Smart Ukulele: An Engineering Innovation

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Abstract

Our tool is a simple ukulele, the instrument of choice among those who want to pursue a hobby in music, yet don't have the money to shell out on a full guitar or piano. With such versatility, we saw the ukulele as an opportunity to shift the statistic and increase people's opportunities to play music. The plan was to place LED's in the fretboard of the ukulele that would indicate where the user should place their fingers in order to strum the proper chord. Then using the Arduino IDE and some piezo-sensors, the ukulele would be able to recognize chords and check to see if they were played correctly.

Toying with the intersections of Arduino, SolidWorks, and our own creativity, we constructed a ukulele using laser-cut wood and 3D-printed plastic parts. We soldered LEDs to the fretboard, attached commercial ukulele strings, and connected it to a circuit board made of breadboards, jumper cables, and integrated circuits. Our final product is something that not only innovates along the intersection of music and engineering but can also be used in the real world to help real people garnering positive feedback from users. Although this is still just an initial prototype, there are many enhancements that could come from this idea, including additional methods to input chords, preset songs, and even a more acoustically accurate instrument that could come in various sizes.

Introduction

The United States can applaud itself on having a literacy rate of over 95%; however, when musical literacy comes into question, the statistic is much scarier. Music is a dead language, yet it is perhaps one of the most commonly spoken languages across the globe. Compare the national literacy rate to the national musical illiteracy rate, and one would find that they are the same. Nearly 95% of Americans are unable to read music, a statistic that we would like to change. We propose the Smart Ukulele as a solution to this discrepancy in interest versus ability.

Methodology

The Smart Ukulele is a ukulele with an array of 16 LEDs in the fretboard, one underneath each string per the top four frets. The user inputs the succession of chords they desire to play. The lights in the fretboard cycle through the succession of chords by activating the lights indicating the position the user's fingers must be placed in order to play the chord. The user can easily follow along and play a song. The option to receive user feedback is available through the use of a piezo sensor, with which the instrument will determine whether the correct chords was played. This gives the user further opportunity to hone their skills.

With manufacturing tools and materials being constrained by what is available at Northeastern University, we chose to construct a prototype Smart Ukulele based on the dimensions of a standard soprano ukulele, but with hollow or otherwise augmented pieces capable of accommodating its additional components. This way, the skills learned on the Smart Ukulele can be easily transferred to any standard ukulele.

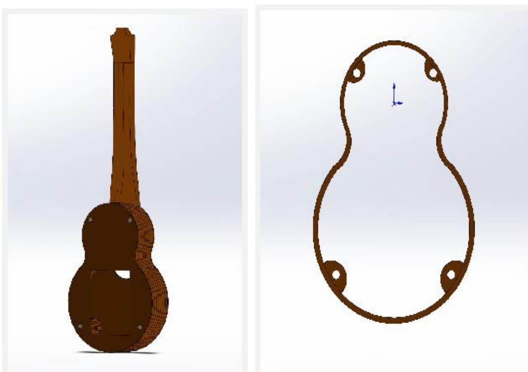

Figure 1: Solidworks and Autocad drawings

We have taken survey data and will use it to inform future iterations of our product to determine its marketability. We can also use this data to apply the concepts to different musical instruments.

Design Approach

Our execution of the Smart Ukulele can be divided into four blocks: The physical ukulele, its LED control system, its feedback report system and its user interface.

We endeavored to make the physical ukulele as close to a normal ukulele as possible despite its modifications, so that the skills learned from the Smart Ukulele can be easily transferable to a traditional ukulele.

Its LED control system was designed to take up as small a space as possible, due to the limited space within the dimensions of a traditional ukulele. The control system also needed to drive 16 LEDs, which exceeds the number of digital output pins on an Arduino, so we designed a decoder as an intermediary between the LED array and the Arduino.

The feedback report system is an added feature inspired by the concept in robotics of a ‘Closed-Loop System’. In robotics, a ‘Closed-Loop System’ is a type of control system which uses feedback signals to both control and adjust itself. This enables a robot to adapt to uncontrolled conditions, and effectively ‘learn’ from its mistakes. We decided to employ this concept in the Smart Ukulele to provide feedback from a piezo frequency sensor to the user and enable them to adjust their playing to match the expected frequencies of each chord.

