Mechanical Design Methodology - Final Report

Quaid Murray, Zoe Meyer, Christian Torres,
Francisco Lara, Steven Yeung, Neil Ricamata

Walker Department of Engineering
The University of Texas at Austin
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1 Project Introduction

Autonomous instruments go as far back as 1810 when Friedrich Kaufmann created his autonomous trumpet player (Vintage Everyday, 2020). Today, there are several ongoing efforts towards music research to innovate and create novel musical instruments. Our objective for this project was to design and manufacture an automated musical device with a budget of $250 that can play at least three (3) songs or tunes. As identified from our customer needs analysis conducted in the project proposal phase, we concluded that our instrument should be optimized in both form and function, be applicable in a wide range of educational purposes, and produce high quality sound with minimal background noise.

After choosing to use a steel tongue drum because of its novelty, compact size, percussive sound, and low price point, each member of the team generated design concepts that used various materials and operation mechanisms. Following the guidelines laid out by the customer needs analysis and considering the difficulty of engineering each concept relative to cost and time constraints, a leading concept was chosen. Our chosen design relied on the mechanical mechanism of a mallet striking an individual note on the drum through solenoid actuation.

We analyzed and reviewed the efficacy of our design through low-resolution prototyping, 3-D modeling, failure method analysis, finite element analysis, and in-person experimentation and testing of our functional prototype. Reviewing all collected data through the entirety of this project, we finished with a functional prototype of an automated steel tongue drum that uses a limited number of inputs and eight (8) independent mallet stands and solenoids to play three (3) recognizable songs with adequate volume and clarity.

2 Project Proposal

2.1 Introduction

For our project proposal, we conducted background research regarding various types of music instruments and how they can be automated. We followed our research with customer interviews to gain insight into the needs of our customer base and required metrics for our final product. From our customer needs analysis, we identified the following as the primary goals for our product: the automated instrument must be optimized in both form and function, produce high fidelity sound, and be able to be used for a wide range of educational purposes.

2.2 Background Information

Automated musical instruments date back decades and were originally intended to provide interesting performances. Over time their uses have extended to the commercial sector where they can serve as attractions, entertainment, or toys. In addition, they can be used as a teaching tool for beginner players (Kapur, 2005). Different types of musical instruments ranging from wind, percussion, and string instruments have been automated in one form or another. All figures referenced in the following section can be found in Appendix B.

For brass instruments, creating sound is complicated. As with other wind instruments, brass instruments require specific air flow into the instrument. In particular, they require buzzing lips. Uri and his team (Shaked, 2018) demonstrated that air flow can be added into the instrument to create sound, although the sound is choppy and untuned. Artificial lips and a chamber are required to replicate the air flow from the human mouth into the instrument. One low-cost method to replicate the lips is to use latex tubes filled with water, as seen in Figure B.1 (BBC News, 1999). These artificial lips solve the 'buzzing lips' problem by creating vibrations within the airflow that enters the instrument. As noted by Uri, the airflow from the air pump is inconsistent, thus, adding a chamber with artificial lips and the instrument's mouthpiece helps fix the airflow problem. Replicating the airflow needed to autonomously play a brass instrument is achievable, however, it is complicated. Referencing the setup from Figure B.1, both the pressure of the water inside the lips and the gap between the teeth can be adjusted to create different tones. Creating an autonomous brass instrument would require a high amount of fine tuning to achieve the desired music output.

Moving on from brass instruments, woodwind instruments can present similar issues. Woodwind instruments use reeds on a mouthpiece to create the vibrations that subsequently create sound. This requires a human embouchure and may require a similar solution to that presented for the brass instruments, such as latex tubes filled with water to produce an autonomous sound. A different solution is to create an acoustic impedance converter from a solid brass rod which would require a design similar to the one shown in Figure B.2 (Raes, 2013-2014). This idea uses a membrane compression driver followed by the acoustic impedance converter that is designed with double coned design with a capillary connecting both of these cones. For the valves that are used to modulate the pitch of the sound, solenoid driven pads can be used to better open and close the tone pads (Raes, 2013-2014). Overall, we found that automating or replicating woodwind instruments could present complicated, and possibly costly, challenges in creating desired sounds.

