uTune: An Automated Guitar Tuning Solution

EE41430 Senior Design: Project Proposal

University of Notre Dame

Fall 2018

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1. Introduction

Stringed instruments have long been utilized to create music by manipulating the properties of the strings to control pitch. These instruments range from lyres and guitars to violins and pianos, and they incorporate a number of different elements in order to control pitch and thus create music. Three key factors that affect pitch are string length, linear mass density, and tension. While linear mass density remains constant in a particular guitar string and the length is used to change pitch while playing, the tension in the string changes the pitch of the open string and thus changes the reference point for all fretted notes.

Many different guitar tuning systems have been developed throughout the course of history. Standard tuning is known as EADGBE from low string to high string, and this is the common tuning used in many mainstream guitar songs of all genres. However, this is not the best tuning system for other playing styles, like fingerstyle, and many particular songs use unique tunings. General and song-specific tunings such as DADGBE (known as “drop D”), DADGAD for fingerstyle, D#G#C#F#A#D# or DGCFAD for a half or full step down, CGDGBD for Constellations by Jack Johnson, C#A#D#G#A#D# for Barcelona by Ed Sheeran, EABGBD# for Yellow by Coldplay, DADF#AD for The Cave by Mumford and Sons, EBEF#BE for In Your Atmosphere by John Mayer, and many others are prominent in the music world and required in a guitarist’s repertoire today.

2. Problem Description

In order to incorporate these various tunings into playing and performance, a guitarist must allocate significant effort to the tuning process. To tune the guitar, the musician must rely on the guitar’s built-in tuning pegs as the mechanism by which to adjust the pitch of each string. Six pegs, one for each string, are situated on the headstock of a guitar, and each can be rotated in one of two directions to either increase or decrease the tension in the guitar string, subsequently increasing or decreasing the fundamental vibrational frequency of that string.

Thus, much time must be spent by the guitarist turning pegs and checking frequencies until all strings have reached the proper tuning—a tedious process that requires a high degree of precision. There are two additional concerns with this fact: a tuned guitar never stays in tune across changes in time and ambient temperature, and the guitar strings may frequently need to be tuned in an alternate way. The process of constantly checking guitar tuning and changing to alternate tunings, especially when audience members are eager for a show to continue, creates an unnaturally and unnecessarily long period of anticipation before songs, lowering performance quality and draining the performer. On the other hand, a musician may have backup guitars in alternate tunings available for immediate switching, which can be very costly and still does not correct for guitars coming out of tune. Ultimately, much time, effort, and patience of the performer and audience alike could be saved by automating this process, creating faster-paced, more exciting shows and giving less-experienced guitar players (who also might not have as precise of a pitch-matching ability) the ability to easily experiment in other tunings.

3. Proposed Solution

To solve the problem of frequent tuning faced by a performer, this project proposes to automate the tuning process through the use of frequency identification and motor control of the pegs on a guitar in a feedback control loop. The process is as follows: when the performer needs to tune the guitar, they will attach the tuning device onto the head of the guitar and select the desired tuning via the LCD control buttons or a wireless phone app which will communicate with an onboard LCD screen user interface to display current settings and relevant real-time frequency information. Next, the user will strum their guitar, and the microphones embedded in the tuner will record the overall sound containing the six string pitches (the performance of the microphones will be assessed based on signal-to-noise ratio and frequency resolution to determine an appropriate number of microphones and spacing, as well as whether balanced audio signal transmission should be implemented). An onboard microcontroller (such as an ESP-based device) will analyze time-based data to compute the current frequency of each string using the Fast Fourier Transform (FFT), subsequently determining if each string needs to be tuned up or down. The results will be communicated with the mobile app in real time. The tuner will then begin controlling all six motors to adjust the frequency in the proper direction by engaging in a feedback loop — continuously recording sound, determining the current frequency, and controlling the motors based on the position of the actual frequencies relative to the desired frequencies. It will cease when each string has been correctly tuned or is no longer producing a loud enough sound to determine its frequency. In the latter scenario, the tuner will indicate to the user that another strum is required. Through the use of frequency analysis, a feedback-loop control system, and high-torque motors, this project will successfully solve the problems of tuning faced by guitarists - this system will save time and provide precise tuning with minimal effort required by the guitarist.

