Glass Tango: A Robotic Glass Harp
Humanities and Arts 3910: Musical Robotics Practicum

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ABSTRACT

Singing wine glasses, or glass harps, are a unique instrument that generates music through the vibration of wine glasses. Musicians play them by coating their fingers either water or alcohol, then applying pressure around the rim of the glass, inciting vibration. Depending on the volume of water and the glass size, the pitch varies. The team intends to automate this process with a musical machine. "Glass Tango" is a robotic wine glass excitation machine that will produce a variety of ringing pitches. It will emulate a more commonly known instrument, the glass harp. The machine that will be developed and manufactured by the team will have between eight and fifteen wine glasses, all of which are tuned to a different note of a certain octave. Each glass will be excited by a certain mechanical action that creates friction between a rubbing material and the rim of the glass, which is the fundamental basis of how a wine glass is excited and produces the distinct ringing sound.

1. CONCEPT, MOTIVATION, PURPOSE

Discovery is the reason the team has decided to pursue this project. From the research performed, a fully automated singing wine glass machine does not exist; therefore, the knowledge and insight gained through design and development will be new breakthroughs in musical robotics. The goal of this project is to determine what is realistically possible when designing and creating a robotic singing wine glass machine. This includes discussions about what dynamic range is possible from a glass and an array of glasses and the speed at which notes can be played (difference between 'note on' and 'note off'). In addition, the team is in search of new sounds and techniques that have been previously unattainable by humans, but are attainable with a robotic instrument. These discoveries will lead to original compositional ideas and new understanding of the musical ability of wine glasses.

Another consideration is replication versus innovation. One of the questions the team is trying to answer is "is it possible to create sounds similar to what humans can make when playing wine glasses?" One measure of success of this project is whether the machine that is created can mimic a human player with regards to style, quality, complexity, and other traits of a musician. Another question the team is looking to answer is "are there things that humans cannot physically do that autonomy can that would influence the sound created by the glasses?" An example of such a trait includes changing the water level in the glasses while playing them to change the pitch of the notes. These sorts of innovations introduce more musical possibility from the instrument being controlled by a machine, but come with more mechanical complexity. For example, being able to change the pitch of the note being played could introduce some glissando-like effects that were not possible previously by human players. This is another measure of success - whether the team is able to create a singing wine glass machine capable of new musical abilities or not.

The team has done some initial brainstorming about high-level design of the machine. The wine glasses will be laid out in an array, and will be mounted to the base of the machine by their bases so that they do not tip over when they are played. Each wine glass will have an exciter and a rotating mechanism, both of which will combine to make the exciter travel across the top of the wine glass in a circular path. There are multiple ways that this can be accomplished:

1. Each wine glass will be mounted to the base of the machine, and an apparatus will be suspended above the array of glasses with one motor, one servo, and one exciter attached to it for each glass. The suspended apparatus will fully control the movement of each exciter so they will spin around the top of each wine glass when playing. This would involve producing a structure that can hold between eight and fifteen "glass excitation units" (including a motor, servo, and exciter) above wine glasses filled with water. The solenoid will control the exciter coming in contact with the glass, and the motor will control the exciter, producing the friction on the glass rim.

2. Each wine glass will be independently mounted to a solenoid-controlled or servo-controlled mechanical base, and an apparatus will hold one motor and exciter above each glass. Each glass's mechanical base will control the glass coming in contact with the exciter, and the motor will control the exciter producing friction on the glass rim.

3. Each wine glass will be independently mounted to a motor-controlled rotating base, and an apparatus will be suspended above the glasses that will hold a servo and an exciter. The servo will control the exciter coming in contact with the glass, and the motor will rotate the glass to produce friction between the glass rim and the exciter.

4. Each wine glass will be independently mounted to a mechanical base that is both motor-controlled and servo-controlled, and an array of exciters will be suspended above the glasses so that each glass has one.

The motor will be responsible for rotating the glass base, and the servo will be responsible for raising, lowering, or otherwise moving the glass to come in contact with the exciter.

"Glass Tango" emulates the performances of glass harpists, but expands the capability of a glass harpist by adding the capability to play any number of glasses at a given time. Glass harpists can usually only play two wine glasses at a time, which limits their ability to produce more complex musical pieces without the assistance of additional harpists. By having independent systems controlling each glass, the machine can play any number of wine glasses at the same time. This capability introduces the possibility of producing sophisticated and layered pieces of music.

While the end goal of the project is to create an automated singing wine glass machine, that is not the purpose for creating the machine. Through an iterative design process, the team intends to experiment and determine the constraints and parameters involved in the overall machine. Constraints must be considered during the design process, as they will limit the ability of the machine. For this project, the team anticipates latency, volume, and possible pitches to be the initial constraints. Parameters are variables that must be chosen that will have an effect on the overall performance, but are not necessarily limiting factors at the outset. For singing wine glasses, this will involve the number of glasses, the volume of fluid in each glass, the type of fluid, and the kind of material used to make the glasses sing. Through experimentation, the team hopes to determine the bounds of what is possible through a musical singing wine glass machine.

2. PRIOR ART

There are many complex components to design to create a functional automated glass harp. Lubrication, excitation material, and precise tuning are design challenges that will need to be overcome. The team only has seven weeks to build a functional glass harp, which is not enough time to solve all of these challenges without research. Three different instruments were studied to help understand how others have solved these problems, and if the solutions are applicable to this project.