As for automating string instruments and percussion instruments, it is much easier to imitate human playing. As opposed to wind instruments, string and percussion instruments are actuated with only physical touch, whether it be plucking, hitting, and/or sliding. As seen in Figure B.4 and Figure B.5, the use of a motor, servo, or solenoid can simulate the plucking of a guitar or the hit of a mallet on a xylophone, respectively. Furthermore, relying on servos and motors decreases the amount of background noise the instrument makes and the time it takes for the note to resonate, presenting important benefits in the production of high quality musical sound.

Our team also came across the Wintergatan marble machine, which is a hand-cranked, fully wooden music machine that uses 2,000 marbles as the percussive actuators of an implemented vibraphone (see Figure B.6). The marbles are circulated within the machine in a rather complex way, but the idea of using marbles to create sound is not an entirely unique one. The novelty of the Wintergatan marble machine is its ability to control the movement of the marbles to produce organized and controlled musical responses (Lewis, 2016). This invention opened our team up to the possibility of using free-falling objects, such as marbles, as the actuators for string or percussion instruments. Looking into the possible microcontrollers that can be used for this project, our team compiled options such as Arduino, NodeMCU, Teensy 3, MSP430, etc. However, we ultimately decided to use an Arduino because the programming is simple compared to the off-the-shelf microcontrollers. More specifically, the main benefits of Arduino: open-source, free, cross-platform software based on popular, well-known languages Wiring and Processing with a low barrier of entry (Sandhu, 2021). Additionally, due to required coursework within the Mechanical Engineering department, everyone in the group owns an Arduino microcontroller and has experience using the software and hardware through completed lab work.

2.3 Gantt Chart and Task List

We made a Gantt chart, table A.1, to plan out the entirety of the project. We assigned reasonable dates for each task that needs to be completed based on deadlines listed on the project handout. Alongside the Gantt chart, a task list, table A.5, was created which further breaks down each task included in the project proposal phase of the Gantt chart. Both of these items are living documents and are updated to reflect the project's progress and any additional tasks that are discovered during the development of the product. The Gantt chart and task list for this section of the project can be found in Appendix A.

2.4 Customer Needs Analysis

As automated instruments are sparse and follow a niche market, it was in our best interest to conduct interviews to gauge the public's perception of our project. We asked ten (10) people of various backgrounds a personalized set of questions (Appendix C.2) to get as much relevant information of what our target audience wants and needs in an automated instrument. The interviewee list, interview questions, and all relevant interview transcripts and notes are given in Appendix C. We weighed each category based on the number of recurring responses to establish the importance of certain features. These weighted categories were assembled into a Customer Needs List, provided in Appendix D. To start, we categorized our interviewees into four groups: educators, K-12 students, robotics professionals, and musicians. Our reasoning behind this was to narrow down our list of specific questions so that we could get information pertaining to each group. In compiling all the interviews together, we found that our customers' responses followed similar needs of colorful yet sleek aesthetics, the ability to play popular music, the potential for teaching capabilities, an affordable cost, a simplistic user interface, an adequately portable and compact shape, low maintenance requirements, and proper safety considerations.

Since our target teaching audience is a range from K-12th grade, it is important that our interviewees have an association with this age bracket. We found that a younger audience preferred an instrument that was colorful and visually vibrant. One of our responses from a 7-year old noted that her "ukulele has different color strings, so that's why (she) like(s) it a whole bunch." (Appendix C, Interview 1) From this insight, we noted that colorful designs cause children to gravitate towards certain instruments and would help incite interest in playing and/or learning this instrument. Our older audience preferred a minimalistic and sleek design. From these responses we decided it would be best to avoid convoluted creative designs in favor of a more minimalistically colorful aesthetic to highlight certain aspects of our product.

Related to the aesthetic of the device, many of the educators that were interviewed during our customer survey conveyed similar interests in terms of the size, maintenance, and safety of the product. More specifically, they requested a device that is sufficiently lightweight for an average woman to carry by herself, is compact enough to fit in a shelf or on a table, is relatively easy to set up and maintain, and is equipped with the proper safety labels and equipment. In other words, educators want a safe device that can be easily used and maintained within a classroom environment. Not only is it important to have a condensed and visually appealing design, but another attraction of this product is the sound quality and music choice. The responses of our audience reflected the design need of our product to produce minimal parasitic noise, resulting in high fidelity sound. Interviewee responses also supported the necessity of choosing widely recognizable songs for the device to play to aid in audience engagement.