Two different physical implementation options are being proposed, depending on the torque requirement to tune the guitar and thus the size and weight of the required motors. In the case of a low torque requirement where small and lightweight motors can be used such that the guitar neck will not drop towards the floor when the device is attached by the guitarist, the device will strap onto the guitar and not be intended to be removed frequently. The device would be light enough to remain on the guitar while the musician is using the instrument. In the case where the torque requirement is high and heavy motors are required, the device will be hand-held. This device would only contain a single motor and would tune each string one-by-one. The first step we need to take is to test the torque requirement on the guitar that we plan on using for our project so that we can finalize the torque requirement and determine the motors we are going to use. Both servo and stepper motor options will be considered depending on the result of this testing. We will have a guitar to test next week and will move forward with this decision from there before the high-level design is finalized.

4. Demonstrated Features

1. LCD display and control buttons
    a. Definition of A4 note
        i. Range from 410 Hz - 470 Hz
    b. Selection of tuning system (defines the frequency of all musical notes relative to A4)
        i. Just intonation: notes in octave determined by selected ratios
        ii. Equal temperament: note frequency = A4 * $2^{n/12}$ where n is the number of note positions above A4 (can be negative)

Interval	Ratio to Fundamental Just Scale	Ratio to Fundamental Equal Temperament
Unison	1.0000	1.0000
Minor Second	25/24 = 1.0417	1.05946
Major Second	9/8 = 1.1250	1.12246
Minor Third	6/5 = 1.2000	1.18921
Major Third	5/4 = 1.2500	1.25992
Fourth	4/3 = 1.3333	1.33483
Diminished Fifth	45/32 = 1.4063	1.41421
Fifth	3/2 = 1.5000	1.49831
Minor Sixth	8/5 = 1.6000	1.58740
Major Sixth	5/3 = 1.6667	1.68179
Minor Seventh	9/5 = 1.8000	1.78180
Major Seventh	15/8 = 1.8750	1.88775
Octave	2.0000	2.0000

Fig. 1 - Breakdown of Tuning Systems

    c. Selection of guitar string tuning
        i. Pre-set common tunings
        ii. Pre-set tunings for popular songs
        iii. Customizable tunings
2. Wireless iPhone app to control tuner
    a. Same features as LCD display and control buttons
3. Automatic tuning of strings after a strum
    a. System accurately detects and monitors the frequencies of each string as they are tuned (i.e. tunes to within certain error range)
    b. Drive motors using H-bridge in correct direction for convergence on requested frequency
    c. Red-and-green LED status display indicates if a string is sharp or flat, and eventually reaches green (tuned) for all six strings
    d. System will reach steady-state tuning faster than a normal guitarist could accomplish the same tuning.

5. Available Technologies

Motors:

- https://www.sparkfun.com/products/12472
    - 6 RPM, high torque
    - $24.95/each * 6 = $149.70 + tax
- https://www.sparkfun.com/products/12285
    - 90 RPM, low torque (might not be enough)
    - $12.95/each * 6 = $77.70 + tax
- https://www.adafruit.com/product/1142
    - High torque, high speed, servo
    - $19.95 each * 6 = $119.70 + tax

Bluetooth devices:

- https://www.digikey.com/product-detail/en/espressif-systems/ESP32-PICO-D4/1904-1029-1-ND/9381738
    - $4.39/each, ships immediately
- https://www.digikey.com/product-detail/en/inventek-systems/ISM20736S-TR/1475-1053-1-ND/6577341
    - $4.57/each, ships immediately
- https://www.digikey.com/product-detail/en/samsung-semiconductor-inc/ARTIK-020-AV2R/1683-1004-ND/6231211
    - $5.25/each, ships immediately

WiFi devices:

- https://www.digikey.com/product-detail/en/microchip-technology/ATWINC1500-MR210PB1952/ATWINC1500-MR210PB1952-ND/6834196
    - $8.08/each, ships immediately (12 week lead time)
- https://www.digikey.com/product-detail/en/seeed-technology-co-ltd/102990965/1597-1548-ND/7650462
    - $3.01/each, ships immediately (2 week lead time)
- https://www.mouser.com/ProductDetail/Espressif-Systems/ESP8266EX?qs=sGAEpiMZZMve4%2fbfQkoj%252bGif8WCprhV4ngk1mHM9Xjs%3d
    - $1.60/each, ships immediately (2 week lead time)

Microphones:

- https://media.digikey.com/pdf/Data%20Sheets/Knowles%20Acoustics%20PDFs/SPU0410LR5H-QB_RevH_3-27-13.pdf
    - $0.73/each, ships immediately
- https://www.cui.com/product/resource/cmc-6027-32t.pdf
    - $1.36/each, ships immediately

6. Engineering Content

In order to design, build, and test this guitar tuner, a variety of complicated engineering tasks are required. First, an on-board LCD interface must be used to allow for the tuner control. There must be a visual display to allow for the navigation between different features, push buttons to select different settings such as tuning system and string tuning, and a switch to select LCD or app mode. LEDs will also be used to communicate with the user. Each motor will have a series of three LEDs that tell the user if the string that the motor is attached to is either in tune (shown as a green LED in the middle), sharp (shown as a red LED above the green), or flat (shown as a red LED below the green).