A glass harp player usually excites a glass by rotating their damp finger around a stationary glass. Friction along the glass rim is utilized in the instrument to physically create the reverberations in the glasses. The player can vary the pressure they apply to the glass as well as the point on their finger that contacts the glass. This pressure changes the timbre of the sound. The reason wine glasses resonate in this way is due to the slip-stick phenomenon. When two surfaces slide along each other, there are instances of the surfaces becoming 'stuck' and 'unstuck' due to the friction between the surfaces. When the surfaces become unstuck, energy is radiated in waves. When geological faults move past each other and become stuck and unstuck, the seismic waves generated result in earthquakes [5]. In the application of this project, the slip-stick phenomenon generates waves from the friction between the rim of the glass and the exciter. The waves resonate inside the glass, producing the note of the glass. The note being played can be tuned by changing the volume of the resonation chamber. For this application, the volume of the resonation chamber is the volume of air in the glass. By adding water to the glass, the volume of air is being reduced, thus changing the note.

2.1 Glass Armonica

The glass armonica is the oldest mechanical glass harp. Benjamin Franklin worked with Charles James to create the instrument in 1761. It is composed of thirty-seven glass bowls mounted on an iron spindle, driven by a foot pedal.

Figure 1: A glass armonica. Glass bowls are placed on corks, lined up on a long rod which is spun by use of a foot pedal.[4]

There was some superstition surrounding the armonica. Quoting German musicologist Johann Friedrich Rochlits: "[The armonica] excessively stimulates the nerves, plunges the player into a nagging depression and hence into a dark and melancholy mood, that is an apt method for slow self-annihilation" [1]. While this is clearly nonsense, there is quite an eerie quality to the music produced. The design of the glass armonica was the first we saw where the glasses were spinning, instead of the actuator (finger) rotating around the rim of the glass. Also, there were interesting experiments performed regarding lubrication. William Zeitler tried implementing self lubricating glasses by having them rotate through a trough of water. This did not work, as the volume of water changed the pitch of the bowls. Additionally, since each bowl is a different diameter, the amount the pitch changed by was different. Finally, the water muffled the glasses, reducing the quality of the sound. This will not work as a solution to the lubrication problem for our project.

2.2 Glassdance

Glassdance is an instrument designed and constructed in San Diego, California by Cris Forster. Glassdace took two years to construct, and was finished in 1983. Since then, several improvements and repairs have been performed, all documented in the Glassdance manual. Glassdance is an instrument that consists of forty-eight rotating glasses of varying sizes. The glasses rotate via a single variable speed motor connected to each glass's aluminum shaft by a series of chain and sprockets. Because the sprockets attached to each glass are the same size, this means that the glasses travel at the same angular speed as each other. The glasses produce a large range of notes, from G above middle C to the third G above middle C. The glasses are played by a human who is wearing special finger gloves made of chamois (goat skin) soaked in denatured alcohol.

Figure 2: Glassdance, created by Cris Forster.

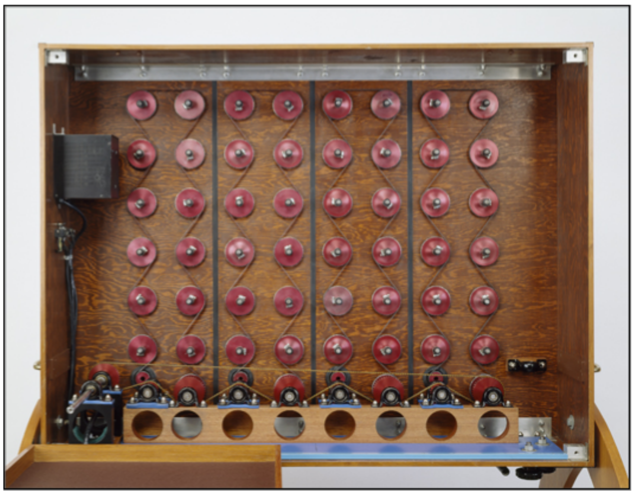

Figure 3: The backside of Glassdance. The sprockets driving the rotation of the glasses is shown. [2]

Unlike traditional glass harps, the glasses on Glassdance are orientated sideways - meaning the 'opening' of the glass faces the player (images can be found on the website found in our bibliography for Forster). This means that fluid inside the glasses cannot adjust the pitch each glass makes. Instead, the glasses were hand blown and shaped to create the pitch range described above. The material of the glass is lead crystal glass, which is an extremely hard and smooth glass. Because of this, special finger gloves are required to create the correct contact between the player and the glasses to create sound. As described in the manual and on his website, Cris explains the results of his countless tests of different materials to play Glassdance:

"[T]he best combination is handmade chamois finger gloves dipped in denatured alcohol. After making the gloves, soak them in alcohol for a few days, and then let them dry out. This removes most of the natural oils in the leather. Play the glasses by regularly dipping the gloves in a small container filled with alcohol" (Forster, 2019).

The information about Glassdance benefits the project in many ways. While the original idea was to change the pitch using varying volumes of water, different sized glasses opens up the opportunity for another way to change the pitch of the glasses. Insight about an artificial exciter was also provided. Understanding that oils in the skin, or excitation material, can have a negative effect on the quality of sound produced (or whether sound is produced or not) is important. An email was sent to Cris Forster to try to better understand the chamois finger glove, to which he offered some support but did not want to discuss specifics.