Figure 2:

Finally, the user interface system was designed to give the user control over their learning experience. There are two modes in which the user can use the product, and a prompt for the user to enter whatever chords they want to cycle through. This gives them an opportunity to practice songs they may have written themselves, as well as popular songs with chords available on the internet. The chords for most songs that exist can be found somewhere, so this makes the product incredibly versatile.

The first mode, Learning Mode, displays the first chord in the list input by the user on the fretboard of the ukulele, and the chords can be cycled through by pressing a simple button. This allows the user to get a feel for how they should place their fingers to play the chords they need for the song, while keeping the song in their mind by having the chords all run in the same order they were input. The second mode, Practice Mode, displays the chords on the fretboard one at a time, and instead of requiring the user to manually cycle through them, it cycles through automatically on a timer. This allows the user to practice shifting from one chord to the next in the order that they will be played in the song, after they've become comfortable with the hand positions themselves.

Methods

Physical Ukulele

The physical ukulele is comprised of 6 pieces: the Neck, Body, Bridge, Fretboard, Nut and Tuning Pegs. The neck was designed in SolidWorks, and is the most free-form shape of any other component on the ukulele. This made the 3D modeling process of this particular piece difficult, as it required a lofted feature that was prone to software calculation error. It was also difficult to get the dimensions correct, as a function of the lofted feature is to fill in the space between profile sketches with an approximation of the shape. The piece was hollowed out with the shell feature up to the head to accommodate the internal LED board and lead wires. The base of the neck has three holes, two for mounting it to the body and one to allow the wires to pass through.

The primary challenge of designing this piece was to make the joint between the neck and the head strong enough to withstand the tension from the strings, and this was a challenge we failed in our initial prototype. We have amended the design to hopefully enable it to withstand the string tension by adding material in the joint which should reinforce it. We also plan to reprint the piece standing upright at a 45 degree angle so that the fault lines created in the 3D printing process are angled in such a way that they are not perpendicular to the force created by the strings.

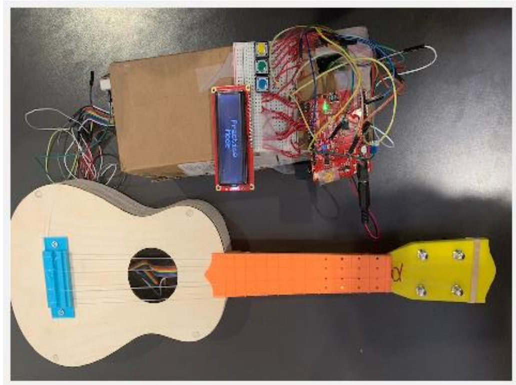

Figure 3:

The body was also designed in SolidWorks, and a drawing file was made and exported into AutoCad to be manufactured through laser cutting and CNC routing [Figure 1]. Two dimensional manufacturing, despite its advantages, is limited by only being capable of producing two dimensional objects. Because the walls of the ukulele are curved, we decided to design the sides by cutting layers of the profile of the ukulele, placing them one on top of the other, clamping and gluing them together. To ensure each layer was lined up with one another, we designed each layer of the ukulele with register holes for dowels to be inserted during the adhesion process. The edge pieces were cut from ¼" plywood to reduce the number of layers necessary to achieve the height of a ukulele. Because they were cut from thicker plywood, they needed to be cut with the CNC router. The top and bottom needed to be thinner to achieve a proper resonance, so they could be laser cut. We designed the back of the ukulele with a removable lid, so that the Arduino and other internal components could be accessed.

One disadvantage of this design was the inability to cut the neck mounting holes and wire access hole through digital fabrication methods, but we were able to line the neck up with the side of the body and drill satisfactorily matching holes with a cordless drill.

The register holes protrude into the cavity of the ukulele body, which is not ideal for resonance, so ideally the next iteration of the Smart Ukulele would omit them by a more time consumptive and manually difficult process of bending and gluing very thin sheets of plywood in layers around the profile of the ukulele, which is the traditional method of building items with curved plywood pieces. However, we consider the body of the Smart Ukulele, given our manufacturing constraints, one of the successes of the project.

The bridge was modeled after a traditional ukulele bridge. It needed no modification to adapt to the Smart Ukulele's functionality. The bridge has to be a certain distance away from the nut which was calculated using an instructional website on building string instruments, and its placement on the body was chosen accordingly.

The fretboard was also modeled after a traditional ukulele fretboard, with the exception of the holes for the lights to be visible, and the nut was incorporated into the fretboard design.