Next, a wireless chip and/or a microcontroller with wireless capabilities must be included on the PCB to allow for Bluetooth or WiFi connectivity, and an iPhone app must be designed and created in xCode to send and receive data with the wireless chip on the device. This will require app development knowledge and Swift programming, programming a wireless protocol chip, and setting up an interface between the two.

Significant engineering will go into the control system for the frequency detection and analysis. This will require setting up microphones or piezoelectric sensors and amplifying the signals provided by those sensors via an operational amplifier or similar. In addition, we will develop an algorithm to compute the FFT of the signal in order to get the frequency spectrum of the recording, isolate the spikes in the spectrum, determine which spikes correspond to string pitches, and compare the frequency of each spike with the desired frequency to determine if each string is currently sharp or flat. We will need to develop a physical feedback control system on the PCB to work in conjunction with the FFT algorithm. We will use this system to drive the motors such that the actual frequency of each string converges to each desired frequency (with an acceptable error tolerance below the pitch-discriminating capabilities of the human ear, such as +/- 3 cents).

A canonical closed-loop feedback system for steady-state error reduction and convergence to a reference frequency is shown below in Figure 2.

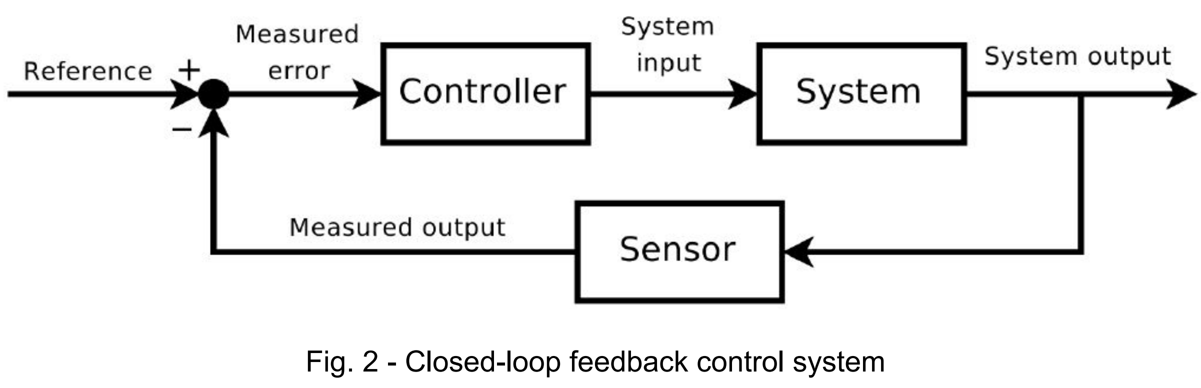

Fig. 2 - Closed-loop feedback control system

In the system shown in Figure 2, the system block represents the loaded motor/peg/string mechanical system; this system will have its own intrinsic step response to any system input, and thus a controller will be designed to achieve a desired response for a given reference frequency and measured output frequency from the microphone (sensor). The closed-loop system with a designed controller gain will ensure stability and a steady-state error that approaches zero over time, allowing the real guitar to converge to the user's desired tuning. The system will cease turning the pegs once the tuning achieved is below the threshold of hearing.

The most challenging engineering portion will be the motor operation, due to the torque and other mechanical requirements in order to accomplish turning a guitar peg (or six simultaneously). Since reports found online yield major discrepancies in the amount of torque required to turn a guitar peg, we will need to utilize a torque wrench to precisely determine the torque required for the specific guitar we are using. This will narrow down motor options: if extremely high torque is required, a handheld device will be designed to tune a single peg at a time, while less required torque will allow for the design of a clip-on device that tunes all six pegs simultaneously. In order to power the motors, batteries will need to be selected which can provide enough voltage and current. This will require thicker PCB traces and a rechargeable lithium battery system potentially with a DC-DC converter if different voltages are required on the board. These motors will also tie into the control system and an H-bridge in order to drive the motor in the forward or reverse direction depending on if the current string pitch is sharp or flat. Finally, the motors must be selected and engineered in order to adjust the pitch to within a certain physically allowable error tolerance.