2.3 GlassDuo

GlassDuo is a musical group featuring two musicians that both play the glass harp at the same time. With twice the amount of hands playing the instrument, it can produce more interesting, involved, and layered sounds than a glass harp that is played by only one musician. This introduces the capability for the duo to create layered chords more easily and frequently. This key concept is the most important takeaway from this particular glass harp as to how the instrument can be improved when enabled robotically. With an array of wine glasses that is as large and complex as that of the GlassDuo harp, the full potential of the sounds that the harp could produce with many chords playing at the same time can be unlocked by automating the harp in this fashion.

The GlassDuo glass harp is a traditional glass harp composed of different-sized wine glasses, which produce sound in the traditional manner of the GlassDuo musicians rotating their fingers around the buvant, or rim, of the glasses. The GlassDuo harp can produce pitches across five octaves, and it is currently the largest professional glass harp in the world ("GlassDuo"). The design of the instrument has been iterated multiple times over the course of the past two decades, with each iteration producing an instrument that had a wider musical range and much less weight than the previous instrument. The most recent iteration of the machine can be seen in the image below.

Figure 4: The GlassDuo's glass harp. This glass harp contains forty-six glasses of different sizes.[3]

The GlassDuo glass harp has forty-six unique standard goblet-style wine glasses. These glasses sit motionless on a metal base designed to hold each glass a certain distance away from each other. Each glass is precisely tuned for a specific pitch with different amounts of water inside the glass. The musicians create resonance by rubbing their finger around the buvant of the glass, but this is no easy action. A very precise amount of friction is required between the glass edge and the finger of the player. This is achieved through a delicate balance between the amount of water between the two entities and the pressure that exists between them, the latter of which is applied and controlled by the musician. However, as described previously, this is required for any glass harp and is not a unique trait of the GlassDuo harp.

2.4 Questions

Together, these three instruments provide a great starting point for design and development of an automated glass harp. A few critical questions have been identified after this research. Will the actuators spin around the glasses, or will the glasses spin under the actuators? What material will be used to excite the glass? How do the glasses remain constantly lubricated? Addressing each of these questions in the design of the machine will be critical to its success.

3. DESIGN REQUIREMENTS

One of the goals of the singing wine glass machine is to be able to play full songs. This overarching goal entails many different specific requirements which the team has identified. The mechanical requirements are discussed first, which lay out what the machine must do and how it should do it. Then, the musical requirements follow, which discuss what the machine should be able to produce as a musical output when complete.

There are several mechanical requirements that our machine must meet in order for it to be deemed a success. The first is that the machine is made up of modular components. This modularity reduces mechanical complexity by breaking complex mechanisms and ideas down into smaller and more manageable pieces. The original idea was refactored into several modules consisting of a rotating glass with a dedicated exciter and a dedicated or shared moistening system (more work must be done to certify which method of moistening will be best, if moistening is required). By working on this project in a modular style, once the small module has been finalized, it can be replicated to expand the machine. This leads into the second mechanical requirement.

Each module of the machine must be as identical as possible (with the exception of the volume of water in the glass in order to have different notes). By cloning the finalized module, there should be no issues within each module; therefore, any problems that arise would be restricted to interfacing modules together. This limits the number of unique problems that must be dealt with. To make the modules as identical as possible, all 3D printed parts will be printed on the same printer using the same filament and the same gcode. The hardware used to assemble the machine will be the same, though there will be small tolerances due to manufacturing. The glasses will all be the same as well, though we have learned that the manufacturing of the glass has a large impact on the resonating pitch it produces. To combat this, each glass must be manually tuned by filling/emptying, then exciting the glass until the desired pitch is reached

Repairs or modifications should be simple to perform. This requirement boils down to proactive designing of the components being used to make sure that each separate system can be accessed easily. This is generally a given requirement; however, the team felt that it is an important enough requirement to mention here to acknowledge the effort going into the designing and planning of the machine. This will include leaving screws easy access so that assembly/disassembly is straightforward, limiting the quantity of components of each module, as well as designing them to print easily and quickly.

For most instruments, the amount of time they can make pitches is not a limitation. However, for this machine, if the exciters run out of lubrication, they will no longer be able to produce sound. To be able to play full songs, the team has set a requirement that the machine can play music for at least eight continuous minutes.

Being able to play chords allows for harmony and musical complexity. Without the ability to play multiple pitches simultaneously, the machine would only be able to play a simple melody, and would rely on other instruments to complement it to create interesting music. Therefore, the team decided that the machine must be able to play three different notes at the same time. Since each glass will only have one pitch, this will require at least three modules. However, to be able to play a wide array of pitches as well, the module count needs to be higher. Ideally, the instrument will have at least fifteen distinct pitches, as this would comprise one full chromatic octave. This would allow for chords in any key to be played.

To be able to play a variety of pieces, a variety of requirements relating to playing notes need to be established. First, the machine needed to be able to play sustained notes by playing them for a long period to time. For the purposes of the team's composition using the machine, a sustained note duration of ten seconds. While the number ten is arbitrary, the idea behind it is that we want to be able to hold a note for long enough to provide plenty of creative freedom.

Contrasting the machine's ability to play notes for up to ten seconds, the machine must also have the ability to cut off/stop playing a note within one second of playing it. If notes resonate longer than this, notes may begin to blend together, causing dissonance. In order to play pieces at a higher tempo, the resonance will need to have a way of being cut off. A duration of one second was chosen for the maximum cutoff time as an attainable goal for the machine to achieve this term.

