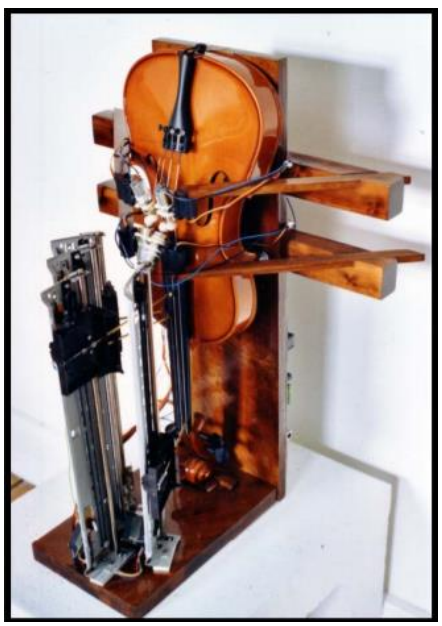

*Figure 5: Violobot, Created by Canada Council for the Arts[8]*

### *The Robofiddler*

Another mechatronic violin with pitch changing capabilities is the Robofiddler. This mechatronic string instrument, shown in Figure 6, has a series of bars that press down on the fingerboard with varying force. A stepper motor winds up a string, which is attached above the bar. As the string is wound up, the bar is lowered, when the string is unwound, the bar is raised up by a spring. The main benefit of this system is that it can create different kinds of pitch changes using harmonics because it can press down upon the strings with a variable force [8]. The downside of this system is that it cannot create pitch bends or slides because none of the actuators move along the string.

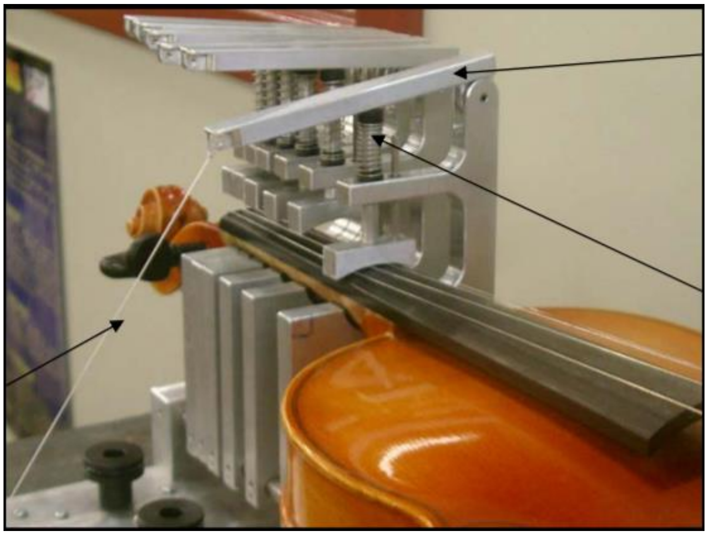

*Figure 6: Pitch Changing Device in the Robofiddler[8]*

### *Pitch Changing Devices: Pro-Con Table*

Table 1 shows the various pros and cons of each pitch changing device:

| | Bend & Slide Effects | Simultaneous Pitch Changes in Opposite Directions | Immediate Pitch Transition | Press with Varying Force |
|---|---|---|---|---|
| GuitarBot | Yes | Yes | No | No |
| Crazy J's Guitar Player | No | Yes | Yes | Yes |
| SL Violin Playing Robot | Yes | No | No | Yes |
| Violobot | Yes | Yes | No | No |
| Robofiddler | No | No | Yes | Yes |

*Table 1: Pros and Cons of Various Pitch Changing Devices[4], [7], [8]*

## Autonomous Tuning Systems: Prior Work

The mechatronic string instruments mentioned above use various actuators to change the pitch of their strings, but they don't sense the pitches of the strings [4], [7], [8]. Autonomous-tuning string instruments are capable of tuning themselves to specified pitches by sensing the current pitch of the strings and adjusting until the desired pitch is reached [9]–[11]. The value of autonomous tuning is in the ability for an instrument to sense and record its string's pitches, which allows the instrument to keep itself in tune with no input from the performer as well as change it's tuning during a performance.

### *Tronical Tuning System*

The Tronical tuning system automatically tunes the strings of a typical guitar (see Figure 7). The system, which consists of a computer, six motorized tuning machines, and six buttons, is mounted underneath the head of the guitar. When the user is ready to begin tuning the guitar, the system instructs them to play certain strings via LEDs. As the user plays the strings they are told to play, the processor senses and analyses the harmonic vibrations in the body of the guitar, which are used to determine the frequency of the string. The system then rotates small motors attached to the tuning machines of the guitar to adjust the tension of the strings until they are at the correct frequency. The user can decide whether to tune every string at once, or individual strings via button commands [9].

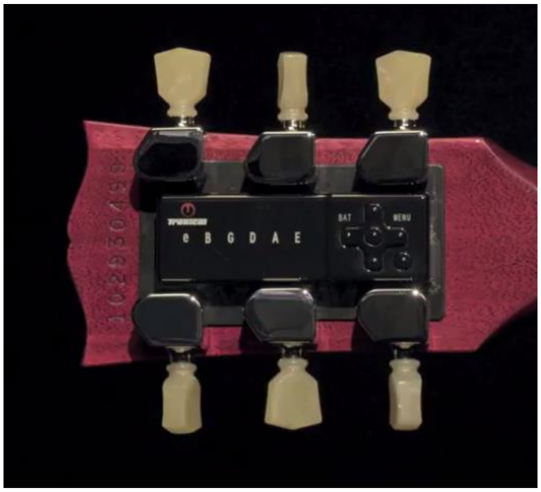


*Figure 7: Tronical Tuning System on a Guitar[12]*

### *Gibson Robot Guitar*

Unlike the Tronical tuning system, which is mounted externally to a guitar, the Gibson Robot Guitar has autonomous tuning capabilities built in to the body of the instrument. The autonomous tuning system is controlled by a push pull knob on the body of the guitar. The knob allows the user to select from six configurable tuning modes. The knob also has LED's to signify when a string is out of tune, being tuned, or in tune during the entire tuning process. The Gibson Robot Guitar has a bridge on the body of the guitar (see the left part of Figure 8) that can measure the vibration of each string. The movement data from the bridge is analyzed by a processor in the body of the guitar to determine the frequency of each string. The frequency information is sent to a processor in the head of the guitar shown on the right of Figure 8. The processor in the head of the guitar is connected to small servo motors which are connected to the tuning machines at the head of the guitar. The processor determines how much to spin the servo motors to achieve the desired pitch [10].

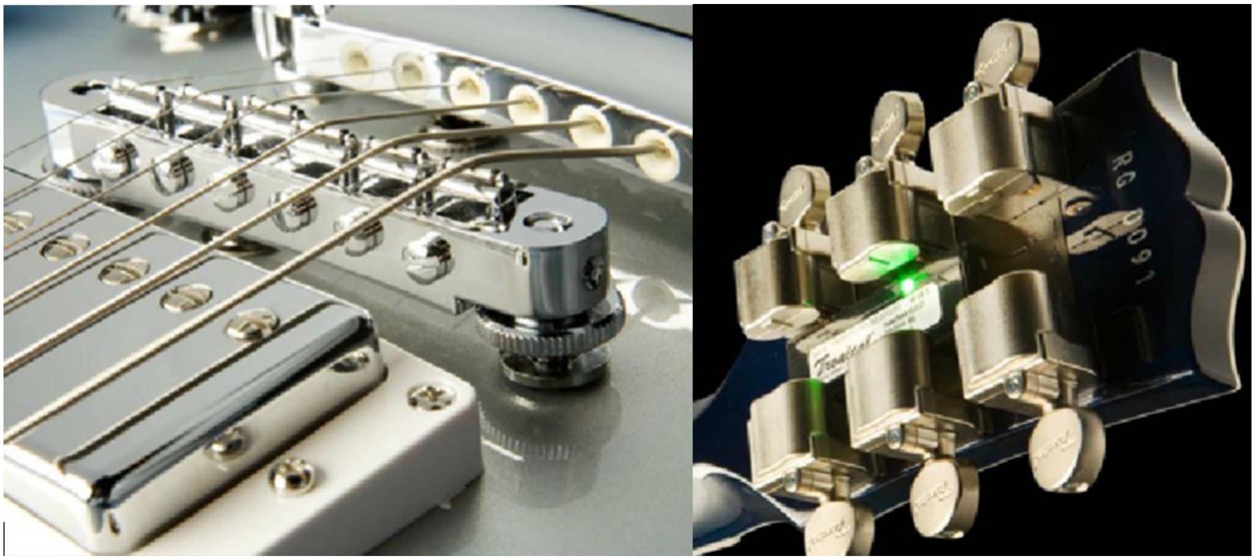


*Figure 8: Gibson Robot Guitar Vibration Sensing Bridge (Left) and Autonomous Tuning Tail Piece (Right)*

### *AxCent Guitars*

AxCent guitars offer an advantage over other autonomous tuning systems. AxCent guitars are similar to Gibson Robot Guitars because they have autonomous tuning capability built into the guitar, but AxCent guitars have a method of tuning during a performance and without needing to play the strings. The user interfaces with this autonomous tuning system through twelve buttons and an LED screen. The buttons are used to set tuning presets and control when the guitar changes its tuning mode. The LED screen displays information about the state of the autonomous tuning system and what the current tuning mode is. During construction the AxCent guitar is calibrated by collecting information on the string's pitches at different positions. The calibration process allows for the strings to be moved to positions regardless of whether or not they are being played, and without the need to measure their frequencies [11]. Although the details of the calibration process are publically unavailable, a patent owned by Transperformance Inc., the corporation that owns AxCent guitars, describes a method of tuning where each string has a transducer that converts its motion into an electrical signal. The signal is then processed from the time domain to the frequency domain, where the pitch of the string can be evaluated. This pitch can then be related to the position of the motor in the tuning actuator. To tune the strings, the body of the guitar houses a mechanism that can slide the strings back and forth as needed [13]. A patent referenced by Transperformance Inc. details a way of tuning from the body of a guitar where each string is attached to a device that is mounted around a screw shown in Figure 9 [14]. When a string is tightened, if there is friction at points where the string contacts the guitar, then the tension in string will not be uniform, and the calibrated position of the string will not correspond to the desired pitch. To address this issue the AxCent guitar uses bridges made from rollers that roll with the string as it's tightened or loosened, preventing friction caused by the string sliding over the bridge. The string is pulled or pushed by the rotation of a motor with a screw for a shaft. This method can provide accurate tuning at variable speed [11].