The tuning pegs were designed in SolidWorks using extrusions and the spline sketch tool to create the unique shape of the pegs. The mirror tool was used to ensure a symmetrical shape of the peg. The dome feature and fillets were used to give them a smooth circular top.

We had the opportunity to print out these personally designed pegs; however, given the affordability of more reliable pegs, we decided to purchase them online. Given how the tension created by the strings was one of the most difficult caveats to overcome, using higher-grade tuning pegs saved us the possibility of having the ukulele snap under pressure.

Light System

The array of LEDs was made with a sheet metal base that was cut to fit inside the ukulele neck. We used layers of copper tape and insulating tape to serve as an improvised PCB to mount the LEDs. A printout of the mechanical drawing of the fretboard was used to line up the LEDs, ensuring they would be directly under the fretboard when the system was assembled. The LEDs were soldered directly to one end of the strips of copper tape and lead wires were soldered to the other end, and were threaded through the hole in the neck and into the body of the ukulele. While this enabled a low-cost low-profile way to embed the LEDs into the fretboard of the Smart Ukulele, it was not a permanent solution and was flawed. As the Smart Ukulele was used, the wires pulled on the strips of copper tape causing short circuits between the LEDs.

The lights were controlled by the decoder, which would process a four digit binary number and turn on the proper LEDs. That meant that the code would have to relate a binary number to each chord, and set the chord inputs from the user to an array of the representative binary numbers.

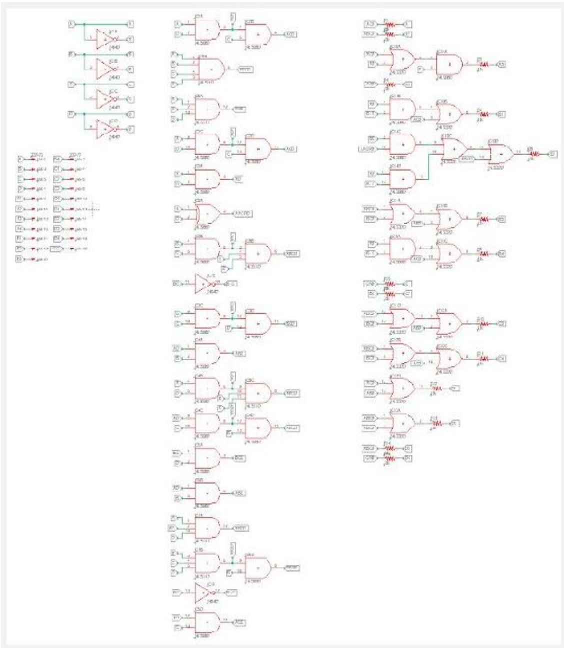

Figure 4:

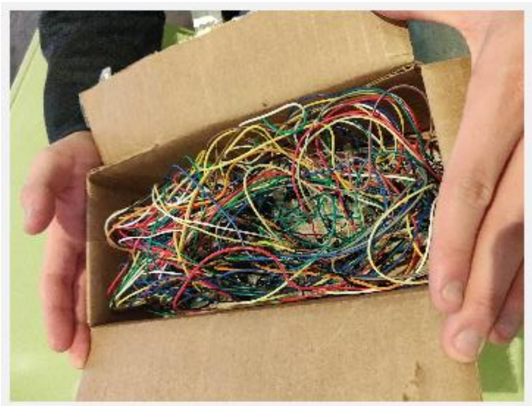

Figure 5: Breadboard Circuit

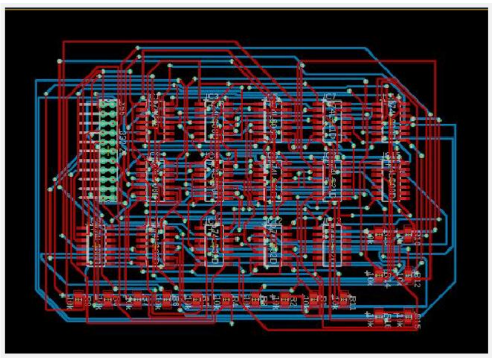

Figure 6: PCD Design

We have 14 chords, so we used binary numbers 0000 to 1101. To do this, we decided to use a series of digital logic gates to code a signal to each LED based on the four digits which would cause them to light up. The way that this was done was in a series of steps. First, each chord that would be used was assigned a four-digit binary number, and the LEDs required for that chord were determined. Then for each LED, a Boolean expression was created which would determine when that LED would light up and when it would not, based on the numbers for the chords in which it was used.