It was found that pressure and rotation speed relate to the ability to and quality of playing a note. To keep the glasses as uniform as possible, they must be spun at the same angular speed. By ensuring a uniform angular speed across all glasses and by controlling the pressures of the exciters on each glass rim specifically, the timbres of the notes will be similar to each other. Similar tibres across the glasses is imperative so that no notes or tones stand out as outliers. Having a consistent quality of sound will allow the instrument to sound more like one instrument rather than several individual glasses.

Through experimentation, the team has shown that due to the technical precision with which the exciter will need to contact the glass, there will be some latency in producing a sound after the initial contact. This latency can be attributed to the fact that the precise combination of water and pressure between the exciter and the glass will not be reached instantly once the exciter comes in contact with the glass. It will take a nonzero amount of time for these two variable elements of the machine to reach states that allow the proper slip-stick action to take place between the exciter and the glass. The requirement of limiting this latency to half a second is based on the order of magnitude of the note cutoff requirement. If staccato notes are held to a duration of one second before being cut off, then the latency of starting a note should be shorter than that.

It is understood that this machine will have a significant amount of physical moving parts, which will require a variety of control mechanisms. These mechanisms will need to be actuated with components like motors and servos, which will undoubtedly create a noise floor in the machine. However, for the machine to be pleasant to listen to by any measure, the volume of this noise floor cannot be higher than the volume of the sounds produced by the glasses.

The physical nature of a wine glass is that of a resonator. A wine glass is not excited through direct physical contact alone; resonance can also be induced by external vibrations in the air if those vibrations are harmonically related to the resonant frequency of the wine glass. The extent to which a glass may be excited by external vibrations will depend on the magnitude of those vibrations and their proximity to the glass. This machine introduces a great opportunity for glasses to incite sympathetic resonance within one another, as they will be very close together in the machine. The design of the machine must prohibit glasses from inciting this resonance in one another, as this resonance could compromise the sound produced by a specific sound glass by introducing more noise.

Many components were planned to be 3D printed, as the team has access to a printer. However, printing takes a considerable amount of time, and this print time must be taken into consideration when printing parts for fifteen sets of glass - exciter pairs. During the design process, steps were taken to reduce the overall volume and size of prints to reduce the total print time. In addition, laser cutting was used to fabricate 2D components, such as the base boards for each module and the two triangular pieces that, when screwed together, created the exciter tower.

4. TESTING AND EXPERIMENTATION

To determine the final design for a glass harp module, many tests were performed for each component. The team tested multiple iterations of three major components: glass drivers, actuators, and lubrication. The glass mount is the composition of fasteners, stabilizers, and mechanical automation that allows the glass to spin at a constant rate. The actuator is the combination of the material that will come in contact with the glass and the mechanical apparatus that will enable this. Finally, lubrication refers to the way in which the slip-stick action is accomplished through the control of water output between the actuator and the glass.

Recognizing the need for the wine glasses to rotate in a consistent manner, a mechanism to hold each glass and facilitate their rotation had to be designed. It was decided that each glass should be held by a 3D-printed "cup", and that each cup should be coupled to a motor. One critical design component to get right was the stability of the rotating cups. The initial cup design was tested with a VEX 393 brushed DC motor. In this test the glass leaned often, causing the glass's rim to keep changing heights and position relative to a stationary exciter, making consistent excitation difficult. The team redesigned the cup to include 3D printed wheels to act as roller bearings that would contact the smooth surface underneath the cup. Testing this design verified that 3D-printed bearings do not work, as the plastic bearings did not spin as expected. The cup was resigned again so that two press fit 8mm x 22mm x 7mm bearings could be installed inside of the cup to provide two low friction contact points that the cup can rotate about. To test this cup design, an M8 bolt was fed through the hole in the middle of the cup and through the bearings to provide an axle about which the bearings could rotate. Virtually all slop in the system was eliminated when the cup was secured by the bolt to the board. In addition, the amount of friction between the cup and the board decreased as well because the friction due to rotation was relieved through the bearings. A cross-section of this cup design can be seen in the figure below.

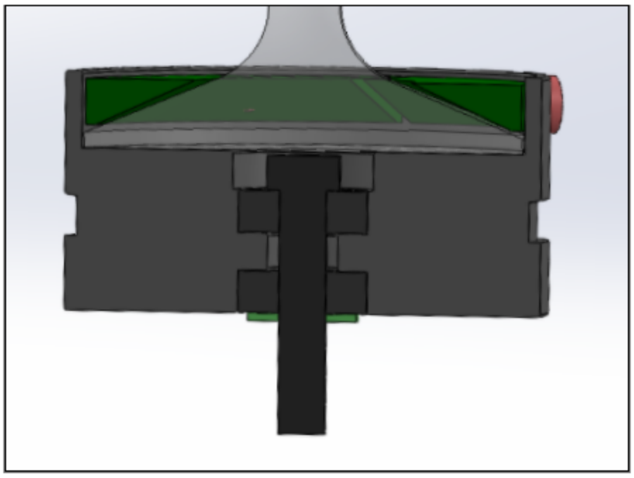

Figure 5: Cross-section of cup with two bearings

With a musical requirement of fifteen unique pitches, many glasses and cups were needed in the instrument, but driving each of these individually was not feasible for two reasons. First, the abundance of components needed for this would be illogical to use, and it would increase the cost of the machine greatly. Second, independent rotating units would produce independent systems that would not rotate at the same speed. Therefore, the machine needed a number of glass-cup modules to be coupled together and driven from the same rotational source. The fifteen-pitch requirement led the team to round up. The team created an arrangement of cups on a 12"x12" wooden board

