Concept, Motivation, Purpose

The main purpose of our robot will be to play songs. We are building upon a previous year's completed project which is able to strum a ukulele autonomously. The initial concept for our project is to add the 'left hand,' which is able to play chords. This is a relatively simple goal, though it can be adapted to many scenarios. A robotic ukulele brings with it the unique aspects of a robotic performer. The precision that a robot brings with it opens up avenues in melody, harmony, and rhythm. Depending on the specific design, a robotic ukulele player may be able to play unusual chords or microtonal music, for example. In addition a robot is consistent in its timings and able to play to a precision that humans cannot, bringing new areas to rhythm. Also, the visual aspect of the robot could be a useful tool for education. It would allow for consistent and quick demonstration of chords without requiring an already trained person.

A ukulele will be played completely using robotics and can play more complex pieces and play more accurately than humans may be able to achieve. Furthermore, the team aims to not only develop this functionality, but ensure the automation is visually interesting and appealing to allow for an enhanced entertainment factor during playing.

Prior Art

Of course, with any project, it's important to consider what has been done in the past. To accomplish this, we looked into various systems that can be used to automate playing a stringed instrument. We did not limit ourselves to the ukulele, as excitation systems for guitar or bass could be easily adapted to the ukulele. The first main style of automation we found is by mounting solenoids over each fret of the ukulele. This was done by projects such as the

UkuRobot and Vladimir Denin's Guitar Robot (figure 1). Each solenoid is only capable of pressing down on one fret on one string. This design brings with it significant speed and precision. The solenoids do not have to move far, and as such are able to respond very quickly. However, these designs do not have very much visual complexity. While they do impress the eye with the sheer amount of machinery that is required to support, control, and power such a high number of actuators, the movement of each solenoid is often not clear. This makes it much more difficult to see what the robot is doing, reducing the visual intrigue.