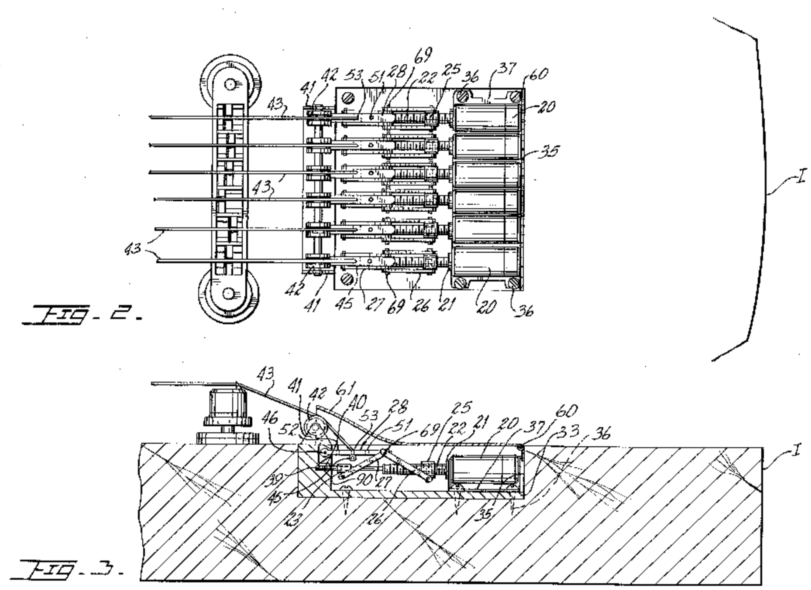

Figure 9: US Patent 4,584,923, Tensioning Strings Via Motorized Screws in Guitar Body[14]

### Don Gilmore's Self Tuning Piano

Don Gilmore has created a system for autonomously tuning a piano that's installed at the factory and only makes small adjustments to the pitch when necessary to keep the piano in tune. The system doesn't have a user interface as it is always active, and doesn't require the user to select pitches for the keys. The system senses the pitch by shining an LED at each string with a photoresistor placed behind the string. The photoresistor outputs a voltage that corresponds to how much light from the LED gets past the string. As the string vibrates, the voltage from the photoresistor changes slightly. This slight change is amplified and using a Fourier transform, the signal is transformed to a set of frequencies, which is analyzed to identify the fundamental frequency of the string. To adjust the pitch of the strings, a small current is sent through the string. This current slightly heats up the string which causes it to slightly expand and loosen. This changes the pitch very slightly, but very accurately. This system can tune a piano string with an accuracy of +/- .001 cents [15].

### Tuning with Tension

Most of the above methods analyze string vibration to measure pitch. Another option is to sense the tension and use it to estimate the string's pitch. WPI's Music Perception and Robotics Lab prototyped a method to do this by attaching a strain sensor to a beam. One end of the beam was mounted to a solid body and the other end to the string. At the other end of the string was a tuning machine controlled by a motor. As the tension in the string changed the beam would bend more or less, the change in bend of the beam would change the strain on the strain sensor. This change in strain caused the resistance of the sensor to change, which was mapped to the pitch of the string. This system was able to tune a string with an accuracy of +/- 8 cents. The advantage of a system that can autonomously tune a string by sensing the tension is that the strings don't need to be excited to be tuned. The strings can be tuned at any time, and the autonomous tuning system can remain a closed loop system at all times, meaning the system is always sensing the pitch of the string. The limitation of this system is that if any parameters of the string are changed, such as the length or the material, than then system will no longer accurately predict the pitch of the string and the estimation function will need to be changed [16].

### *Autonomous Tuning Systems: Pro-Con Table*

Table 2 shows the various pros and cons of each pitch changing device:

| | User Interface | Frequency Detection | Frequency Estimation using Non-Frequency Measurements | Tuning Before Performance | Sensing During Performance | User Can Define Goal Pitches | Reduces Friction Between Strings and Bridge |
|---|---|---|---|---|---|---|---|
| Tronical | Yes | Yes | No | Yes | No | Yes | No |
| Gibson Robot Guitar | Yes | Yes | No | Yes | No | Yes | Yes |
| AxCent Guitars | Yes | Yes | Yes | Yes | No | Yes | Yes |
| Self Tuning Piano | No | Yes | No | Yes | Yes | No | No |
| Tension | No | No | Yes | Yes | Yes | Yes | Yes |

*Table 2: Pros and Cons of Various Autonomous Tuning Systems*

## Interactions between Musicians and Machines

In addition to being able to sense and change the pitch of its strings, a robotic string instrument should have a way for a performer to interact with the autonomous tuning system. The instrument needs to respond to the performer in a way that allows for dynamic pitch changes without limiting the performer's expressive capabilities. Understanding the different ways that an individual can provide information to a machine will help design a system that allows a musician to utilize the autonomous pitch changing capabilities of the robot.

Mapping a gradual change in the resistance of a circuit to a parameter that needs to be controlled is a common way to interface with a machine. A simple example of this is the use of a dial connected to a potentiometer to control the gain of an amplifier. Potentiometers are continuous variable resistors that can be placed in a number of housings such as dials, levers, and foot pedals. Potentiometers are used in electronic synthesizers to map a performer's input to pitch bends and the amplitude of different oscillators in the synthesizer [17].

Proximity sensors are another way that the parameters of autonomous tuning mechanisms could be mapped to the actions of a performer. These sensors send out short bursts of sound or light, then record the amount of time it takes for the burst to be reflected back to the sensor or the angle of reflection. Figure 10 shows the path that the infrared light from an IR distance sensor takes to measure its distance away from an object.

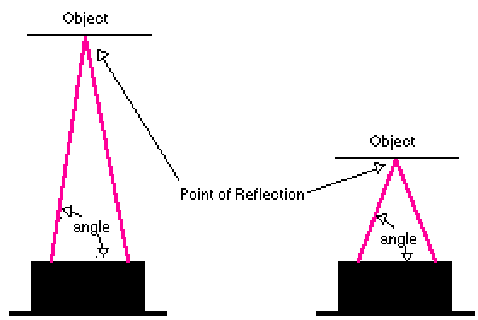

*Figure 10: IR Sensor Uses Measured Angle of Light Path to Determine Range[18]*

This information is used to calculate the distance that an object is from the sensor. With proximity sensors mounted on the instrument towards the performer, it is possible to map the performer's location relative to the instrument to the parameters of the autonomous tuning system. A Theremin is an example of an instrument that uses the performer's distance from it to control different parameters. When playing a Theremin, one hand's distance from an antenna controls the pitch, while the other hand's distance from a different antenna controls the volume [18].

Force sensors mounted to surfaces that an individual grips or steps on can be used to control the parameters of a performance. A force sensor is a small fine wire mesh. When a force is applied to the mesh, its resistance changes. This change in resistance can be mapped to the force applied to the sensor [16]. Figure 11 is an image of a force sensor, called a strain gauge. The grid is the mesh of wires that changes resistance as it bends.

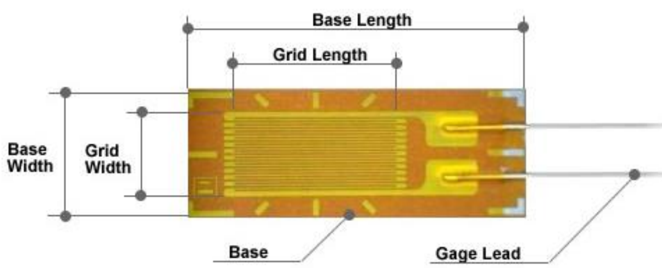

*Figure 11: Force Sensing Strain Gauge Diagram[19]*

Accelerometers and Gyroscopes are sensors that can measure linear and angular acceleration. These devices can be mounted to a performer or object and provide data about the performer or object's location. Detected movements can then be mapped to different aspects of the performance [20]. For example, the Electronic Sitar Controller created by Ajay Kapur uses an accelerometer inside of a headset, shown in Figure 12 to allow a performer to trigger different parts of the performance via head movements [21].

*Figure 12: Electronic Sitar Headset with an Accelerometer for Triggering Performance Events[21]*

## Limitations of Prior Work

Mechatronic string instruments with pitch changing capabilities do so by changing the vibrating length of their strings. Whether they do this by pressing the string into a fret board or by sliding a rod along the length of the string, changing the vibrating section of the string's length limits the playability of the instrument by a performer. Most of these mechatronic instruments are played entirely autonomously. For an instrument that is meant to be played by a person and a machine simultaneously, constantly changing the vibrating length of the string is limiting to the human performer.

Of the prior autonomous tuning systems, none of them are designed to work constantly throughout a performance. Most use only frequency analysis to tune strings before a performance and the only way to tune during a performance is via dead reckoning. These limitations prevent the sliding pitches from being used as a part of the piece. A system that could tune at all times can use bending and sliding pitches through the piece to expand the expressive capabilities of the instrument.

# Design Specifications and Requirements

The robotic string instrument created during this project should be able to sense and control the pitch of its strings, and produce portamenti, sliding, and pitch bending effects at all times during a performance. Current autonomous tuning systems rely on frequency analysis and can only determine the pitch of a vibrating string. Therefore they cannot function at all times during a performance, which limits the interactivity of the instrument. In order to sense and control the pitch at all times during a performance, a new method of autonomous tuning must be designed.

## Hardware

The entire instrument must be able to fit within a 36" x 12" x 4" carrying case to keep it stable during transportation. The sensors for determining pitch and actuators for changing pitch must be less than $30.00 per string because of budget constraints. Any custom circuitry required to control the instrument should be designed and built on a PCB board. A microprocessor must be selected capable of controlling the entire system. A power supply capable of simultaneously sensing and tuning every string on the instrument must be identified.

The ten strings should be selected so that each string's range is from the pitch the string makes at seven pounds of tension to the pitch the string makes at fifteen pounds of tension. Each string's highest pitch should be the middle pitch of the next highest string. This overlapping range allows for closer harmonies during performances.

## Tuning System

The tuning system created for this instrument must be able to sense the pitch of each string in a way that allows the instrument to create various pitch changing techniques like *portamento* and *vibrato* at all times during a performance. The actuators of this tuning system should be able to adjust the pitch of any string by a semitone in 100 ms or less. This 100 ms value was chosen because it is generally the smallest rhythmic interval found in human musical performance [22]. The tuning system should be able to tune to a desired pitch with an accuracy of +/- 3.6 Hz because that is the common just noticeable difference [23].

The tuning system must be able to process the signals from the sensors to determine the pitch of the strings. The software should have a form of closed loop control to keep every string at a desired pitch. The software should adjust the pitch estimation function over time to compensate for small changes to the instrument that alter the strings' pitches. The software must be able to interpret signals from a computer and from a controller used by the performer that determine the timing, magnitude, direction, and speed of the dynamic pitch changes.