To turn the 3D-printed cups and their respective wine glasses, a brushless DC (BLDC) motor was the desired motor to use due to its significantly lower noise compared to a brushed DC motor. Initially, a hobbyist 1000KV BLDC motor was chosen as the driver and speed tests were done with an off the shelf Electronic Speed Controller (ESC). However, this ESC drove the motor too quickly, and the glasses did not resonate. Speed reduction could have been achieved through additional gearing or pulleys, but these would increase the noise and mechanical complexity of the system. Other off the shelf solutions were researched, including the ODrive, NearZero, and a TI BLDC development board. However, all of these solutions were over $100, and would only control two motors. Based on available belt lengths, it was determined that five glasses would be included in one "module", meaning a total of three, five-glass modules are needed to meet the machine's musical requirements. With one motor driving each five-glass module, three motors are required, which makes the professional BLDC motor drivers prohibitively expensive. It was concluded that creating a custom ESC build for low speed control was the most cost effective solution to drive each BLDC.

Upon sourcing parts for the custom ESC, the circuit was constructed and tested with the BLDC. It was found that the ESC successfully drove the motor at a much slower speed than the off-the-shelf ESC. However, the motor did not have nearly the amount of torque needed to rotate a full module. This was an unforeseen mechanical requirement that the team did not originally consider. The team opted to use a brushed DC motor instead. Driver circuitry is much less complicated and the output torque is much higher. Unfortunately, this significantly increased the noise floor of the system.

Through initial research, the team anticipated the material and design of the actuator to be the most challenging and complex component of the project. However, this was found to not be the case. In initial testing, it was found that readily available materials in combination with water excited the glasses just as any human player could with their finger. The first rounds of experimentation were focused on recreating the feel and function of a human finger with a latex glove, padding, and a wooden dowel. Both a plastic bag and paper towel worked well as padding material. It was found that the paper towel worked slightly better than a rolled up plastic bag, as it provided slightly more cushion.

Once the team had settled on a potential actuator design material wise, the next challenge was to automatically lubricate the actuator and glass. Without this, the fluid would move to other parts of the glass, and the slip-stick mechanism would no longer occur. A few designs were considered, but only two were tested. The main challenge was applying the correct volume of fluid over time, as too little or too much fluid will fail to produce a tone. The first solution was a spray bottle with water in it. When pointed between the exciter and wine glass, it applied enough water to allow it to continue resonating. While this would work, it significantly increases the complexity of the overall mechanism. Each module would need its own bottle, an actuating servo, and a mount. The other idea considered was a drip tubing system. If each module had its own tube routed to it, provided fluid by a low volumetric flow pump, lubrication could be applied at a low rate to each module. However, this increases complexity again, as routing tubing to each module from one pump is complicated, and none of the team members have experience.

The final lubrication method tested was a sponge. The sponge was dampened and held to the rim of the glass in order to lubricate the rim right before the exciter. This did not require extra actuation from extra servos, and avoided the need to route extra lubrication to the rim of the glass and/or the sponge. However, the team discovered through testing that the sponge served an extra purpose. As it turns out, a slightly compressed sponge will excite the glass on its own, without an extra source of lubrication. This significantly reduces the complexity of the excitation and lubrication module. A sponge in combination with a servo horn were combined to create the final actuator.

Because of the height of the glasses and the cup, 3D printing the tower would take too much time. To solve this problem, actuator towers were laser cut out of wood. On the top of the tower is the servo mount, where a 9g servo motor will be secured. The servo bracket has a slot in it, which will connect with the hole in a piece connected to the tower. This allows the team to manually adjust the height of the servo when assembling each module. Due to slight variations in glasses and mounts, the pressure applied and the height for each servo will be different. The slot allows the team to manually tune each glass without relying on precise control of the servo. Connected to the stand bracket is the perpendicular wooden piece. The bracket rigidly attached to this piece. The tangent wooden piece connects to the perpendicular wooden piece and creates a tower for the exciter to be mounted to. This tower is then secured to the platform by three screws.

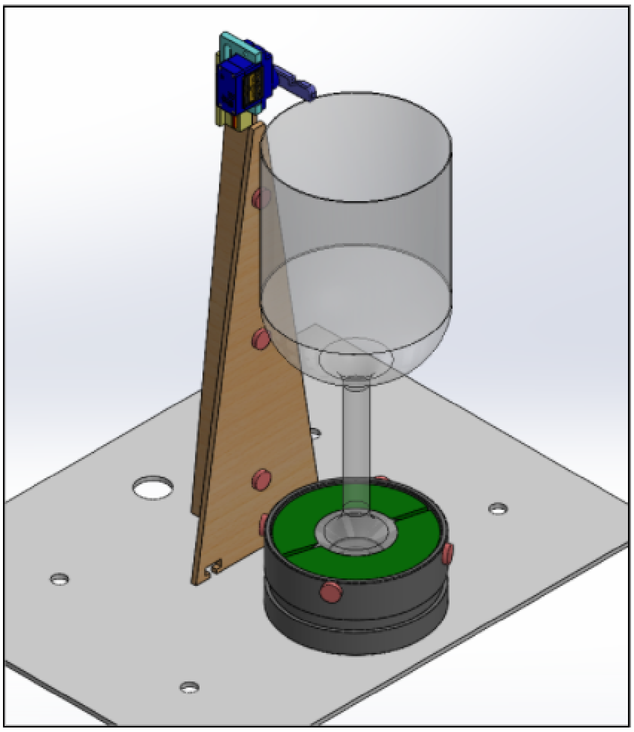

Figure 6: Isometric view of the exciter mount.