These Boolean expressions could be then simplified by taking each digit of the binary numbers as a separate Boolean variables, so the variables A, B, C, and D represented the first, second, third, and fourth digits of the binary number. Then, after some Boolean simplification a schematic was built using Eagle. This schematic was made into a design for a PCB, but due to time, cost, and skill set constraints, it was instead breadboarded as shown in Figure 5.

The PCB is shown in Figure 6. Thus, the result was a large circuit that could accept four digital signals (the four-digit binary number) and output 16 digital signals, one for each light.

With only three buttons, we had to ensure that the user still has all of the functionality outlined in our goals for this project. The LCD screen showed the user a list of chords that could be cycled through and selected with our three buttons. Then by pressing 'Done' with the center button, the Smart Ukulele would shift to Learning Mode. The user could strum through the chord until they felt ready to move on, then press the right button to move onto the next chord. Upon reaching the end of the list of chords previously selected by the user, the chords would be repeated in the same order as before. If at any point the user wished to go back a chord, they could simply press the left button. By pressing the center button while in this mode, the Smart Ukulele would shift into Practice Mode, where the chords cycle through based on a timer, instead of the press of a button. The list could be restarted from the beginning by pressing the left button, and the Smart Ukulele could cycle back to the chord input mode by pressing the center button once again.

Feedback System

The feedback system provided us with an opportunity to take our prototype from the developmental stage to a fully-fledged product. An important feature that we were unable to accomplish on this first prototype was the instant feedback of whether or not the user actually strummed the chord correctly. By placing piezo sensors that detect frequency in the body of the ukulele, we would be able to store values of each chord in an array on the Arduino IDE and check the user's chords against it. For example, we would use the piezo sensors to calculate the frequency recorded when a C major chord is played. That value would be saved to an array, along with the 13 other chords. Then when the user strums a chord, the code would call a function designed to check the frequency of the strum against the array of preset chord frequencies and return which chord is being played. An if statement would then check to see if that returned chord matches the chord that the user should have been playing.

The integration of the piezo sensor came with a variety of challenges, one of which involved our lack of breadboard space. We also needed time to test each chord several times and find a range of values that would qualify as "successful." However, the inclusion of such a feature would open the doorway to a plethora of opportunities for where we could take this ukulele. Instant feedback would allow us to measure direct data from the ukulele, something more quantifiable than survey results. We would have the ability to record data over time and present the user with charts that represent an improvement over time. Eventually, piezo sensors would give us the ability to create a more complete, and more useful, product.

User Interface

The user interface is operated through an Arduino RedBoard, using an LCD screen and three buttons in a line. The full code can be found in an appendix at the end of the report, but below is an overview of how it works. In Arduino code, the main program is always a loop. First, the code checks which mode to be in and proceeded accordingly. If it is in chord selection mode, it prints all of the selected chords on the top line of the LCD, and in the bottom line it displays the appropriate menu option. The menu is controlled with a switch. If the user presses the left or right button, the program simply shifts the switch variable so that it cycles through the options. If the center button is pressed on any of the chords, the program uses the value of the switch variable to determine the chord selected and add it to the list, so that it is then printed on the top line of the screen. If backspace is selected, the previous chord is removed from the list. A separate variable is used to keep track of the cursor for the chord selection, and assign the values to the appropriate index in the array of selected chords. Each chord has a number assigned to it to distinguish them. If done is selected, the program moves on to the next mode.

In the next mode, the LCD screen always displays the text, "Learning Mode". The program goes through the values in the selected chords array and uses that value to determine the combination of HIGH and LOW signals to send to the four output pins. These signals are the digital signals of the digits of the binary number coded to the chord that needs to be output. This is the signal the decoder needs to output the correct signals to the LEDs to display the chord.

Each time the user presses left or right, the program shifts forward or back in the chord list and outputs the four signals required to display the next chord. This repeats until the center button is pressed, at which point the code moves to the last mode. In the last mode, the LCD screen always displays the text, "Practice Mode". The program starts cycling through the chords in the list based on a timer variable, which is updated in conjunction with a delay. The index of the chord being displayed can be set back to 0, resetting the song, by pressing the left button. Pressing the center button at this point returns the program to the chord selection mode, so the entire process can be cycled through.