# Design

## Structural Design

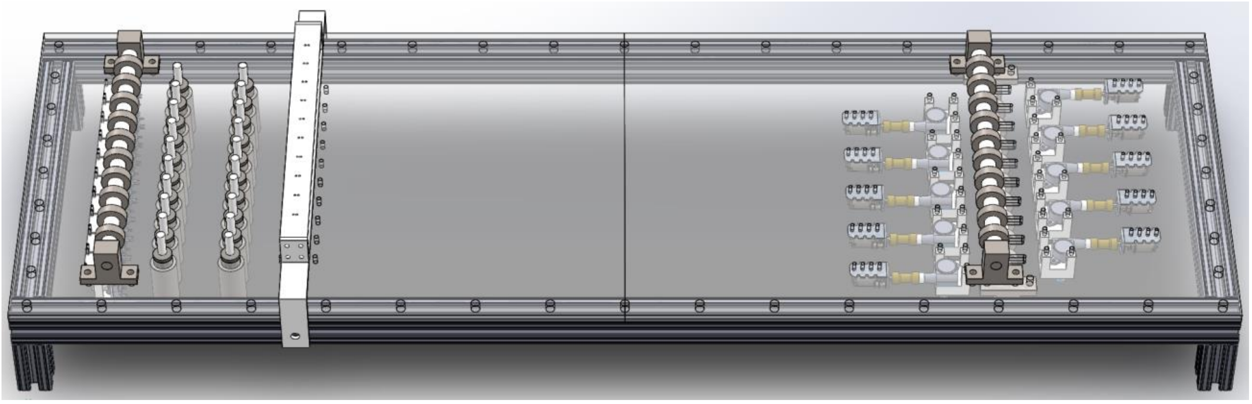

*Figure 13: Cyther V3 Complete Instrument CAD Model*

The structural design of *Cyther V3*, shown in Figure 13, is based on the need for the instrument to be modular and portable. The instrument's length, width, and height are such that it fits snugly inside the 36" x 12" x 4" carrying case so that it is not damaged during transportation. The aluminum T-slotted aluminum channel provides a sturdy frame which two separate sheets of acrylic are mounted to. The two acrylic sheets each span half the length of the instrument and can be replaced independently of each other. All the pitch detection and estimation hardware is mounted to one acrylic sheet, and all the pitch changing hardware is mounted to the other sheet. If at any point a quick fix needs to be applied, one of the acrylic sheets can be replaced with an identical acrylic sheet with duplicate hardware mounted to it. The replacement hardware can easily be plugged into the circuit boards because the wiring uses connectors. This modular design addresses potential unforeseen damage to the instrument.

In addition to being modular and portable, *Cyther V3* is designed to allow the strings to move as freely as possible during a performance. Friction between the strings and the bridge can create non-uniform tension throughout the individual strings [24] and add inefficiency to the tuning system resulting in slower, less precise pitch changes. To reduce the friction between the strings and bridge, the bridge, shown in Figure 14, is made from radial bearings mounted around a shaft.

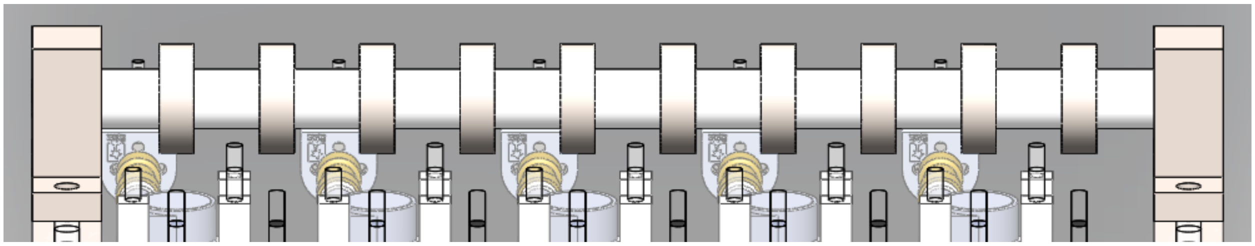

*Figure 14: Cyther V3 Bridge Made from a Shaft and Radial Bearings*

The bearings rotate around the shaft as the string is adjusted, which allows for the tension throughout the string to be constant.

## String Selection

Table 3 shows the ten strings selected for the instrument. The strings were chosen from the D'Addario string catalog [1]. Each string was selected so that its highest pitch was the next highest string's middle pitch. Each strings range is from the pitch it makes at 7 lbs. of tension to the pitch it makes at 15 lbs. of tension.

| String # | D'Addario Item # | Frequency at 7 lbs. (Hz) | Frequency at 15 lbs. (Hz) | MIDI Note at 7 lbs. | MIDI Note at 15 lbs. | Range |
|---|---|---|---|---|---|---|
| 1 | NW048 | 49.16522824 | 71.97052473 | 31.05848066 | 37.6556947 | G2 - D3 |
| 2 | NW039 | 59.84292063 | 87.60106591 | 34.46098763 | 41.05820167 | A#2 - F3 |
| 3 | NW032 | 71.90465087 | 105.2576311 | 37.63984164 | 44.23705568 | D3 - G#3 |
| 4 | PL024 | 88.5397845 | 129.6089732 | 41.24273092 | 47.83994496 | F3 - C4 |
| 5 | PL020 | 106.2484075 | 155.531743 | 44.39925233 | 50.99646637 | G#3 - D#4 |
| 6 | PL017 | 124.9988343 | 182.9795572 | 47.2129334 | 53.81014744 | B3 - F#4 |
| 7 | PL014 | 151.7815167 | 222.1853898 | 50.57391111 | 57.17112515 | D#4 - A4 |
| 8 | PL0115 | 184.7693741 | 270.4746685 | 53.97866548 | 60.57587952 | F#4 - C#5 |
| 9 | PL0095 | 223.6955788 | 327.4567976 | 57.28839863 | 63.88561267 | A4 - E5 |
| 10 | PL008 | 265.5985394 | 388.7964509 | 60.26092427 | 66.85813831 | C5 - G5 |

*Table 3: Strings Chosen for Cyther V3 and the Frequency and MIDI Range of Each String*

## Tuning System Actuation

The pitches of *Cyther V3's* strings are changed by controlling the tension in each string. The motor driven tuning machine, shown in Figure 15, changes the tension in a string by winding the string around a guitar tuning key modified to be mounted to, and spun by, a motor controlled by an Arduino. The tuning machine contains a worm drive with a ratio of 16:1. This increases the torque used to wind the string and prevents the tension in the string from applying any forces to the motor, which prevents the motor from having to constantly be powered, stabilizing the frequency of the string and increasing the lifespan of the instrument.

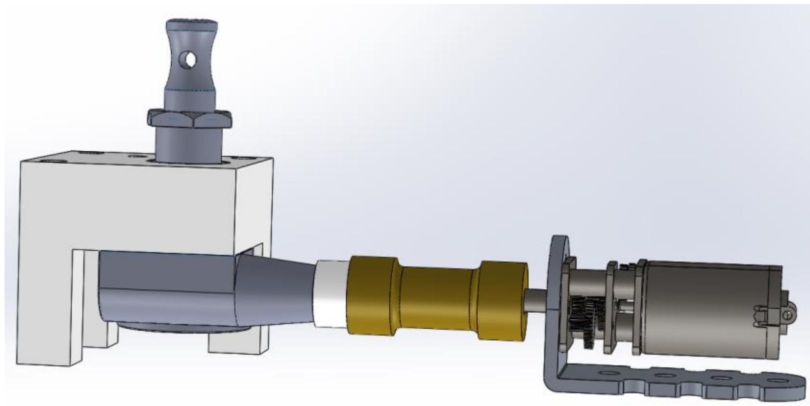

*Figure 15: Motor and Worm Drive used to Change the Tension of the Strings for Autonomous Tuning*

The strings selected for the instrument can safely handle 17 lbs. of tension. The motors used to wind the tuning keys should have a stall torque equal to four times the maximum tension to stay at optimal power levels. The Pololu 100:1 Micro Metal Gearmotor was chosen for its size and 30 oz. in. stall torque. These values can be used in Equation 1 to determine the maximum tension that the tuning system can create in a string. The tuning system used by *Cyther V3* can theoretically create a maximum of 120 lbs. of tension in a string. This value is much greater than the tension required for producing the desired pitches but this extra torque helps offset friction, gear train inefficiencies, and unpredictable misalignment of parts due to manufacturing inconsistencies, which reduce the amount of force the motor can transfer to the string. This ensures that the motor won't damage itself while trying to tune any of the strings.

$$Maximum\ String\ Tension\ = \frac{Motor\ Stall\ Torque\ \times\ Worm\ Gear\ Ratio}{Distance\ from\ String\ to\ Axis\ of\ Rotation}$$

*Equation 1: Maximum Tension a String can be wound to by the Tuning System*

## Tension Sensing

Unlike other robotic string instruments, *Cyther V3* can estimate the pitch of a string without needing to sense its frequency. The frequency of a vibrating string is a factor of its length, weight, and the tension [1]. When the length and weight are known constants, the frequency can be determined by only sensing the tension in the string. The tension sensor shown in Figure 16 measures tension through a potentiometer coupled to a spring. The ball end of the string is pressed against the spring cap. The rest of the string runs through a small hole in the cap, through the middle of the spring and out the bottom of the tension sensor, where another hole in the tension sensor leads the string to the bridge on the top of the instrument. As the string is tightened or loosened, the amount of force applied by the ball end of the string to the spring cap changes, which changes the amount the spring is compressed. As the spring compresses, the attached wiper on the potentiometer moves. The voltage across the potentiometer can be measured and used by the tuning algorithm to keep each string in tune. The structure of the tension sensor does not contact the wiper of the potentiometer or the side of the spring in order to create as little contact as possible between moving parts. If the cap makes contact with any stationary parts then it might stick and will not accurately reflect the force on the spring. This leads to error in the pitch estimation curve.

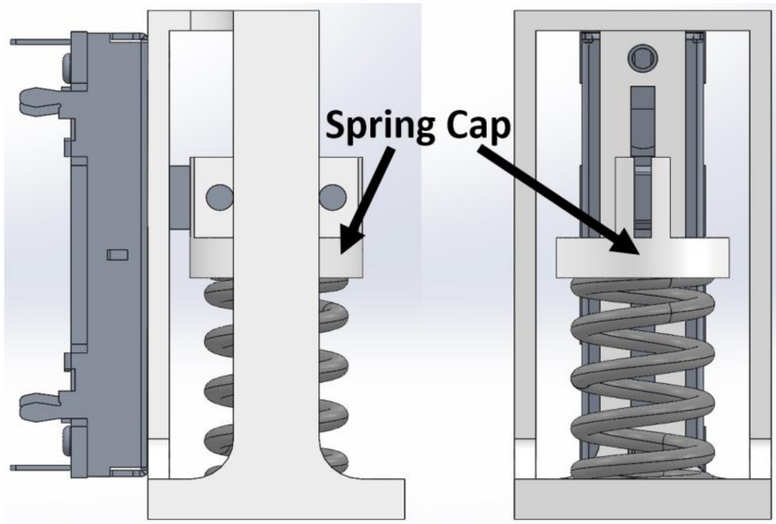


*Figure 16: Tension Sensor used for Pitch Estimation*

While the instrument is being played, the tuning system keeps each string at a desired frequency. It does this by comparing the current potentiometer value of each tension sensor to a value determined by the tuning algorithm. The motor then tightens or loosens the string depending on whether or not the potentiometer value is lower or higher than the goal value created by the tuning algorithm. Once the measured potentiometer value matches the goal potentiometer value, the motor stops. This method of tuning is used because the system doesn't require information on the current pitch, which prevents any error in the tuning system from compounding. If the tuning system changed pitch based on distance or time intervals, error in one pitch change would affect the quality of all the future pitch changes.