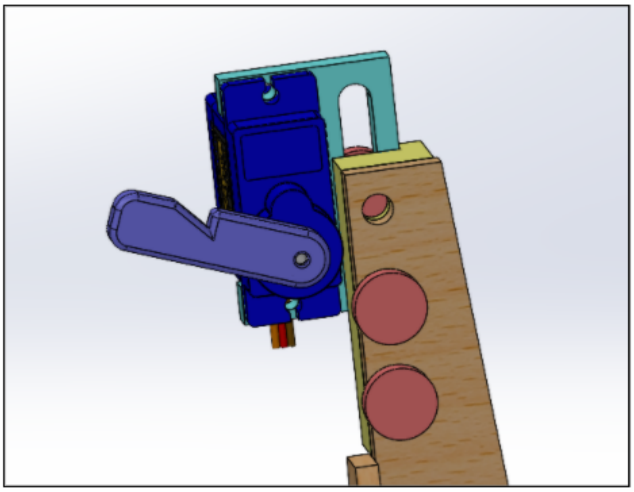

Figure 7: Side view of servo motor with custom horn that the sponge will be attached to.

5. FINAL DESIGN

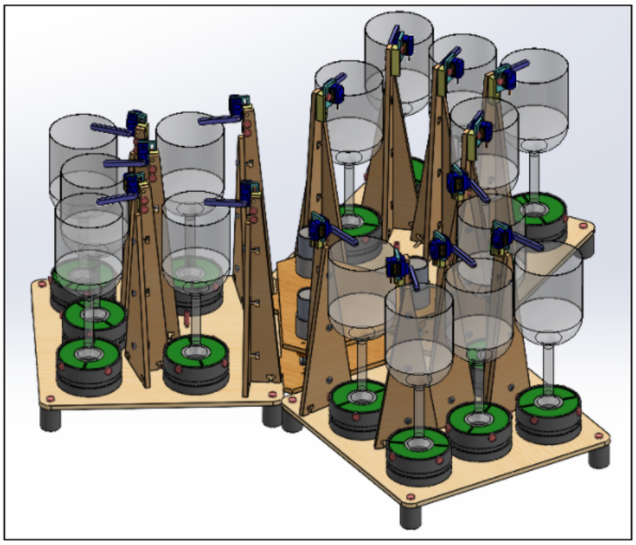

Figure 8: CAD model of Glass Tango with three modules of five glasses (belts are not included in the model).

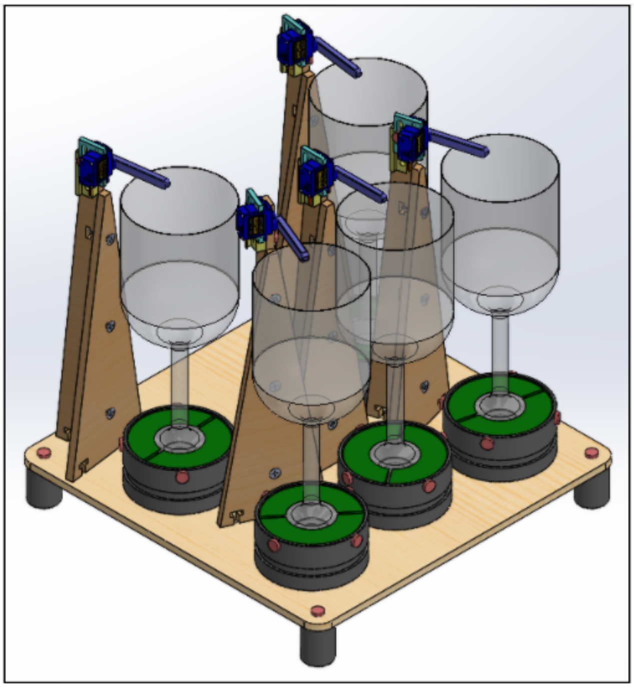

Figure 9: One module of Glass Tango. Included in one module are five rotating glass assemblies, five exciter towers, a base board, and four vibration dampening feet.

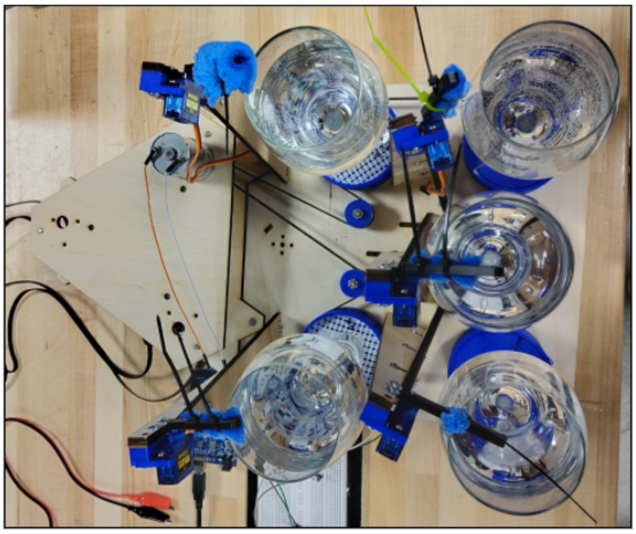

Figure 10: Top view of one module of Glass Tango. Pictured are the rotating glass assemblies, exciter towers, the belt, and the brushed DC motor.