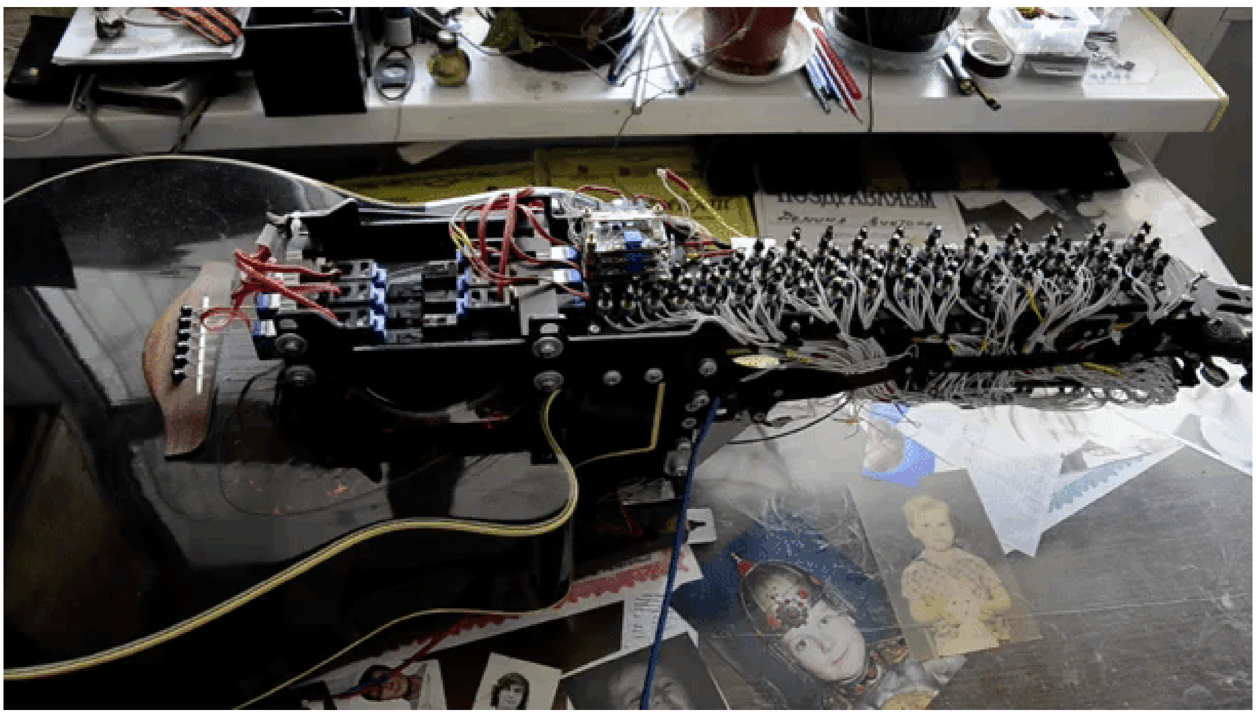

Figure 1: Vladimir Denin's guitar robot. Note the fretboard blanketed in solenoids

We also found some more unique designs for automated ukulele playing. One is the Automated Guitar, which has a complex strumming system that is capable of closely mimicking the movements of a human hand. On the chord side, the mechanism is highly mechanically complex, using only one input to change chords. This input flows through a complicated gearbox to produce different chords. While this is a unique design, it is not very fast or flexible. The Lego robot strumming a ukulele uses spinning wheels above the fretboard to change chords. As the wheels spin, different arms come down to press on the strings. This is a simple system that also has some visual interest, however it is unable to flexibly change songs. Each wheel can only play a limited number of chords.

In addition to these previously created robots, we also looked at some other designs. One is the system on the Marble Machine X to play the bass. This system uses four wheels that roll along the string, called ‘cyber-capos.’ These capos are designed to be human playable, so the musician can adjust the tuning while the bass is plucked automatically by marbles. If we were to adapt this system, we would make it such that the wheels roll automatically. An advantage of this system is that you have four completely independent end effectors. As such, you can play any chords (or even new chords) and change quickly. They are also visually intriguing as it is highly visible what each one is doing. However, it would be difficult to have an open string with this design. There are ways around that such as raising the capo. We also looked at completely theoretical designs for inspiration and context. One is “Resonant Chamber” by Animusic (figure 2). This design incorporates many independent arms. These arms create a highly interesting visual performance, but they sacrifice speed. Each arm has to move far to reach the next note. In addition, such a system would likely be more difficult to build in real life as each arm has many degrees of freedom.

Figure 2: Animusic's Resonant Chamber

Requirements and Preliminary Design

Design Requirements

As the goal of this machine is to mimic the musical performance a human can create using a ukulele, we have a good understanding of the type of musical requirements that are at play.

Timbre: While playing, the robot should sound as though the string is played by a human

Timing: The robot should be able to play chords at at least 100 bpm. This tempo is high enough that it would be able to play most pop songs, as many don't change chord every measure.

Pitch: The robot should play the intended pitches with high accuracy. If the design uses the frets of the ukulele, this is intrinsically covered, as the frets are what shortens the strings in that case. Pitch range is a more interesting question as a mechanism has possibilities beyond a human's ability to play. As we are attempting to make an interesting mechanism with a heavy motion component we analyzed all ukulele chords and selected the most commonly used so as to have a clear pitch range we are attempting to create. The chords that we found to be required for this mechanism are C, E, E7, Em, F, G, A, Am, Bbm, and B7. We also found Dbm, D, D7, Dm7, Em7, Emaj7, Gbm, G7, A7, Bb, Bb7, B, Bm, and Bm7 to be desired but not required chords (Appendix A). As this system will have the ability to play a wide variety of current ukulele songs, the software must also be adaptable such that the system can easily play any song desired.

Looks: The robot should have an interesting design with high visual appeal while it is playing.

Preliminary Design

To aid us in choosing a design, we created a design matrix with the four concepts that we felt were the most promising. The first of these concepts was a system in which four wheels would roll up and down the ukulele strings. This was inspired by Wintergatan's "cyber capos" on the Marble Machine X, seen in figure 3. The wheels would be rolled up and down via a rack and pinion or on a belt. Each wheel would take its own motor, adding size and cost to the project. For rotational accuracy and speed, we would likely choose a stepper motor to move the wheels. This allows us to have high precision, which is important as this system bypasses the frets. To enable open strings, each wheel would have to be able to be lifted up independently of the others.