In terms of functionality and user-interface, our interviewees suggested our device have user-actuated inputs, giving the device an extra element of user interaction. Interviewees made it clear that the user-inputs should not be overly complex, and that the device should be simple to operate after a basic, easily-followed tutorial. This user-interface also gives our team the opportunity to layer instruments within the device, using one instrument as the actuator of a separate music instrument. For example, piano keys could be used as both the user-interface and the actuator to produce the response of a mallet hitting a xylophone. This aspect of user-interfacing can open doors for disabled students that don't meet the physical or mental requirement to play an instrument in the traditional way. One of our highest weighted features pertained to the performance of this product. It was made clear in our responses that robotic music is often seen as mundane. People, "would like to see a robot add emotion or color to the music it's playing." This is what separates live music from heavily programmed music. To solve this issue we decided on incorporating a way to add volume dynamics and time fluctuations when playing a tune.

Finally, our interviews suggested that music departments would only be willing to pay, at most, $150-200$, with most responses hovering around the $50-$100 mark. Since we are dabbling into a very specific market, product pricing is not overly important to the design of the device, as the originality of our musical instrument means that we do not have to worry about financial competitiveness. That being said, our instrument cost should be as minimal as possible due to stringent budgets within K-12 school districts, and the device may need to be priced according to specific, targeted clients rather than an entire school department.

2.5 House of Quality

Using the customer needs list, our team was able to determine the most important needs of the customer and how these could be translated into the product design. With this information, we assembled a House of Quality (HoQ)–given in Appendix E–to categorize these needs and assign metrics. These needs were classified into one of the following categories: aesthetics, performance, music, shape/size, cost, user interface, and safety. We concluded that for most needs a quantifiable measurement can be mathematically determined using common laboratory instruments or through the use of computer software like computer-aided design (CAD) models and/or finite element analysis (FEA). For example, background/parasitic noise can be quantified using a common decibel meter, while robustness of the product can be determined using FEA predictions and safety factor calculations. Other metrics are not so easily quantified, like aesthetics, recognizability of the song, and safety risk. For these needs, we decided to conduct measurements through customer surveys, assigning each subcategory a final quantifiable rating out of 5 total points. In this way, an opinion based need can be numerically measured and given a range of acceptability.

Unfortunately, due to the novelty of our product, comparable product competitors do not reliably exist. Therefore, we were unable to perform product comparison within our HoQ. Without the benefit of product comparison, we consciously determined target metrics for each need assignment. Our team was then able to use these target metrics to help us determine design requirements in the Engineering Requirements and Specifications section of this report (Section VI).

2.6 Engineering Requirements and Specifications

From the information that we were able to gather from customer feedback and background research, we were able to create a list of engineering requirements and metrics that we could use to assess our product. The requirements list, given in Appendix F, utilized valuable information from the House of Quality (Section V).

Understanding the practical limitations of our time frame and student resources, determining whether a requirement was a demand or a wish was difficult. For example, a struggle we had was determining whether minimizing the weight and volume of the device should be a demand or wish. However, looking over and discussing our customer feedback, we felt that both the compactness and weight of the device was a wish.

The verification tools that we plan on using include customer surveys, common Decibel meters, computer-aided design (CAD) models, finite element analysis (FEA), and simple product tests. The CAD modeling tool will be particularly important during the design phase of the project because it will provide insight when attempting to reach our volume, weight, strength, compactness, and safety goals.

2.7 Problem Statement

The overall goal of this project is to design and prototype an automated musical instrument to demonstrate an array of engineering principles to a K-12 audience. Our focus is to play at least three (3) different recognizable songs and/or rhythms via automated, mechanical means. From collected customer insights, we ascertained that our primary needs for this device are to produce high fidelity sound, minimize complexity of use and maintenance, optimize device portability and compactness, and create a novel product that can be used for educational purposes across a wide range of academic levels. We will explore percussion instruments actuated in unique ways such as with free falling objects or through precise rotational mechanisms.