Figure 11: Back view of one module of Glass Tango.

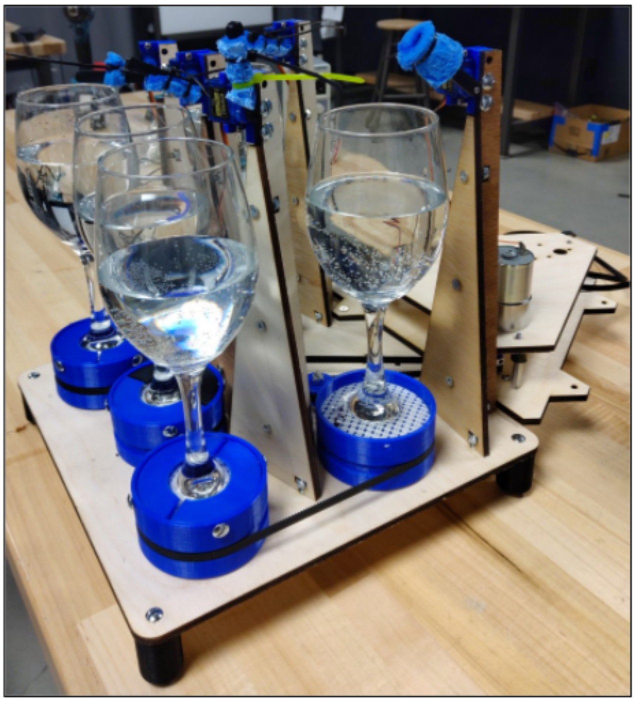

Figure 12: Isometric view of one module of Glass Tango.

With testing and experimentation complete, the assembly, testing, and tuning of the final machine began. While the components for all three modules were printed, cut, and ordered, one module was fully assembled to test and debug functionality. Once all of the hardware was assembled, all of the wine glasses were tuned. Each glass was marked with its note, starting at F3 and going up to G3. Five glasses were mounted into the module and final testing began.

The brain to control everything was an Arduino Mega microcontroller. A Mega was chosen because it has enough pins to drive all fifteen servos on Glass Tango. Software was written to tune servo positions to their playing positions, and to take in MIDI data over a Serial connection. This allowed the team to manually tune each servo's position, and to have music written in Ableton actuate the servos corresponding to the MIDI note.

To reach the desired motor speed of 320-375 RPM (determined experimentally), the motor was provided 18V of power from a DC power supply. The servos needed 5V, so a voltage regulator was connected to the same supply to power the servos. Signal pins were connected to the Mega, and mapped to the correct notes within software.

6. DISCUSSION AND RESULTS

Unfortunately, the team failed to get the machine to work consistently. There were a few times when servo actuation did cause the glass to resonate, but the team failed to repeat this behavior. However, it was clear that the mechanical design almost worked. By applying a very light amount of pressure to the end of the servo horn when it should have been playing, the glass would start resonating. Due to this, the team believes that if more pressure was applied by the servos, the glasses would resonate properly.

Another issue was with the voltage regulation circuit. The team did not realize until very late that voltage regulation would be required, as a voltage divider does not work with a variable load. While a voltage regulator was found, it needed a heatsink to dissipate the heat it was generating. Without it, the servos could only be driven for about thirty seconds before losing power.

The final issue was irregularities in wine glasses purchased. When spun by the cups, most of the wine glass rims stayed at a steady height. However, some did not rotate perfectly about their central axis, causing the rim to wobble back and forth. This changes the amount of pressure the servo would apply, further reducing the chances of successful excitation.

However, every other major component of the system worked. The cups spun at the correct speed for resonance, and would not slip against the belt under normal operating conditions. Servos correctly actuated with control signals from the Arduino, and mapped properly to MIDI on/off signals from Ableton.

7. CONCLUSION AND REFLECTION

This project offered many opportunities to discover new ideas and practices when it comes to both engineering and music. Combining the two disciplines together into one project generated many complex problems that required innovative and out-of-the-box problem solving. While the team was unable to accomplish all goals set at the beginning of the term, many goals were met along the way to the current state of the project. For example, the work done on this project is proof that the concept of actuation controlling singing wine glasses is possible. There are not many examples of automated glass harps, let alone fully autonomous glass harps. The knowledge the team has gained and documented is research in an unexplored area of musical robotics. Glass Tango is a positive step towards a high quality, fully autonomous glass harp.

More progress could have been made towards a more completed end product had there been more time for the team to work on the machine. It was difficult to fully design the robot in SolidWorks, fabricate the parts using 3D printing and laser cutting, determine parts to purchase, wait for the parts to arrive in the mail, and assemble, test, and debug a system that combines mechanics, electronics, and software to produce complex musical ideas. The team has the means required to fully assemble the full three modules of five glasses and to get them working, but time ran out.

The first step the team would continue forward with would be working to determine how to use BLDCs to actuate the rotating cups. Having to transition to brushed DC motors was a great choice for functionality, but not for practicality. The instrument would sound much better if it was not accompanied by the whine of brushed motors.

The next step would be to spend more time dialing in the sponge and rim slip-stick relationship when being controlled by a servo. The team had luck generating resonance in the glasses by holding the sponge piece against the rim, but could not replicate the same results with the servos. Reasons why this could have been the case were mentioned above. A solution to this problem would promote Glass Tango from a concept to a machine.