To collect data on the success of this product, we needed some way to test its effectiveness. This was difficult, as the effectiveness depended on how much the user appreciated and enjoyed the product, and how easy it was to use, which are difficult points of data to quantify. The simplest solution we could think of was to have people at the cornerstone expo fill out a survey, asking 5 questions and requesting a response in the form of a rating on a scale of 1 to 10.

Practicality

One of the main features of our product lies within its ease of use. With only three buttons and one LCD screen, the user still has a wide range of inputs, and the product doesn't lose any features. The simplicity is key to our design as we wanted to ensure that the user undergoes a fundamentally easier process to learn when compared to private lessons or music books.

Results and Discussion

To receive feedback from the public, we created a survey for the people at the engineering expo to fill out which serves to reflect their opinions on our product. From the survey, we were able to see that every person who filled out a form had some musical experience. This could suggest some voluntary response bias or undercoverage when it comes to the statistical significance of our results. Since the survey and approaching the table were completely voluntary, it makes sense why these participants volunteered, since they were most likely initially intrigued by the musical aspect of our project on display.

As our data shows, the Smart Ukulele came off as a success at the expo and gave us confidence that our product would help others in the instrument-learning process, a fundamental goal we had when beginning our endeavor. All responses show an increase in enjoyment and ease when using our product, and report scores higher than 5 in most cases, besides one asking about future learning commitment.

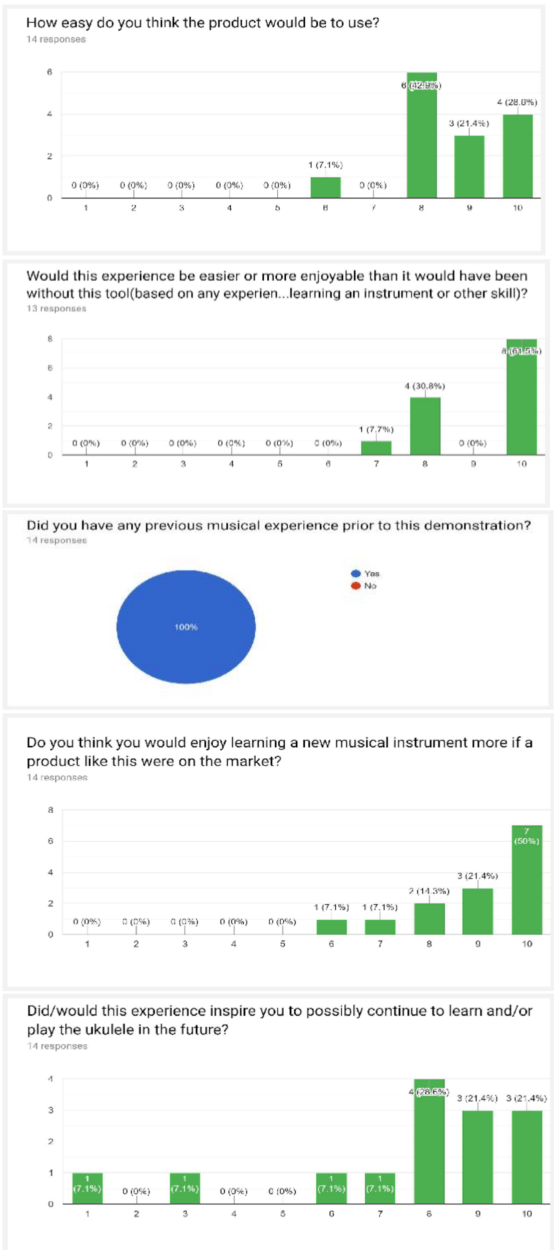

Figure 7: Feedback from the public

Conclusion

Our project was initiated with the idea that we would be able to improve the musical literacy rate across the country. With that expectation, we hope that the Smart Ukulele will accomplish what it was created to do, whether that’s in the form of a middle school girl who wants to so song covers on YouTube, or confused college freshman who’s unsure of whether he wants a minor in music and wants to test out an instrument first.

Our device doesn’t create sustainable energy or solve the rapidly increasing threat of climate change. However, the Smart Ukulele is a product meant to boost the abilities of others and we hope that it can bring the positive effects of music into the lives of its users. Based on the preliminary data, it appears that these goals could reasonably be achieved with this product.

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