## Frequency Sensing

Even though *Cyther V3* can estimate the frequency of its strings from their tensions at all times during a performance, being able to also sense the frequency of its strings helps to increase the reliability of the autonomous tuning system. Measured frequency can be compared to estimated frequency. If the measured frequency and estimated frequency are different, the string can be adjusted and the potentiometer to frequency relationship curve is also adjusted so that future tuning of the string is more accurate. This modification of the relationship between tension and frequency is essential for long-term use of the instrument because factors such as temperature, warping, string replacements, and instrument repair, which can, over time, change the vibrating length of the string, altering the pitch.

Each string on *Cyther V3* has an optical pickup that measures its frequency. The pickup, shown in Figure 17 positions a 650nm laser diode (bottom) across from a photoresistor (top). When the light from the laser hits the photoresistor, the resistance across the photoresistor drops. Each string passes between a laser and a photoresistor, which prevents some light from reaching the photoresistor, increasing the photoresistor's resistance. When the string vibrates, the shadow it casts onto the photoresistor oscillates, causing the resistance of the photoresistor to oscillate at the same frequency as the string. The oscillating resistance is shown in Figure 18.

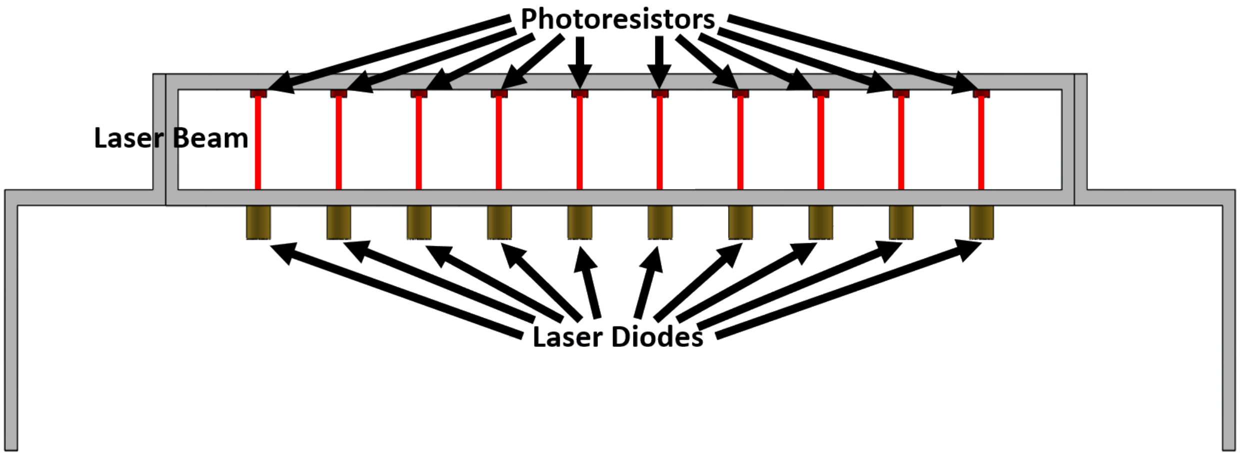


*Figure 17: Optical Pickup used on Cyther V3*


*Figure 18: The Voltage across a Photoresistor in the Pickup as the String Below it vibrates*

In order to ensure that the frequency measurements are accurate, the Arduino uses a series of checks and averages, shown in Figure 19.

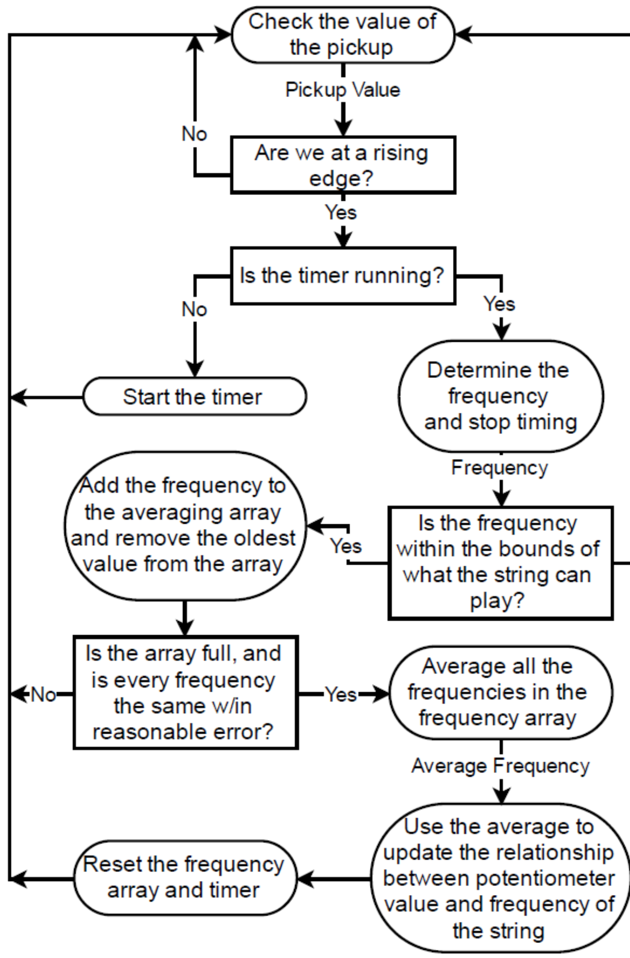


*Figure 19: Flowchart for Frequency Measuring and Averaging*

The Arduino polls the optical pickups every main loop iteration checking for a vibration. When a rising edge is sensed, the Arduino starts a timer that runs until the next rising edge is sensed. At this point the timer has measured the period of the wave. Using Equation 2, the frequency is calculated, and then the Arduino determines whether or not that frequency is within the bounds of what the string is capable of playing. If not, the frequency is ignored and the process is repeated. If the frequency is within the range of possible frequencies the string can play, it's added to an array of the previous ten frequency measurements. When this array is full, the Arduino checks if all the values are within a range of each other to account for errors in the frequency measurement due to the complex nature of the string's vibration. If not, the Arduino waits for another frequency measurement, then replaces the oldest measurement in the array with the new one and checks for consistency again. Once the ten most recent frequency measurements are within reasonable error of each other, all the values in the array are averaged and the average frequency is passed to a function that updates the curve relating potentiometer value to string frequency.

$$frequency = \frac{1}{period}$$

*Equation 2: The Relationship between Frequency and Period[25]*

## Relating Potentiometer Value to String Frequency

In order to tune the strings to desired pitches, each string must have a potentiometer to frequency relationship curve (PFRC). This equation can be determined by combining Equation 3 and Hooke's Law, which states that there is a linear relationship between the length of a spring and the force applied to it [26]. The unit weight and length of each string will remain constant, and the potentiometers used in the tension sensors change value linearly with respect to distance traveled. This information can be used to simplify the PFRC. Equation 4 shows the general form of the PFRC, a linear relationship between the potentiometer value and the square of the frequency measurement.

$$String\ Tension = Unit\ Weight \times (2 \times Length \times Frequency)^2$$

*Equation 3: The Relationship Between String Tension, Unit Weight, Length, and Frequency [1]*

$$Potentiometer\ Value = A \times Frequency^2 + B$$

*Equation 4: The PFRC with constants A and B*

The constants of the PFRC are determined experimentally, once for each string, by measuring the frequency and potentiometer value at three different frequencies that span the range of the string. Linear regression is used to find a best fit curve, then A and B are set to the constants of the best fit curve.

The Arduino must be able to adjust the PFRC as more data is collected and as the instrument changes over time. To adjust the PFRC, a curve-adjusting algorithm (CAA) is used. Whenever the frequency of a string is measured, the CAA updates the PFRC. The CAA begins by creating a set of points along the current PFRC that are evenly distributed within the playable range of the single string. For example, if the curve adjusting function creates a set of five points, the experimentally determined constants are A = 0.002667 and B = -6.667, and the playable range of the single string is from a frequency of 100 to a frequency of 200, Figure 20 shows the set of five points that would be created.

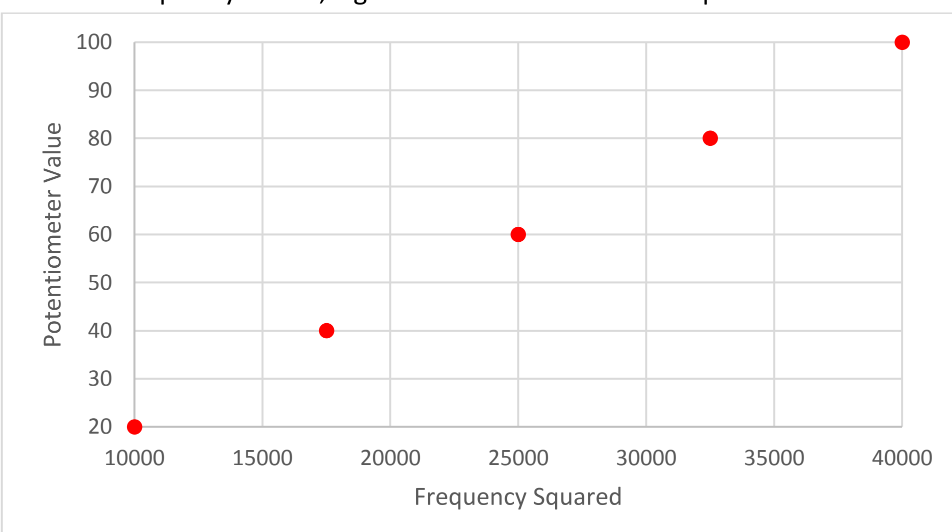


*Figure 20: Simple Representation of Step One of the Curve Adjusting Function*

Immediately after the set of points has been created, the CAA adds another point to the set. This new point is created by squaring the frequency measurement given to the CAA and measuring the value of the potentiometer in the tension sensor. This added point is responsible for the CAA's change to the PFRC. Continuing from the example above, if the frequency measurement provided to the CAA was 170, and the potentiometer value of the tension sensor was 55, then the new set would be the set shown in Figure 21, where the blue dot represents the new data point.

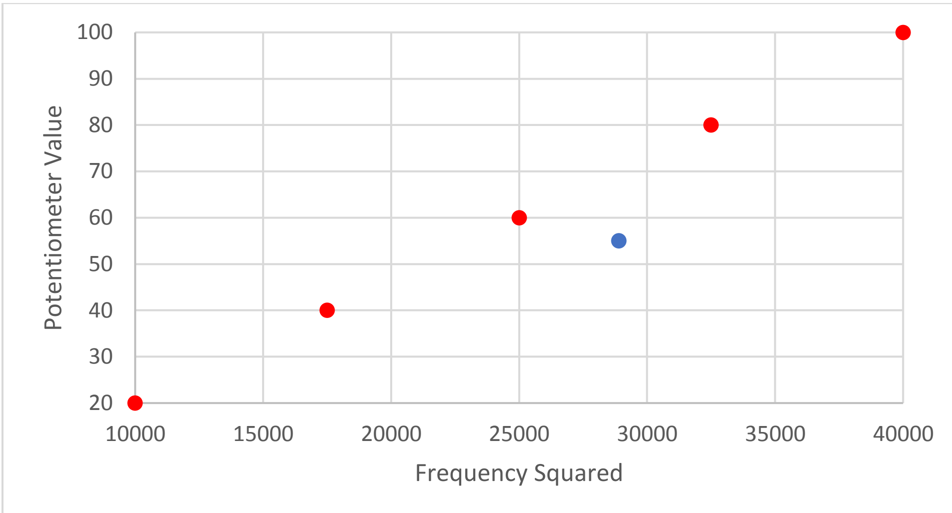


*Figure 21: Simple Representation of Step Two of the Curve Adjusting Function*

The final step of the CAA is to use linear regression to create a new best fit curve from the entire set of points, and then replace the PFRC constants with the constants from the new best fit curve. This new line, shown in Figure 22 will be the line from which the set of points is created the next time the CAA is called. Changing the number of points created in step one of the CAA will change how aggressively the PFRC will accommodate new data. With fewer points the PFRC will quickly move towards new data, and with more points the PFRC will make much smaller adjustments toward new data.