There is also a mechanical aspect to this project since we need the device to interact physically with the guitar tuning pegs. This turns into two engineering problems that we must solve. First, we need to design an enclosure for the device that is strong enough to withstand the torque from the motor(s) without breaking. In the case of multiple motors, this will require a rigid enclosure for all six motors that can sturdily attach to the head of the guitar. In the case of a single motor, this requires an ergonomic design that is easily held in one's hand and allows the user to easily oppose the torque of the motor with his/her hand. The second physical problem we face is creating a motor attachment that can robustly hold onto the tuning pegs of the guitar. It is important for this to be a secure and snug fit so that it is impossible for the motor to turn, even the slightest bit, without also turning the peg.

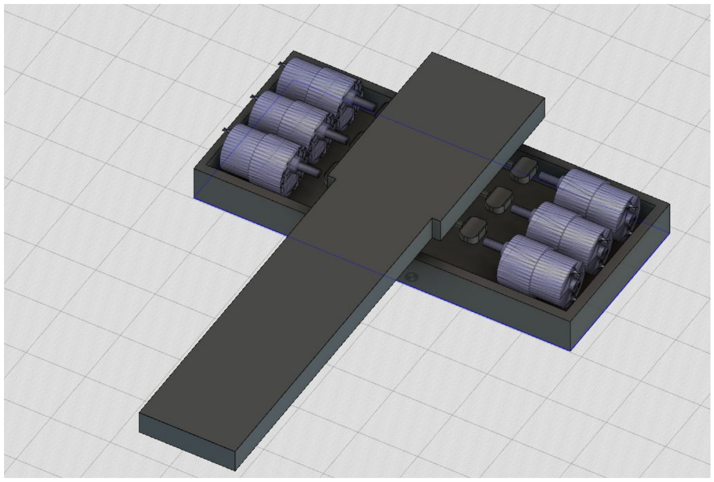

Fig. 3 - Fusion360 Mockup of a 6-motor Tuner Design with ROB-12472 Motors

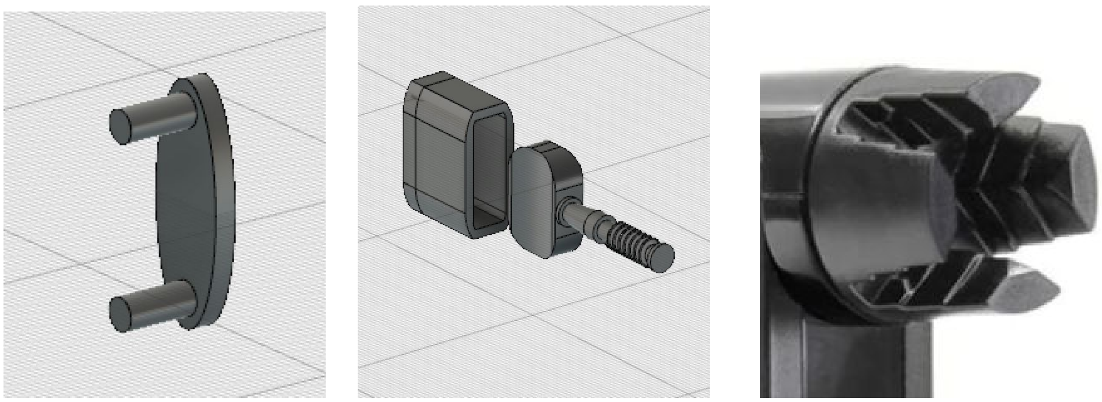

Fig. 4, 5, 6 - Fusion360 Mockups and Screenshot (from Roadie Tuner) of Possible Motor-to-Peg Connectors

7. Conclusion

Tuning is an essential aspect of a musical performance, but it should not be a burden for a performer while they are in the middle of making music. A performer, especially an inexperienced one, can spend a significant amount of time focused on tuning. Additionally, the human ear is not as high resolution as modern microphones due to critical bandwidth perception limitations. Therefore, an automated guitar tuner is a desirable and useful item.

Through the use of the subsystems and functions specified throughout this proposal, this automatic guitar tuner will utilize microphones to analyze the frequencies of each string, and based upon the user's selections, will control the motors in order to finely, accurately, and quickly tune the guitar. This will resolve the key problems we set out to address: going out of tune gradually over time and due to temperature changes, and requiring quick changes to different tunings during performances. Ultimately, this product will enhance the experience of performers and audience members, will make playing guitar a more accessible pastime for less-experienced musicians, and will present a high-value and much-needed system to a large audience.