There are many further steps one could take. The initial one would be certifying that the BLDC rotating the glasses and the servo actuation making the glasses sing worked well together. Then, certifying that the interface between Ableton and the robot was operating properly would allow simple melodies to be played. Finally, expanding Glass Tango to its intended three modules of five glasses would finalize this first iteration of a fully automated glass harp. From there, slight modifications to increase the quality of sound could be done. Also, knowledge and insight from this version of Glass Tango could inspire a redesign that improves upon the work presented in this paper.

At the beginning of this paper, several questions were posed as goals to work towards answering. The progress and preliminary testing of GlassTango produced confidence in the team that it is possible for a robotic glass harp to create sounds similar to what humans can make when playing wine glasses. After more development iterations, Glass Tango would be playing an original composition with high note quality and ability to play complex harmonies and melodies. The team is also confident that, provided Glass Tango was completed, it could play music a human could not. Theoretically, Glass Tango could play up to fifteen notes at once, whereas a virtuosic glass harp player can play up to four glasses at once. Being able to play many more glasses than a single human opens up the possibility of more complex and creative composition potential when composing for a glass harp. These ideas have been possible to work with using virtual instruments and/or multiple players on physical instruments, but never by a single, physical player on a physical instrument.

8. MUSICAL USAGE

If Glass Tango used brushless DC motors instead of brushed DC motors to drive the belt rotating the glasses, this machine could participate in performances with other instruments and musicians. The sound produced by glasses resonating is quite loud, so it does not need an amplifier to accompany other instruments in an ensemble.

The sound that glass harps create is unlike any other instrument outside of its family. The notes that it creates have an eerie, piercing quality. When the pressure applied to the rim of the glass is just right, there are little to no harmonics resonating along with the fundamental frequency of the glass. This instrument is capable of backing up other instruments through harmony, or carrying the melody itself, as it is quite versatile.

For the team's final composition, a virtual instrument was created with very similar properties to that of Glass Tango. The piece had the harp line carry the harmony in the first section, then it traded off with another instrument to play the melody. Finally, the piece resolved with a chord sequence as both melody and harmony.

9. REFERENCES

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[2] C. Forster. *Glassdance Manual.* 2019.

[3] GlassDuo. Glass harp of the glassduo.

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[5] U. G. Survey. Earthquake glossary.

APPENDIX

A. BILL OF MATERIALS

Mechanical				
Part	Location	Qty	Price	Total Cost
12"x12"x0.25" Wood Board	Makerspace	8	$2.20	$17.60
PLA	Kyle / Makerspace	1000	$0.03	$30.00
Steel Truss Head Machine Screw, Zinc Plated Finish, Meets ASME B18.6.3, Slotted Drive, #8-32 Thread Size, 3/8" Length, Fully Threaded, Imported (Pack of 100)	Link	1	$3.05	$3.05
Steel Thread Rolling Screw for Metal, Zinc Plated, 82 Degree Flat Head, Phillips Drive, #8-32 Thread Size, 3/4" Length (Pack of 100)	Link	1	$2.95	$2.95
100 Pack 608-2RS Skateboard Bearing, Rolling Bearings, 8x22x7mm 608rs Bearing	Link	1	$19.96	$19.96
Steel Hex Nut (Pack of 100)	Link	1	$8.21	$8.21
M8 x 40mm Shoulder Bolt (2 Pack)	Lowe's	1	$1.58	$1.58
M8 x 40mm Bolt	Home Depot	13	$0.90	$11.70
M8 Washer (5 Pack)	Home Depot	3	$2.29	$6.87
M8 Nuts (First Batch) (4 Pack)	Lowe's	1	$1.48	$1.48
M8 Nuts (Second Batch)	Home Depot	11	$0.50	$5.50
Fun Express - Neon Swirled Bouncing Balls - Toys - Balls - Bouncing Balls - 48 Pieces	Link	1	$6.79	$6.79
BEMONOC Pack of 2pcs 2GT Driver Belt 1360-2GT-6 Timing Belt in Closed Loop Rubber L=1360mm W=6mm 680 Teeth	Link	2	$12.62	$25.24
Prime-Line 9131034 Machine Screws, Metric, Pan Head, Phillips Drive, M3-0.5 X 12MM, Grade A2-70 Stainless Steel, 10-Pack	Link	1	$3.07	$3.07
(Pack of 5pcs) Timing Pulley Wheel(16Teeth 5mm Bore) +Hexagon Wrench for 3D Printer 6mm Width Timing Belt(16T)	Link	1	$6.01	$6.01
Wine Glasses	Dollar Store	15	$1.07	$16.05

Electrical				
Part	Location	Qty	Price	Total Cost
Smraza 10 Pcs SG90 9G Micro Servo Motor Kit for RC Robot Arm/Hand/Walking Helicopter Airplane Car Boat Control with Cable, Mini Servos Arduino Project	Link	1	$19.74	$19.74
Miuzei 10 pcs SG90 Servo Motor, Micro Servo 9G SG90 Kit for RC Robot Arm/Walking Helicopter Airplane Car Boat Control, Micro Servos for Arduino Project	Link	1	$14.89	$14.89
Brushed DC Motor	Link	3	$14.86	$44.58

Final Cost:	$245.27

Items Used But Not Accounted for in Bill of Materials:
Arduino Mega
Breadboard
Jumper Wires (M-M, M-F)
Assorted Screws / Spacers / Washers / Standoffs
VEX Rubber Joints (3)