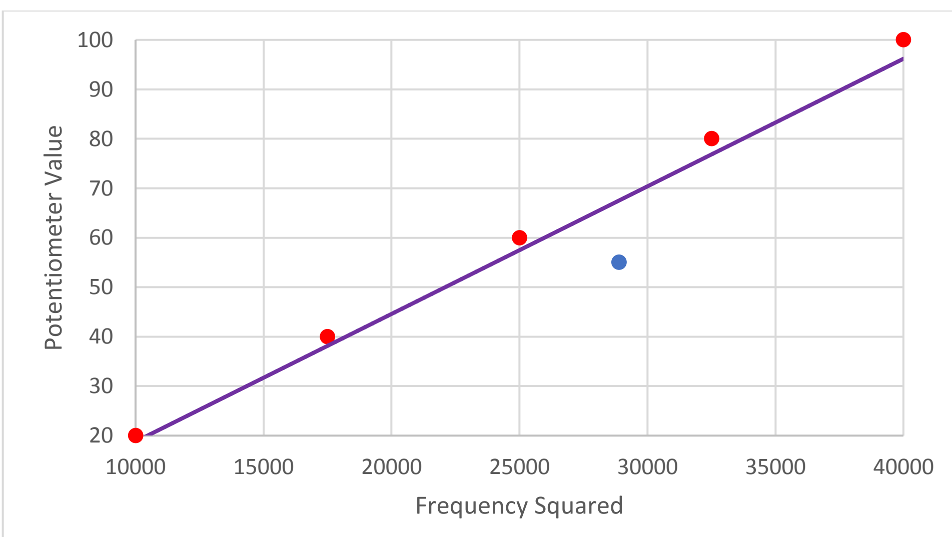


*Figure 22: Simple Representation of Step Three of the Curve Adjusting Function*

## Software Interface

The pitch of the strings and the activation of the tuning system are controlled with serial commands to the Arduino. This allows a composer or performer to give both predetermined and impromptu commands to the instrument. Table 4 shows available input commands.

| Command | Syntax | Inputs | Example |
|---|---|---|---|
| Frequency Analysis Toggle | F | - | F |
| String Tuning Toggle | T | - | T |
| Set Frequency | ![int],[float]! | An Integer that represents the string to tune. A floating point number that represents the goal frequency. | !3,234.32! |
| Set Constant "A" | A[float]A | A floating point number that represents the value of A. | A0.0012A |
| Set Constant "B" | B[float]B | A floating point number that represents the value of B. | B214.15B |
| End Performance | S | - | S |

*Table 4: Serial Commands for Cyther V3 Control*

The **frequency analysis toggle** command controls whether or not the Arduino is polling the pickups for a frequency. If this is off, there will be no adjustments to the PFRC. This command can be used to prevent the CAA from making dramatic and inaccurate changes to the PFRC when the performer is changing the vibrating length of a string by hand. The **string tuning toggle** command controls whether or not *Cyther V3* is adjusting the tension in each string. If this is off, none of the strings will change pitch. This command can be used to stop the motors from making small back and forth adjustments when the tension sensor senses small changes in tension when the string is being plucked. The **set frequency command** can be used to adjust the desired string to the desired frequency. This can be used during performances to create bending and sliding effects, as well as change the tuning of the instrument. The **set A and set B commands** can be used to change the constants of the PFRC. The ability to set the constants of the PFRC is useful when replacing strings or when the instrument has been played for so long that the original constants that were determined experimentally are no longer accurate. Even though the CAA will change the PFRC while the instrument is played, being able to manually adjust the constants can help accurately tune from the beginning of the performance. The **end performance command** will stop *Cyther V3* from being capable of tuning or sensing until it has been reset and display the current constants of the PFRC. This should be used at the end of a performance or when disassembling *Cyther V3* to prevent accidents.

## Circuit Board Design

*Cyther V3* has ten identical one string tuning systems that each require a connection to a 6V power supply and eleven connections to the Arduino. In order to use a common power supply, and to lessen the number of connections running from the instrument to the Arduino, three circuit boards were designed. All the circuit board schematics can be found in Appendix B: Circuit Board Schematics.

### Potentiometer Board

A circuit board was designed for the potentiometers on *Cyther V3*. This board allows every potentiometer to use the same 5V supply from the Arduino and for the Arduino to read each potentiometer from the same analog pin. The circuit board wires all the potentiometers in parallel with a 5V supply and connects each of their outputs to a 16:1 analog demultiplexer. The Arduino uses four digital pins to determine which potentiometer value is being read and one common analog input for all the potentiometers. The ability to only use one analog input for all the potentiometers was necessary because the Arduino didn't have enough analog inputs for each potentiometer and each pickup to get its own pin.

### Pickup Board

A circuit board was designed for the pickups on *Cyther V3*. This board contains a voltage divider for each photoresistor, which allows the Arduino to measure the change in resistance across the photoresistor as the string vibrates. The board also allows every laser diode and voltage divider to use the same 5V supply from the Arduino. A resistor of equal value to the photoresistor with no shadow cast on it from a string was used in each voltage divider so that when a shadow was cast onto the photoresistor from the string, the largest possible change in voltage would be measured. This increases the resolution of the pickups, which makes it easier to determine when the wave is at a rising edge. Each pickup has its own analog input on the Arduino so that the Arduino can easily and quickly change which string's frequency is being measured.

### Motor Board

A circuit board was designed for the motors that tune the strings. The circuit board allowed each motor to be powered from the same 6V 10A power supply, while having their speed and direction controlled by the Arduino. Five dual H-bridge chips allow each motor to be controlled by the Arduino with three pins while receiving power from the 6V 10A supply. Two of the pins determine the direction the motor spins, the other pin enables the motor to spin. By using PWM output pins on the Arduino for the enable pin on the H-bridge, the motors can spin at variable speeds. The circuit board is powered by a 6V 10A supply, which is enough for each motor to spin simultaneously and to power the H-bridges. A 5V regulator is used on the board to step down the 6V signal from the power supply in order to power the H-bridge chips with 5V.

# Results

## Hardware

The motors that were used in the *Cyther V3* were designed to have extra torque to make up for manufacturing inconsistencies and so they could operate at lower power and therefore last longer. While tuning from minimum to maximum string tension, the motors were able to tune the strings to their maximum tension without stalling. The motors used more current when tuning the strings up than when tuning them down. Table 5 shows the current the motors used at different times compared to stall current.

| Stall Current | Stop Current | Tune Up Current | Tune Down Current |
|---|---|---|---|
| 843 mA | 9 mA | 384 mA | 253 mA |

*Table 5: Motor Current at Different Times during Tuning*

While *Cyther V3* was being played, the motors created acoustic noise that interfered with the ability to hear the string. Figure 23 shows how the noise level of the motor compares to the noise of the string when the motor is holding the string steady and when the motor is tuning the string and spinning. Once the listener is more than two feet away from the instrument, the spinning motor drowns out the sound from the string. This isn't a significant problem because the strings are meant to be amplified with an electromagnetic pickup.

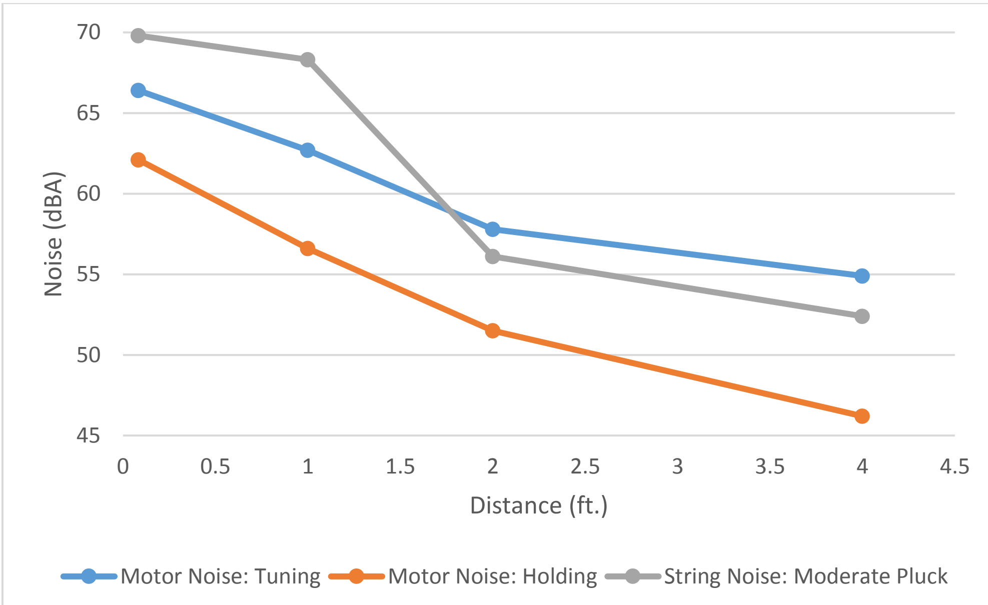


*Figure 23: Noise from the String and Motor at Varying Distances*

During the manufacturing process, errors and lack of project time prohibited completion of the PCB's. As a result, a breadboard was used to test the system on one string. The breadboard used the same equipment that the circuit boards were designed to use and was wired in the same way. The circuits worked as expected: the signals from the potentiometer and pickup were processed by the tuning software without any pre-filtering of the signal and the Motor circuit allowed the Arduino to control the motor while getting power from the 6V power supply.

Unexpectedly, the laser diodes used in the pickups weren't equally bright. As a result, each photoresistor had a different resistance when the laser was shining on it. This problem was solved by measuring each photoresistor's resistance when the laser was on and picking a resistor equal to the measured resistance (instead of using one resistor value for every pickup).

## Tuning System

The frequency analysis capabilities of the instrument were tested by observing the pickup's waveform and comparing the frequency measured by *Cyther V3* to a series of known frequencies. A graph of the signal from the optical pickup over time as the string is plucked, shown in Figure 24, was used to analyze the quality of the pickup. The graph shows that there is a period of around 1.5 seconds where the amplitude of the string's oscillation is inconsistent before settling into a decaying oscillation.