3 Design Review

3.1 Introduction

In this design review, we outlined our project by creating a black box model and function tree. From there, we conceptualized designs using two (2) distinct concept generation methods – a mind map and the 6-3-5 method. This resulted in several possible concepts which we summarized into a morphological matrix. Each member of the team used a different pathway within the morph matrix to create their own distinct concept and sketch. Sketches were compared using rough calculations and three (3) different Pugh charts, and two (2) leading concepts were chosen. The entirety of this design review process is detailed in the following chapter.

3.2 Functional Modeling

The black box model shown in Figure G.1 outlines potential inputs and outputs of our automated instrument. For our system, the energy inputs are electrical energy (EE) or mechanical energy (ME). The energy output consists of noise and heat. We selected these energy inputs as they are feasible forms of supplying energy to our system. This energy would be transformed into sound produced by the instrument and heat from various components (e.g. servos, solenoids, etc.).

As our system is automated, the only material inputs would be someone interacting with the system and providing falling objects (e.g. marbles) into the system. The material outputs would be identical to the material inputs assuming the falling objects are not recycled within the system. The signal inputs are on/off switch, buttons, and program (e.g. computer program). These inputs result in on/off indication and song selection. For the user to interact and communicate with the system, we selected the listed signal inputs. These inputs would provide a clear indication of whether the system is on or off as well as give the user the ability to select a song to be played by the system. The functional model shown in Figure G.2 aims to achieve the following main goals: a system which plays an instrument, a user interactable system, and a system which creates high fidelity sound.

For the system to actually play the instrument, we broke down this goal into five subfunctions: supporting device, importing power, converting electrical energy to mechanical energy, converting mechanical energy to sound, and note selection. As our instrument is automated and must include electrical components, power must be imported to provide electrical energy for the system to function. For the energy to interact with the system, a component must convert the electrical energy into mechanical energy. The mechanical energy must then be utilized to produce a sound from the instrument itself. A mechanical mechanism must also be implemented to select the specific note the instrument will play. Lastly, a structural framework must house the instrument itself and require components for the system to play the instrument.

To create a user interactable system, two sub-functions were established: input selection and signal input. Input selection is how the user interacts with the system itself. The system can then communicate with a signal input method which relays the signal to a computer. The noise dampening sub function was added onto the functional model after we selected the steel drum as our instrument to create high fidelity sound. The steel drum has a slight ring after being struck which can be minimized by incorporating a damping mechanism.

The main sub functions that would benefit the most from creative idea generation are the subfunctions used to play the instrument. Specifically, the convert EE to ME, convert ME to sound, and select note subfunctions. There are countless amounts of different methods and combinations that can be established from these sub functions and there are no straightforward solutions. Creative idea generation would limit far fetched ideas and establish realistic ideas.

3.3 Creative Idea Generation Concepts for Critical Sub-problems

Our team employed two distinct concept generation methods to help inform our morphological matrices and subsequent final concepts (see Design Review Section V): mind mapping and the 6-3-5 method. Our resulting mind map as shown in Figure H.1 was a result of verbal idea generation where our team considered each sub-function specified in the functional model (Figure G.2) and freely brainstormed any possible solutions to the problem. The ideas generated came from the background research and customer interviews conducted in the project proposal, prior musical experience, and basic engineering principles. Through mind-mapping, our team was able to visualize which sub-functions allowed the most amount of innovation, such as converting electrical energy to mechanical energy, converting mechanical energy to sound, selecting notes on the instrument, and supporting the device structurally. We created a mind map with all sub-functions and their solutions stemming from the central function of automating an instrument.

We also utilized the 6-3-5 method for further concept generation, the results of which are presented in Figures H.2-H.7. Within the scope of our 6-3-5 rotation, we noticed that our edits mainly consisted of questions regarding the feasibility of the design. Sometimes these questions were the result of a misinterpretation of the sketch or of the capabilities of the instrument, and interestingly, these misinterpretations often brought up relevant design concerns and/or redesign ideas that proved beneficial for the final concept sketches in Appendix K.