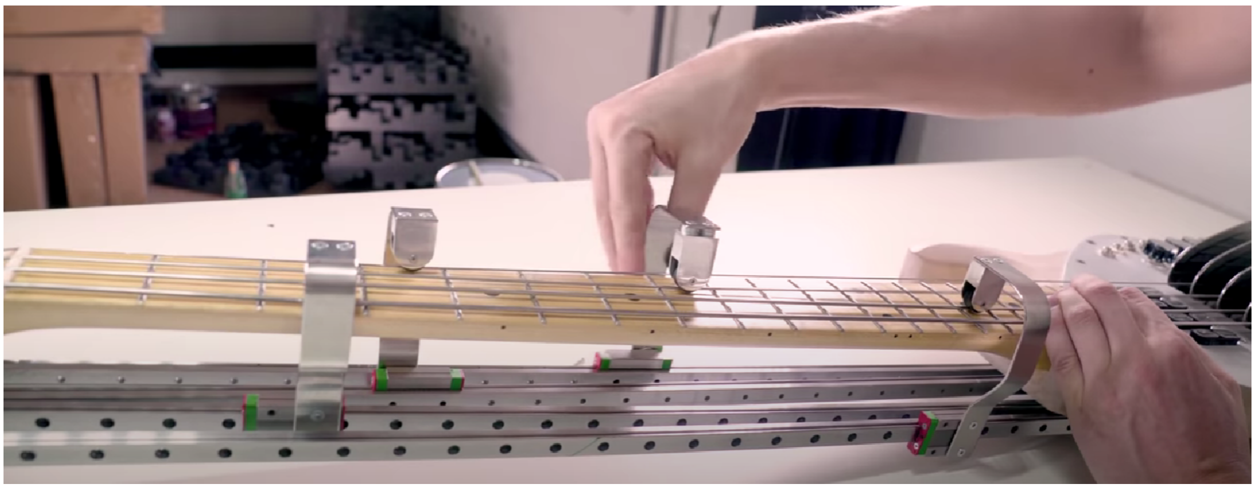

Figure 3: Wintergatan's 'Cyber Capos'

The second possible design was a solenoid-based design. This would feature a solenoid placed over every position that we would want the string to be pressed down. This design is inspired by many similar solutions that have been created in the past. These solenoids would enable the robot to play quickly and precisely, as there is very little motion required. However, as is often the case, that lack of motion also corresponds to a lack of visual appeal. This would also be quite costly, as a large number of solenoids would need to be purchased.

The third possible design is a set of robotic arms that would press down on the strings, much like a human hand. This design would be very visually interesting, but also likely the most difficult to accomplish.

The fourth and final option is very similar to the solenoid option, except with pneumatics actuating the piston rather than magnets. This would be a costly, noisy, and difficult to build solution given the requirements of working with pressurized air. The final design matrix is presented below in Table 1.

	Weight	Wheel		Solenoids		Arms		Pneumatics	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Ease of Making	1.5	3	4.5	4	6	1	1.5	2	3
Visual Appeal	10	4	40	2	20	5	50	2.5	25
Speed	2	3.5	7	5	10	1	2	4.5	9
Volume (sound) of Mechanism	2	3.5	7	4	8	4	8	1	2
Precision	3	5	15	5	15	2	6	5	15
Cost	2	4	8	4	8	5	10	1	2
Timbre	1	5	5	5	5	5	5	5	5
Total			86.5		72		82.5		61

Table 1: The design matrix

The final choices were close between the wheels and the arms. After spending time on initial designs for each system, we chose the arms. We decided that the arms would be a very visually appealing mechanism, as well as an interesting robotics challenge. We also looked at the feasibility of completing them within the seven-week term, and came to the conclusion that it would be doable.

The preliminary design for the arms consists of three three-degree-of-freedom (3DOF) arms located near the fretboard. We would have two arms placed below, and one above. This allows us to reach the notes that we need to reach without too much conflict between the arms, as shown in Figure 4. The chords that we based this on can be found in Appendix A.