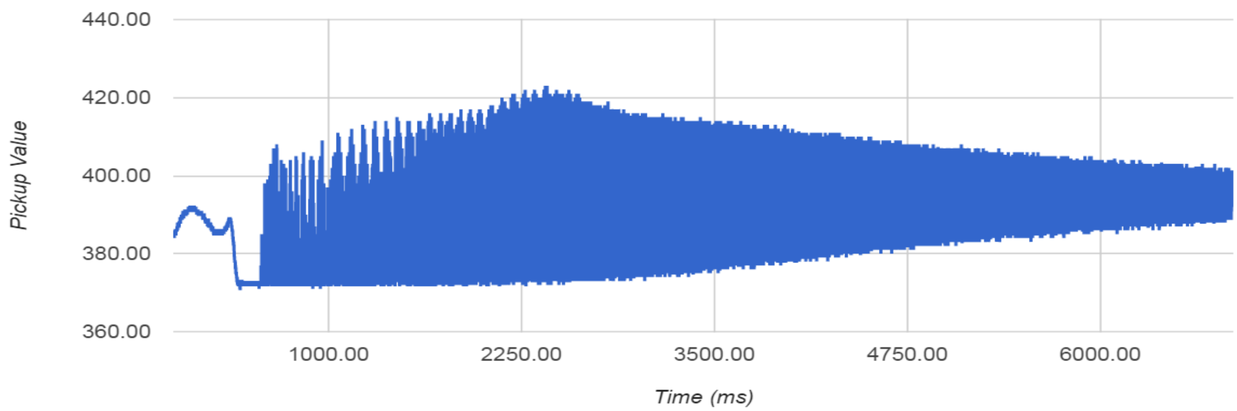


*Figure 24: Graph of Pickup Value over Time When the String is plucked*

When the Arduino senses the pluck, there is a delay before it determines the frequency of the string. Table 6 shows the amount of time it took the Arduino to determine the frequency of the string at different frequencies. The average amount of time when determining the frequency of a string that was plucked was 183.8 ms. There were some cases when the string was plucked very hard that it took the software around a second to determine the frequency. By using solenoids to pluck the strings the impulses will be more uniform and predictable, which will help shorten the amount of time it takes to analyze the frequency.

| Frequency (Hz) | Frequency Measurement Delay (ms) |
|---|---|
| 167.51 | 239 |
| 187.63 | 118 |
| 198.43 | 112 |
| 212.77 | 349 |
| 221.74 | 101 |

*Table 6: Delay in Frequency Measurement at Various Frequencies*

The accuracy of the frequency analysis was measured, first by using a waveform generator to send a signal directly into the Arduino, replacing the pickup signal. By eliminating the pickup, this experiment was used to test the quality of just the software responsible for the frequency analysis. Table 7 shows the frequency determined by *Cyther V3's* software when a sine wave with a magnitude of 4V and offset of 2.5V was measured at various frequencies. Based on this data the Arduino can measure the frequency of a wave with an error of < 0.0037% which is well within the error that the human ear can perceive.

| Frequency From Waveform Generator (Hz) | Frequency Determined by Arduino (Hz) | Error (Hz) | % Error |
|---|---|---|---|
| 90 | 90.27 | 0.27 | 0.003 |
| 130 | 129.89 | -0.11 | 0.000846154 |
| 170 | 171.31 | 1.31 | 0.007705882 |
| 210 | 210.14 | 0.14 | 0.000666667 |
| 250 | 250 | 0 | 0 |

| | | | |
|---|---|---|---|
| 290 | 289.22 | -0.78 | 0.002689655 |
| 330 | 331.25 | 1.25 | 0.003787879 |
| 370 | 370.88 | 0.88 | 0.002378378 |
| 410 | 410.26 | 0.26 | 0.000634146 |

*Table 7: Comparing the Frequency from a Waveform Generator to the Measurement of that Frequency by the Frequency Analysis Software on the Arduino*

Once it was determined that the software was capable of accurate measurements, another experiment comparing FFT analysis of an audio recording of a string to *Cyther V3's* software's analysis of the pickup signal was performed. This experiment was used to determine how reliably *Cyther V3* can measure the frequency of a string during a performance. Table 8 shows the measured frequency of the string as determined by an FFT compared to the frequency measured by the Arduino. There is a maximum error of .017%, which is higher than the previous test. A probable reason for the higher error is that the vibration of the string is not a perfect sine wave and it's more difficult to measure the rising edges of a complex waveform. These results are promising because the frequency was never off by more than 3.6 Hz, which is the smallest change that the average human ear can perceive [23].

| Frequency From FFT Software (Hz) | Frequency Determined by Arduino (Hz) | Error (Hz) | % Error |
|---|---|---|---|
| 172 | 169.21 | -2.79 | 0.01622093 |
| 182 | 178.9 | -3.1 | 0.017032967 |
| 194 | 193.44 | -0.56 | 0.002886598 |
| 202 | 202.45 | 0.45 | 0.002227723 |
| 211 | 210.11 | -0.89 | 0.004218009 |
| 224 | 220.77 | -3.23 | 0.014419643 |

*Table 8: Comparing the Frequency of the String Determined by an FFT to the Measurement of the Frequency by the Frequency Analysis Software on the Arduino*

To test the capabilities of the tuning system a series of pitch changes were analyzed to determine the speed and accuracy of the tuning mechanism. Table 9 shows these tests.

| Music Interval | Frequency Change (Hz) | Goal Frequency (Hz) | Measured Goal Frequency (Hz) | Measured Goal Frequency Error (Hz) | Measured Goal Frequency % Error | Tuning Speed (ms / semitone) |
|---|---|---|---|---|---|---|
| E3 - F3 | 9.8 | 174.61 | 174.53 | -0.08 | 0 | 247 |
| F3 - E3 | -9.8 | 164.81 | 161.82 | -2.99 | -0.018 | 247 |
| E3 - F#3 | 21.19 | 185 | 191.22 | 6.22 | 0.034 | 196 |
| F#3 - E3 | -20.19 | 164.81 | 153.63 | -11.18 | -0.068 | 151.5 |
| E3 - G#3 | 42.84 | 207.65 | 207.06 | -0.59 | -0.003 | 147 |
| G#3 - E3 | -42.84 | 164.81 | 164.48 | -0.33 | -0.002 | 112.5 |
| A3 - G#3 | -12.35 | 207.65 | 205.36 | -2.29 | -0.011 | 191 |
| G#3 - A3 | 12.35 | 220 | 221.74 | 1.74 | 0.008 | 248 |
| A3 - G3 | -24 | 196 | 202.45 | 6.45 | 0.033 | 143 |

| | | | | | | |
|---|---|---|---|---|---|---|
| G3 - A3 | 24 | 220 | 218.84 | -1.16 | -0.005 | 169 |
| A3 - F3 | -45.39 | 174.61 | 165.85 | -8.76 | -0.05 | 131.25 |
| F3 - A3 | 45.39 | 220 | 216 | -4 | -0.018 | 138 |
| D#3 - A#3 | 77.52 | 233.08 | 221.74 | -11.34 | -0.049 | 100.714 |
| A#3 - D#3 | -77.52 | 155.56 | 161.03 | 5.47 | 0.035 | 103.286 |

*Table 9: Tuning System Test Data*

The speed of the tuning system is slightly less than the goal speed of 100 ms / semitone. When tuning down, tuning system moves faster than when tuning up, which is in accordance with the increased current use when tuning up. The average tuning speed is 166.089 ms / semitone. This could be improved by buying more powerful motors, or by reducing the friction in the tuning system. More powerful motors were available but they were outside of the budget constraints of this project.

Based on the data, the tuning system is not accurate enough to go undetected. A majority of the pitch changes lead to pitches that are more than 3.6 Hz off of the desired pitch. Some of the smaller pitch changes were less than 1 Hz off, but the large changes where the string jumped a fifth were consistently more than 3.7 Hz away from the desired pitch. The data shows that the curve adjusting function worked well: whenever the measured frequency was off from the desired frequency the curve was corrected so that the error in tuning decreased and never compounded. Table 9 shows evidence of this because every pitch change was executed one after another and the error in some cases decreases from a preceding pitch change which wouldn't happen if the error was compounding.

# Recommendations for Future Work

## Improvements to the Instrument

The circuit boards that have been designed should be manufactured and tested. The Voltera One can be used to manufacture the boards, but the steps that should be taken are not the same as what the user manual recommends: 1) The holes should be drilled with the CNC machine, 2) the bottom layer should be printed and baked, 3) the vias should be filled but not baked, 4) the top should be printed and baked, 5) the surface mount components and the through hole components should be attached to the top layer with the solder paste. The solder paste will have to be manually applied to the holes. Using a soldering iron with the conductive ink is too prone to permanently damaging the boards.

A method of ensuring that the motor and the tuning machine rotate about the same axis should be developed. Currently there is no way to ensure that the motor and tuning machine line up properly, which results in the motor wobbling. Removing the wobble could potentially reduce noise and increase the speed if the wobble is increasing the friction of the system. Another way to make the tuning system tune faster would be to replace the motors with more powerful alternatives. Another improvement that can be made to the motors is replacing then with a quieter, brushless alternative. Even though the strings will be amplified with an electromagnetic pickup, reducing the noise of the motors is still a priority.

More testing should be done to determine the source of the tuning system's inaccuracy. A Possible reason for the tuning error is that the resolution of the Arduino's ADC was not high enough. If the range of frequencies that span one value of the potentiometer in the tension sensor is more than 3.7 Hz, the instrument cannot reach a desired frequency within the desired error. Another possibility is that the PFRC is nonlinear, and by using a linear relationship to determine the desired potentiometer value, the desired potentiometer value does not correspond to the desired frequency. More experimentation should be done to determine the cause of the tuning inaccuracies.

If the source of the error is the potentiometer resolution then a smaller potentiometer, or higher resolution ADC should be used. If the source of the inaccuracy is the nonlinearity of the best fit curve, then a different kind of curve should be generated. Another way to attempt to fix the tuning system is to add a section to the best fit curve code which associates a weight with each new frequency measurement that corresponds to how accurate that measurement is. With this information, more accurate frequency measurements can have more of an effect on the best fit curve, while outliers won't ruin an accurate curve.

## Additions to the Instrument

There are two main additions that *Cyther V3* is designed to accommodate. The first of these additions is a high-level user interface. This interface should allow a performer or composer to specify a series of tuning speeds, directions, and intervals that trigger at specific times in sync with the solenoids. The user interface should allow a composer to load an entire piece of music to be played by *Cyther V3*. The serial commands that *Cyther V3* uses now can be used by the interface to achieve the composer's or performer's desired effects.

The second recommended addition is the creation of a physical tool that can be used by a performer to dynamically change the pitch of the strings during a performance without needing to know the desired pitch changes ahead of time. One way this could be achieved is to create a mallet with an accelerometer inside it and a button on its handle. When the performer presses the button, the movement of the mallet could control the most recently played string's pitch.

# Conclusion

The goal of this project was to create a dynamic and interactive tuning system. Although this project has come a long way, there is still a lot of work that needs to be done to complete *Cyther V3*. The tuning system is currently capable of tuning to specific frequencies by relating the frequency of the string to the value of a potentiometer in a tension sensor. The instrument can then change the tension in the string until the desired potentiometer value is reached. When a string is played, the instrument can sense the vibration in the string using an optical pickup and measure the frequency of the string. Using the frequency measurement, the curve that relates the frequency of the string to the tension sensor's potentiometer value can be updated to prevent the error in the tuning system from compounding. The tuning system can be controlled via serial commands to tune to specific frequencies and update the best fit curve.