For example, one member thought the steel drum had a note in the center of the dome and brought up concerns about the range of motion of the mallet actuators being too limited to strike the note sufficiently, which although not relevant for the nonexistent center note, is extremely important for the striking of all the notes around the circumference of the drum. For another concept, it was misunderstood that the drum was to rotate as mallets dropped from a stationary place above the drum, and the question of the feasibility of the marbles to hit subsequent notes quickly and smoothly was called into question. While the design allowed for note changes through drum rotation, the question prompted our team to wonder if the drum could rotate quickly enough for the song to sound cohesive and smooth or if significant "readjustment" pauses would exist between each note strike. Utilizing the results of our mind map and 6-3-5 concepts, we were able to fill in a morphological matrix and create six (6) distinct, fleshed out concepts as described in the next section of this report.

3.4 Prior Art

One of the important sub-functions of our system is signal input. In several of our concept designs, the signal input is handled by an Arduino. Components such as servos, solenoids, etc. feed into the Arduino and can then be controlled by a computer program. To enable this process, a breadboard can be used as an intermediate. In addition, the breadboard allows for multiple components to be wired at once. An example circuit is showcased in Figure I.1.

When exploring the conveyor belt mechanism for marble recall as part of Concept A, the issue of how to remove the marbles from the top of the conveyor belt arose. A currently existing design that could be utilized is that of the Wintergatan Marble Machine, shown in Figures I.2 and I.3. The machine lifts the marbles up via a conveyor belt with wooden treads that have a series of slits along their width that correspond to the prongs of the marble "grabber" at the top of the belt. In this way, the marbles are raked off the treads and dispensed for further marble release, passively using the movement of the conveyor belt itself to unload the marbles.

Another existing idea we could implement for marble recall includes a helical elevator. Ideally 3d printed, the design shown in Figure I.4., shows a method to turn rotary motion into a vertical marble lift that fits within a compact space, great for reducing our final instrument footprint.

3.5 Morphological Matrix

The morph matrix shown in Table J.1 combines the sub-functions generated from our functional model and the ideas generated through our mind-map and 6-3-5 work into an organized table. The morph matrix is composed of a column containing our sub-functions and a large general solution block to list methods that address a given sub-function. For example, for the sub-function of "convert electrical energy to mechanical energy," we identified five (5) possible solutions: the use of a servo, motor, piston, linear actuator, or solenoid.

Using the completed morph matrix, each group member picked one solution from each sub-function row to generate a "mix-and-match" concept, shown in Tables J.2-J.7. Because each morph matrix pathway was different for all group members, the result was six (6) distinct concepts, labeled Concept A-F. Concept A (Table J.2 & Figure K.1) is based on the mechanism of falling marbles to actuate notes on the steel drum. Using a basic wall plug, two (2) servos are powered, rotating a conveyor belt that takes rubber marbles from below the instrument to above the instrument, where they are time-released based on the action of a solenoid that adds/removes the cover on a small rubber funnel. To change notes, the steel drum is methodically rotated using another servo, presenting a new note for the falling marble to hit. The three (3) servos and the solenoid are controlled by an Arduino, and the "used" marbles are collected by a large rubber funnel that feeds back into the bottom of the conveyor belt. Both the belt and the steel drum are supported by an aluminum bar frame. While this concept would be visually appealing, it is fairly complex in the large number of required parts and the difficulty of timing all mechanisms to work cohesively. Also, the conveyor belt must be tall enough to drop the marbles from an acceptable height, increasing the boundary dimensions of the device.

Concept B (Table J.3 & Figure K.2) revolves around the use of solenoids to produce sound. The steel drum is surrounded by a frame that holds eight (8) solenoids; one for each note on the steel drum. The solenoids sit directly above the notes of the steel drum. The solenoids are controlled by an Arduino and extend to strike different notes on the steel drum to produce sound. One of the main advantages of this design lies in its simplicity. No rotating parts or complex recall mechanisms would be required. Compared to the other concepts, it is likely the easiest design to build. However, this results in a relatively less novel and challenging design.

Concept C (Table J.4 & Figure K.3) focuses on the use of servos connected to multiple mallets (one on each note) to strike the steel drum. By having a mallet for each note, we can avoid rotating the drum or mallets, which leads to a more stable and efficient design. Notes can be played simultaneously without delay, which is a problem in other concept designs. However, with the use of servos, the mallets will be unable to rebound off the drum, thus preventing the drum from vibrating properly. Concept D (Table J.5 & Figure K.4) revolves around the utilization of marbles dropped from two (2) crossed ramps and a continuous servo to control the frequency of marble drops. Balls are released from the top of each ramp and hit the desired note. The marbles are then caught into a collection zone and funneled into the recall system which consists of two (2) helical elevators. An advantage of using a ramp system instead of a free-falling system is that the angle of bounce can be manipulated based on where the ramp is aimed, leading to a more predictable trajectory. However, this system shows its faults when accounting for actuation speed. Depending on the ramp angle, length, and height, the delay changes from the release point of the marble to the actuation of the note. This might lead to heavy timing struggles when integrating both the marble release and the rotating drum.