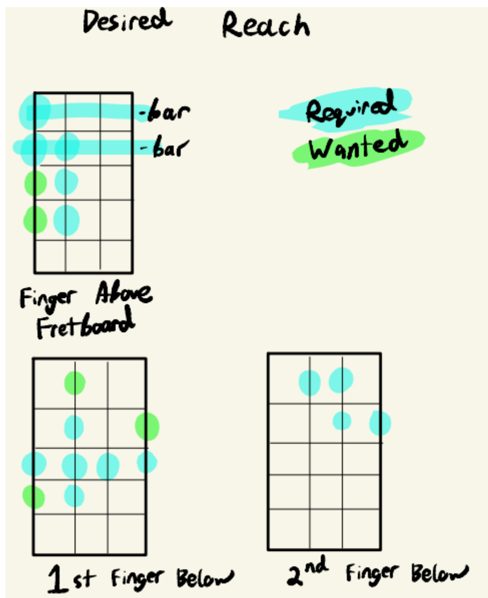

Figure 4: The desired and required reach for each arm

In addition to playing notes in the standard matter, the top arm will also be able to bar the first two frets, to expand the number of chords that the robot is able to play. Each linkage in the arm will likely be 3D-printed, though the specifics remain to be determined. Basic sketches of these arms, as seen figure 5, were made using SolidWorks to analyze design feasibility. This showed us that our desired 3DOF arms are physically possible to make, and gave us a rough idea of scale.