*Cyther V3* will be a robotic string instrument with unique capabilities. The ability to tune at all times during a performance will give robotic string instruments new expressive potential. The suspenseful sound of an orchestra slowly descending pitch, the wholesome resolution of bending a pitch into perfect harmony, and the power of the blues on a slide guitar were previously unable to be performed by a robotic string instrument. *Cyther V3* will be capable of these types of expressions and more. Furthermore, the ability for a performer to induce these changes, while algorithmic harmonization software plays along, will advance the depth and variety of human and machine instrument interaction.

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# Appendix A: One String Tuning Code

```
#include <TimerOne.h>

// Variables for Pickup
#define pickPin A0 // pin pickup 1 signal is read from

// Variables for Potentiometers
#define potPin A10 // pin potentiometer is read from

// Variables for Motors
#define motora1 22 // pin to control direction of motor 1
#define motora2 23 // pin to control direction of motor 1
#define motorctrl 2 // pin to control speed of motor 1
float goalFreq = 155.56; // the lowest pitch on the 12 tone scale the string can play

// Variables for Frequency Analysis
#define sampleRate 5000 // Hz
#define threshold 400 // count up when voltage divider with photoresistor output is
above this value
#define minFreq 128.27879 // Hz at 5 lbs of tension for string PL014, string 4
#define maxFreq 236.53441 // Hz at 17 lbs of tension for string PL014, string 4
#define countOffset 0 // waveCount offset for accurate frequency determination
#define sampleSize 10 // how many frequency measurements we take and average
#define allowedError 5 // the error between frequency measurements that is ok
int freqState = 0; // what point we are in the frequency analysis process
float lastFreq = 0; // the last frequency measurement, used for determing if we should
call curveAdjust
float sampleSet[sampleSize]; // an array of frequency measurements which is averaged
to determine the actual frequency
unsigned long lastCount = 0;
unsigned long count = 0;
int lastValue = 0;
int value = 0;
int waveCount = 0;

// Variables for Curve Adjusting
#define sampleNum 4 // the number of points to take from the current best fit curve
before adding the new point in
#define lowestFreq 151.78152 // the lowest frequency we want to play
#define highestFreq 222.18539 // the highest frequency we want to play
float bestFitCurveA = 0.001052; // PotVal = A * freq^2 + B
float bestFitCurveB = 228.548812; // These values were determined experimentaly

// Serial command variables
int freqEnable = 0;
int tuneEnable = 0;
int newGoal = 0;

void sample()
{
  count++;
}

void setup()
```

```
{
  Serial.begin(115200); // use the serial port
  Timer1.initialize(1000000 / sampleRate); // set up the timer
  Timer1.attachInterrupt(sample); // an interrupt occurs
  pinMode(pickPin, INPUT); // set up the pins
  pinMode(potPin, INPUT);
  pinMode(motora1, OUTPUT);
  pinMode(motora2, OUTPUT);
  pinMode(motorctrl, OUTPUT);
  digitalWrite(motora1, LOW);
  digitalWrite(motora2, LOW);
  digitalWrite(motorctrl, LOW);
}

void loop()
{
  if(tuneEnable)
  {
    changePitch();
  }
  if(freqEnable)
  {
    getFrequency();
  }
}

void serialEvent() // Reads serial input for commands of the type "![string#]
[frequency]"
{
  char inChar;
  String dataString = "";
  if(Serial.available() > 0)
  {
    delay(1);
    inChar = Serial.read(); // get the new byte
    if(inChar == 'F') // turn off or on frequency analysis
    {
      freqEnable = freqEnable ^ 1;
      if(freqEnable)
      {
        lastFreq = 0;
      }
      Serial.print("Frequency Anaysis Status: ");
      Serial.println(freqEnable);
    }
    else if(inChar == 'T') // turn off or on tuning
    {
      tuneEnable = tuneEnable ^ 1;
      digitalWrite(motora1, LOW);
      digitalWrite(motora2, LOW);
      digitalWrite(motorctrl, LOW);
      Serial.print("String Tuning Status: ");
      Serial.println(tuneEnable);
    }
    else if(inChar == '!') // giving a string command
```

```
{
  while(Serial.available() > 0)
  {
    inChar = Serial.read();
    if(inChar == '!')
    {
      goalFreq = dataString.toFloat();
      Serial.print("Start Time: ");
      Serial.println(millis());
      newGoal = 1;
      dataString = "";
      Serial.print("The new frequency is ");
      Serial.println(goalFreq);
    }
    else
    {
      dataString += inChar;
    }
  }
}
else if(inChar == 'A') // giving a string command
{
  while(Serial.available() > 0)
  {
    inChar = Serial.read();
    if(inChar == 'A')
    {
      bestFitCurveA = dataString.toFloat();
      Serial.print("The new slope is ");
      Serial.println(bestFitCurveA,4);
    }
    else
    {
      dataString += inChar;
    }
  }
}
else if(inChar == 'B') // giving a string command
{
  while(Serial.available() > 0)
  {
    inChar = Serial.read();
    if(inChar == 'B')
    {
      bestFitCurveB = dataString.toFloat();
      Serial.print("The new intercept is ");
      Serial.println(bestFitCurveB,4);
    }
    else
    {
      dataString += inChar;
    }
  }
}
else if(inChar == 'S') // giving a string command
```

```
    {
      freqEnable = 0;
      tuneEnable = 0;
      digitalWrite(motora1, LOW);
      digitalWrite(motora2, LOW);
      digitalWrite(motorctrl, LOW);
      Serial.print("A = ");
      Serial.print(bestFitCurveA,4);
      Serial.print("  B = ");
      Serial.println(bestFitCurveB,4);
      delay(2000);
      exit(0);
    }
  }
}

void changePitch() // takes a string and the frequency you want the string to be, then
moves every string to the position it should be
{

  int potVal = analogRead(potPin);
  int goalVal = bestFitCurveA * goalFreq * goalFreq + bestFitCurveB;
  if(goalVal == 0 || goalVal == potVal) // we should stop the motor
  {
    //Serial.println("Stop");
    digitalWrite(motora1, LOW);
    digitalWrite(motora2, LOW);
    digitalWrite(motorctrl, LOW);
    if(newGoal)
    {
      Serial.print("Stop Time: ");
      Serial.println(millis());
      newGoal = 0;
    }
  }
  else if(goalVal > potVal) // we need to tune up
  {
    //Serial.println("Tune up");
    digitalWrite(motora1, HIGH);
    digitalWrite(motora2, LOW);
    digitalWrite(motorctrl, HIGH);
  }
  else if(goalVal < potVal) // we need to tune down
  {
    //Serial.println("Tune down");
    digitalWrite(motora1, LOW);
    digitalWrite(motora2, HIGH);
    digitalWrite(motorctrl, HIGH);
  }
}

void getFrequency() // has to look at the string and try to measure its frequency,
compare it to the desired, and change the equasions
{
  switch(freqState)
```

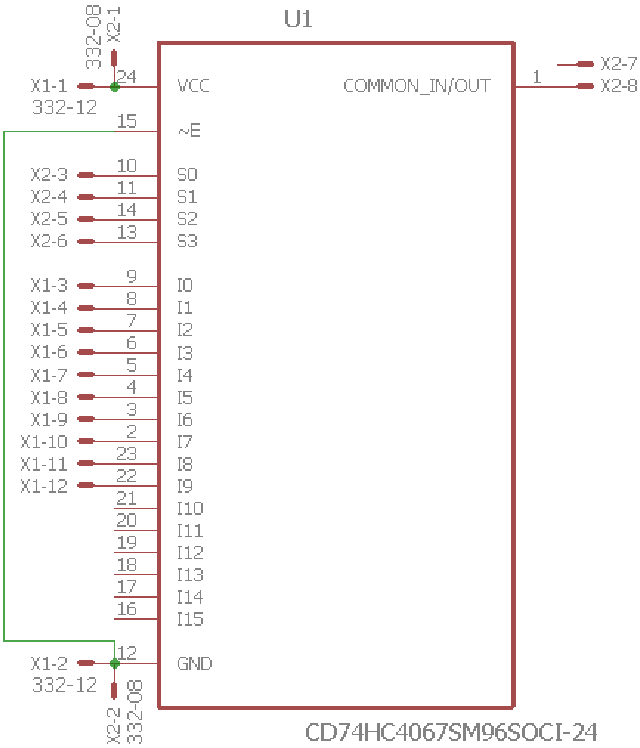
```
  {
    case 0:
      if(analogRead(pickPin) >= threshold)
      {
        waveCount = 0; // this is how many times count has incrimented in between
peaks
        lastCount = count; // this is the value of count when the loop ran last
        for(int i=0; i++; i<sampleSize)
        {
          sampleSet[i] = 0;
        }
        freqState = 1;
      }
    break;
    case 1:
      if(count != lastCount)
      {
        //Serial.println("We have counted up by ");
        //Serial.println(count - lastCount);
        waveCount += count - lastCount;
        lastCount = count;
        lastValue = value;
        value = analogRead(pickPin);
        //Serial.println("waveCount is equal to ");
        //Serial.println(waveCount);
      }
      if(lastValue < threshold && value >= threshold) // if we sense a rising edge
      {
        float checkFreq = 2 * (float)sampleRate / (float)(waveCount + countOffset);
        //Serial.println(checkFreq);
        waveCount = 0;
        if((checkFreq > (minFreq - allowedError)) && (checkFreq < (maxFreq +
allowedError))) // make sure the frequency we measured is possible
        {
          //Serial.println("use it");
          for(int i=0; i<sampleSize-1; i++)
          {
            sampleSet[i] = sampleSet[i+1];
          }
          sampleSet[sampleSize - 1] = checkFreq;
          int goodData = 1;
          for(int i=0; i<sampleSize-1; i++)
          {
            for(int j=i+1; j<sampleSize; j++)
            {
              if((sampleSet[i] > sampleSet[j] + allowedError) || (sampleSet[i] <
sampleSet[j] - allowedError))
              {
                goodData = 0;
              }
            }
          }
          if(goodData)
          {
            float frequency = 0;
```

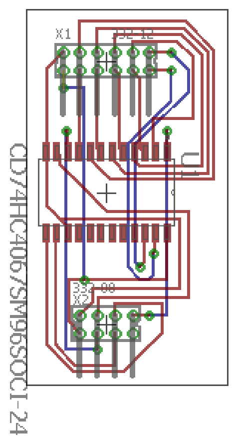
```
            for(int i=0; i<sampleSize; i++)
            {
              frequency += (sampleSet[i] / sampleSize);
            }
            if((frequency > (lastFreq + allowedError)) || (frequency < (lastFreq -
allowedError)))
            {
              Serial.println(frequency);
              lastFreq = frequency;
              adjustCurve(frequency, analogRead(potPin));
              freqState = 0;
            }
          }
        }
      }
    break;
  }
}

void adjustCurve(float frequency, float potVal)
{
  Serial.print("Old constants: ");
  Serial.print("A = ");
  Serial.print(bestFitCurveA,6);
  Serial.print("  B = ");
  Serial.println(bestFitCurveB,6);
  // Creates two arrays of  + 1 length and fills it with sampleNum evenly distributed
points along the best fit curve of the given string
  float f[sampleNum];
  float x[sampleNum + 1];
  float y[sampleNum + 1];
  for(int i=0; i<sampleNum; i++)
  {
    f[i] = lowestFreq + (highestFreq - lowestFreq) * i / (sampleNum - 1);
    x[i] = f[i] * f[i];
    y[i] = bestFitCurveA * x[i] + bestFitCurveB;
  }
  // This adds the most recent data point to the arrays
  x[sampleNum] = frequency * frequency;
  y[sampleNum] = potVal;
  // Now we create a new best fit curve from the evenly distributed samples and the
newest point
  float xbar = 0;
  float ybar = 0;
  float xybar = 0;
  float x2bar = 0;
  float n = sampleNum + 1.0;
  for(int i=0; i<sampleNum + 1; i++)
  {
    xbar += x[i] / n;
    ybar += y[i] / n;
    xybar += x[i] / n * y[i];
    x2bar += x[i] / n * x[i];
  }
  // Then we update the Values
```

```
  bestFitCurveA = (xybar - xbar * ybar) / (x2bar - xbar * xbar);
  bestFitCurveB = ybar - bestFitCurveA * xbar;
  Serial.print("New constants: ");
  Serial.print("A = ");
  Serial.print(bestFitCurveA,6);
  Serial.print("  B = ");
  Serial.println(bestFitCurveB,6);
}
```

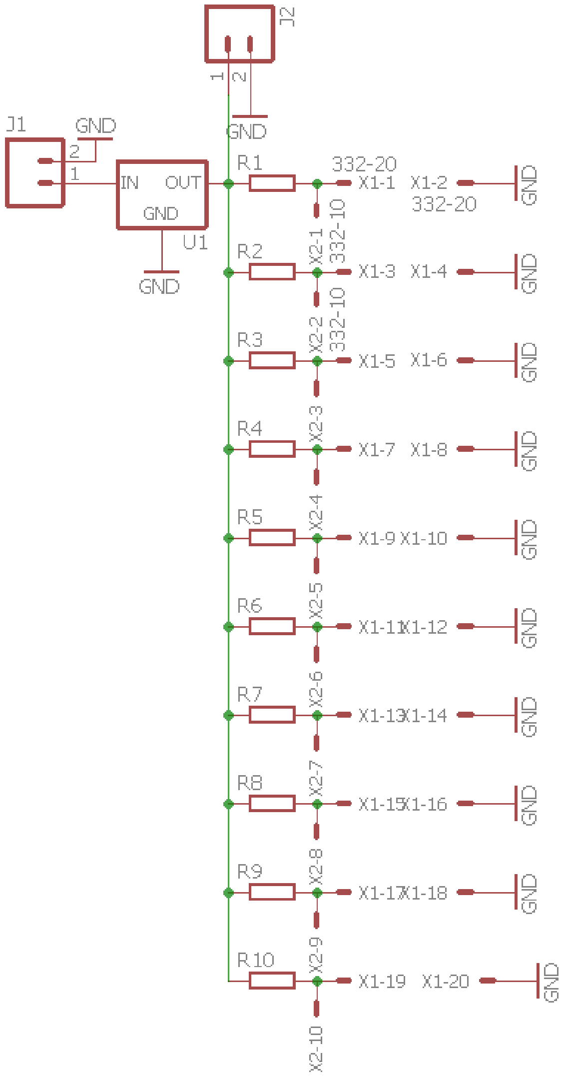
# Appendix B: Circuit Board Schematics

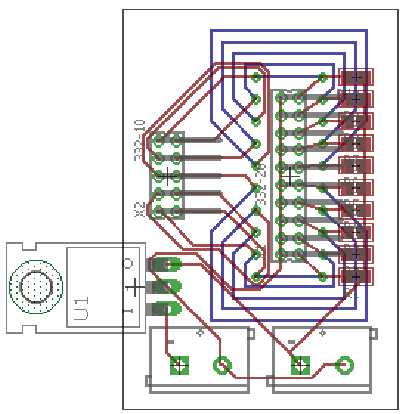
## Potentiometer Board



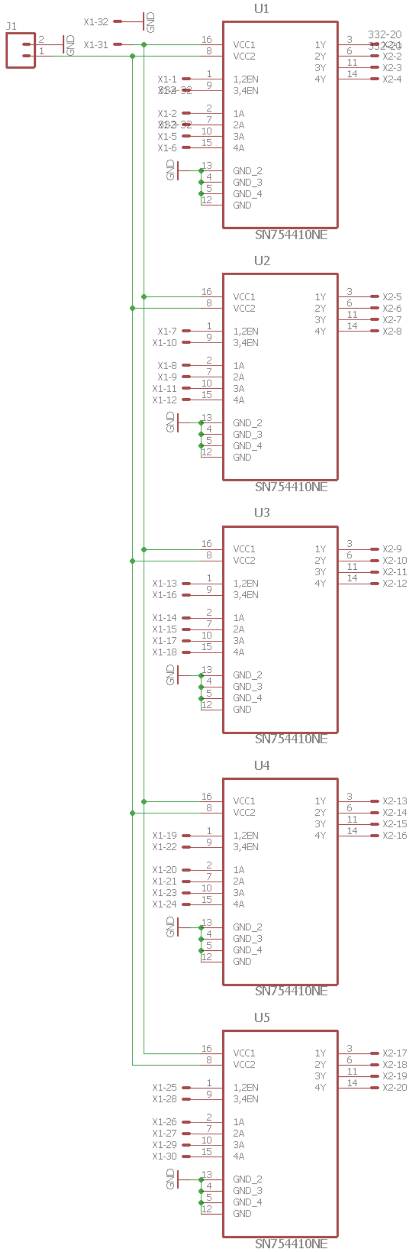



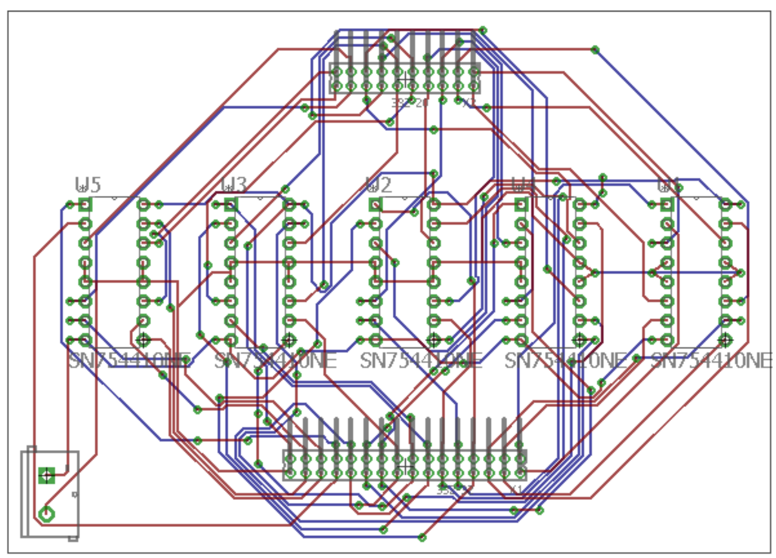
## Pickup Board



# Motor Board


J1
U1
SN754410NE
U2
SN754410NE
U3
SN754410NE
U4
SN754410NE
U5
SN754410NE


U5
U3
U2
SN754410NE
SN754410NE
SN754410NE
SN754410NE
SN754410NE

## Appendix C: Parts List

| Part | Quantity | Link to Purchase |
|---|---|---|
| 80/20 Framing (72") | 2 | https://www.amazon.com/dp/B001F0K4KA |
| 80/20 Framing L Mounting Bracket | 10 | http://www.mcmaster.com/#47065t236/=14gidh2 |
| Acrilic Sheet | 1 | https://www.amazon.com/dp/B006U1JN0Q/ref=biss_dp_t_asn |
| Brushed Motor | 10 | https://www.pololu.com/product/3065 |
| Encoder (2) | 5 | https://www.pololu.com/product/3081 |
| Motor Mount (2) | 5 | https://www.pololu.com/product/1599 |
| Spring | 10 | http://www.centuryspring.com/compression-spring-71421.html |
| Potentiometer | 10 | http://www.mouser.com/ProductDetail/ALPS/RS08U111Z001/?qs=sGAEpiMZZMtC25l1F4XBUwVi5%252bD8WO2jauozwkhrepU%3d |
| Tuning Machines (6) | 2 | https://www.amazon.com/dp/B00EB11OHC |
| Tuning Machine - Motor Shaft Adapter | 10 | https://www.amazon.com/dp/B00OK6DQ60 |
| Shaft | 3 | https://www.amazon.com/dp/B0045DUX5A |
| Shaft Mount | 6 | https://www.adafruit.com/product/1182 |
| Ball Bearings (10) | 3 | https://www.amazon.com/dp/B002BBICBK |
| Arduino mega | 1 | https://store-usa.arduino.cc/products/arduino-mega-2560-rev3?utm_source=redirects&utm_medium=store.arduino.cc&utm_campaign=303_Redirects |
| Multiplexer | 1 | https://www.sparkfun.com/products/9056 |
| H-Bridge Chip | 5 | http://www.mouser.com/ProductDetail/Texas-Instruments/SN754410NE/?qs=sGAEpiMZZMtYFXwiBRPs07TlpCamzEu5 |
| Size 0 Machine Screw 1" | 40 | https://www.mcmaster.com/ |
| Size 0 Machine Screw 1/2" | 10 | https://www.mcmaster.com/ |
| Size 0 Nut | 50 | https://www.mcmaster.com/ |
| Size 0 Washer | 50 | https://www.mcmaster.com/ |
| Size 0 Lock Washer | 50 | https://www.mcmaster.com/ |
| Size 8 Machine Screw 1" | 6 | https://www.mcmaster.com/ |
| Size 8 Nut | 6 | https://www.mcmaster.com/ |
| Size 8 Washer | 6 | https://www.mcmaster.com/ |
| Size 8 Lock Washer | 6 | https://www.mcmaster.com/ |
| Size 8 Rubber Washer | 12 | https://www.mcmaster.com/ |

| | | |
|---|---|---|
| M2 Machine Screw 3/4" | 40 | https://www.mcmaster.com/ |
| M2 Nut | 40 | https://www.mcmaster.com/ |
| M2 Washer | 40 | https://www.mcmaster.com/ |
| M2 Lock Washer | 40 | https://www.mcmaster.com/ |
| M2 Rubber Washer | 80 | https://www.mcmaster.com/ |
| M3 Machine Screw 3/4" | 20 | https://www.mcmaster.com/ |
| M3 Machine Screw 1.5" | 30 | https://www.mcmaster.com/ |
| M3 Nut | 50 | https://www.mcmaster.com/ |
| M3 Washer | 50 | https://www.mcmaster.com/ |
| M3 Lock Washer | 50 | https://www.mcmaster.com/ |
| M3 Rubber Washer | 100 | https://www.mcmaster.com/ |
| laser diode (10) | 1 | https://www.amazon.com/dp/B01EL7QZCE |
| photoresistor (20) | 1 | https://www.amazon.com/dp/B00AQVYWA2 |