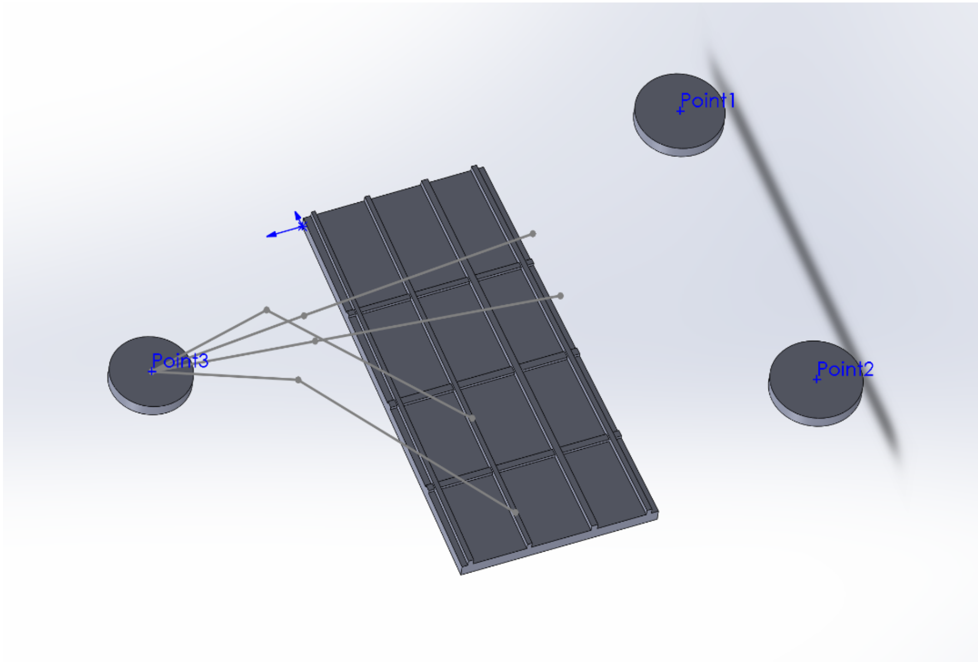

Figure 5: Design feasibility sketches

Actuating the arms will require three micro-servos. One will be placed at the base to rotate the entire arm, with two forming joints to allow a satisfactorily large range of motion. We hope to use FeeTech FB90 servos, as we already have some from previous robotics classes. Although specifics about the weight of the construct of each arm has not yet been determined (weight of entire PLA or other material used to construct each arm), we predict the servos will be able to provide sufficient torque to accomplish necessary movement because each servo has a stall torque of 1.5 kg-cm. Furthermore, the servos themselves do not weigh much, with a weight of 13 grams, so because this weight is small and PLA is also relatively light with a density of 1.24 g/cm^3, we believe these servos will provide sufficient torque for movement and depression of strings. Another option beyond servos placed on the arms is to use a system of strings to actuate the arms. This would allow us to use larger motors, as we do not have to lift the motor. However, incorporating strings would increase the mechanical complexity of the arm Further development of the arm concept is necessary as a design for the end of the arm, or fingertip, has not yet been determined. We are looking into acquiring silicon from the soft robotics lab, as well as some other materials. What makes this problem somewhat easier is that the fret is what shortens the string. The arm just needs to be able to consistently hold the string down such that it is pressed against the fret.

The other difficult component of constructing the arms is programming the software to allow them to properly move to chords. We decided that it will likely be too difficult to implement full path planning to move fluidly between two chord positions. That would require maneuvering around other arms and other complex motions. At the cost of some speed, we will be coding motions from a set neutral position to each chord, and resetting back to that neutral position after each chord is played. This allows us to reduce the programming workload to a reasonable level. The robot will be able to take in a list of chords and a tempo and play them in order. If time allows, we would like to implement a system to read tablature, though that is its own challenge.

Final Design

The structure of our design is based on a 3D-printed block attached to the neck of the ukulele, as can be seen in Figure 6. This block gives stability to three robotic arms which will move to press down strings. These arms will be made out of 3D-printed PLA with three servos mounted within the print of each arm link, allowing each arm three degrees of freedom. One servo will be mounted in the base vertically, allowing the arm to rotate, while the other two servos are mounted in the arm. We chose to mount the servos in the arm rather than using cables for simplicity. Creating and programming the arms is a challenge, so we elected to reduce the complexity as much as we could to keep the project feasible in the given time frame. Having these arms does cost some playing speed, but it achieves our aesthetic goals. We wanted to create a robot with significant moving parts, and the arms met that goal well. Having the servos in the arms also requires them to be able to lift more weight. We chose FeeTech FB90 servos as they meet the required torque, as stated previously. Furthermore, these servos provide position feedback which will be helpful when coding the movement of each arm.

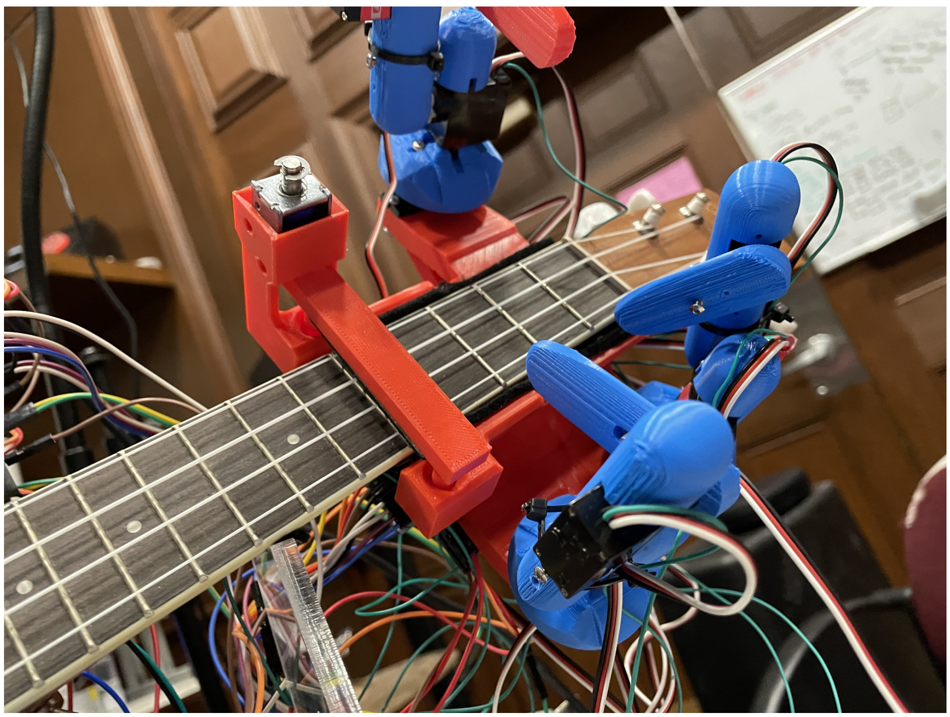

Figure 6: The arms and dampener mounted to the uke

A problem we ran into while implementing our preliminary design is that the arms are not able to press down on the strings in the same way that human fingers do. After testing, we determined that the force required to hold a string to a fret is much higher than we expected, making that avenue unfeasible. Instead, we elected to use the fingers themselves as a sort of fret. The finger makes contact with the string, thereby shortening the string and changing the pitch. This requires greater precision of motion, but far less torque. The servos are capable in this regard.

In addition to the arms, we will have a bar placed across the strings further down the fretboard. The bar is placed just after the fourth fret. This positioning allows it to be mounted to the same 3D printed block that the arms are mounted to. This bar will be actuated up and down by a solenoid to damp the strings. Damping the strings allows us to move the pick to achieve more complex strumming patterns and mutes the transition between chords. Using a solenoid allows the bar to move quickly and consistently. It is not visually stimulating, but it is not the main aspect of the robot.

During prototyping, we experimented with using silicone at the end of each finger. While we were attempting to use the frets, the silicone was highly useful to keep the finger on the string. However, once we switched away from using the frets, the silicone became disadvantageous. The silicone damped the string on its own. We found that scoring the end of the finger with a knife produced a good sound. The finger did not vibrate on or slip off of the string. Furthermore, we attempted to ensure each arm will be able to depress one specific string without affecting others through the specific CAD design of the third link of each arm. In the end, we decided to forgo barring. We did not realize how much force would be required and our servos are unable to provide it.

The strumming system, which can be seen in Figure 7, is largely unchanged from the previous project. It uses a different servo driver which produces quieter running, improving the general sound quality, but most of the components are the same.

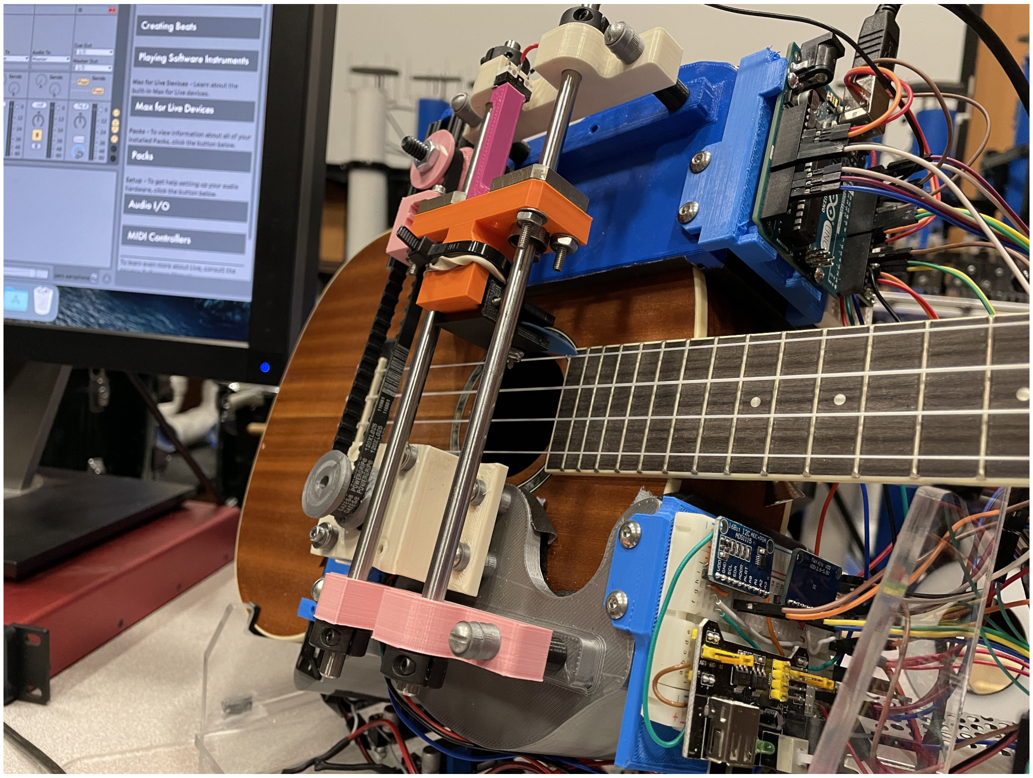

Figure 7: The strumming system

Evaluation

We had four main categories of requirements for the robot. The first was timbre. Due to the fact that we are now directly shortening the string with the arm, this has become a more difficult requirement to meet than it was initially. However, the servos are precise enough that once positioned initially they can reliably produce a good sound. They push into the strings well enough that there is no vibration or harsh sounds. In addition, the damping bar functions effectively. It quickly damps the strings without too much sound produced at the wrong pitch. The solenoid is able to move it very quickly, allowing us to damp for short periods of time during chord transitions. Our second requirement was timing. In this aspect, the arms perform better than expected. From testing, they can play at up to ~160 bpm. Because we put the arms down as soon as possible, the timing of when they touch the strings is less important. The strings are excited when strummed, not when pressed by the fingers. The third requirement relates to pitch precision. From our testing, the servos are accurate and able to return to a pre-set position. This means that we can calibrate all of the positions once and remain accurate going forward. The fourth and final requirement is about looks. The ukulele is now heavily modified and even static is highly visually interesting. The three arms sticking up draw the eye very effectively. While moving, they are dynamic and fun to watch.

Musical Usage and Reflection

This robot turned out quite well. We had to forgo some of our initial design ideals, but in the end it is a competent ukulele player. The midi input is not standard midi, but it is still quite usable. We elected to use octaves to denote the type of chord. However, there are areas of this project that could be improved. Our selection of chords that we are able to play is significantly lower than we had initially hoped for. This is due to a variety of reasons. One is that the arm placement is not perfect. Due to time constraints, iterating on our design of the base was difficult. The print itself took a long time, and it would require complete disassembly of the arms to change out a design. The arm link shapes could also be improved to achieve a more diverse set of chords. The arms are just not able to reach the required distance to play all of the chords that we wanted while maintaining good timbre.

In designing and building this project, we did face a few hurdles. One significant one was power. Each servo has a stall current of 700 mA, and we have the capability to stall all nine of them at once. We failed to do the math on the required current for this at the beginning, and went through many iterations of power systems until we found one that could supply enough current at the proper voltage.

In the future, there are many directions that this robot could go. The inclusion of arms gives many tonal possibilities. For one, the arms could be placed in between frets to explore microtonal pitch sets. We did not have the time or experience to experiment with this, but it could present interesting avenues. Also, the arms could be made to bend strings, bringing more tonal intrigue. The path planning on the arms could also be improved. Currently, the problem of trajectory planning is avoided by resetting the arms in between each chord. However, with more time, the transition time between chords could be reduced by having the arms move directly (or as close as possible to directly) to their next position. On the strumming front, the current system is stuck in one defined strum pattern (up, down, up, down). There are many possible systems to allow a more flexible pattern, such as rotating the pick out of the way and moving it above the strings. On the software side, the MIDI input system could possibly be made more user-friendly. It is currently very manual, requiring each note to extend slightly before and after it should actually be played so that the arms have time to move. Also on the software side, it would be very interesting to have a system to read sheet music. This would make the robot an effective teaching tool, as it could take in sheet music and demonstrate finger placements. In the age of remote learning, this could become even more useful.

Appendix A: Bill of Materials

assembly	part	manufacturer	part #	quantity	cost(per)	vendor
	Microcontroller	Arduino	Uno	1	$20	Personal supply
Arm	Servo	FeeTech	FS90-FB	9	8.95	Pololu/Personal supply
Arm	Linkages		PLA	~38 grams per arm	$0.04/gram	Personal Supply
Damper	Solenoid				~$15	
Damper	Track		PLA	2	$0.04/gram	Personal Supply
	Crosspiece		PLA	1	$0.04/gram	Personal Supply
	Softening Material		Felt	3in		Personal Supply
Chassis	Neck Mount		PLA		~0.5	

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