Concept E (Table J.6 & Figure K.5) is also a free-falling marble concept. The steel drum is held by a 3-D printed ramped frame that collects the marbles after falling onto the drum and directs them towards a helical elevator. The elevator carries the marbles to a 3-D printed collector above the steel drum. The collector is shaped as a funnel with eight (8) slots. Each slot can hold three (3) marbles and the remaining marbles are resting above the slots, such that they will fall into the slot that drops a marble. At the end of the slot, there is a servo that, when stationary, will hold the marble from falling and then will rotate to release the marble into the note. Concept E is not only very unique, but is also relatively simple when considering the required number of parts and the work required to build the prototype. Like the other free falling marble concepts, though, the issue of marble accuracy, timing, and recall present significant challenges to the feasibility of the design.

Concept F (Table J.7 & Figure K.6) is designed similar to Concept C. However, rather than using servos to rotate the mallet to strike the steel drum, Concept F uses solenoids to strike the steel drum. The solenoids are located in between the pivot point and the steel drum because the solenoid when activated will pull the mallet shaft down. The structure design currently consists of eight (8) identical 3-D printed structures surrounding the steel drum with eight (8) solenoids and mallets paired with the structure. One disadvantage of individual structures is that they will not maintain position after striking the drum repeatedly. The advantage of using solenoids over servo motors is that a solenoid does not maintain position on the steel drum and only briefly strikes the steel drum allowing the drum to vibrate correctly. In addition, Concept F uses a dampening sock instead of a resting mallet to dampen the sound.

3.6 Pugh Chart

To evaluate our six (6) morphological solutions, we utilized a Pugh Chart (Appendix L) with three different (3) datums. We chose the three (3) datum based on the three (3) different mechanisms of playing the instrument: falling marbles, rotational servos, and solenoids.

To analyze the different solutions, we looked into the cost, volume, mass, setup/disassembly, impact force, and the total number of parts, which came from our engineering requirements list and customer needs analysis. We are interested in the total cost since we need to remain under the $250 budget. From our customer needs analysis, we learned that teachers want a machine that is easily storable and portable. Thus, we want to minimize the volume and mass to maximize portability and storability. Another insight gained from our customer needs analysis is that teachers do not want to spend much time setting up and disassembling the machine; hence, we want a machine that does not require a setup other than turning it on. For safety reasons, we used back-of-the-envelope calculations, which can be found in Appendix M, to estimate the impact force, since it can be dangerous if someone puts their hand inside the system. To estimate maintenance, we use the total number of parts as a metric as having a few parts eases maintenance complexity.

From our Pugh Chart, we selected our two leading concepts. These were Concept E (free-falling marbles) and Concept F (multiple mallets & solenoid). One of the main reasons for choosing Concept E is the unique design. During our customer interviews, we received a high demand for a unique way to play an instrument to intrigue children. Nonetheless, Concept E has a simple design. It has the lowest total part number of our morphological solutions, which minimized cost, maintenance, and construction complexity. One of our greatest concerns for this design is the distribution of marbles from the refilling mechanism. If a given note is played too many times, there exists the scenario that there are no more marbles on the slot for that note. To eliminate this scenario, we will need to design a funnel that will refill the slots even in that scenario. Another concern is the trade-off between loudness and accuracy. The higher we drop the marble the louder the note will be played, but the accuracy of the marble will decrease. Additionally, if there is a high ambient airflow, it will affect the accuracy. Thus, it limits the environment in which the machine can be used.

Our second leading concept, Concept F, was also very straightforward and efficient. It utilized one mallet for each note on the drum so different notes can be played simultaneously without delay. The design is similar to Concept C but differs by using solenoids instead of servos, which will allow the mallets to rebound off of the steel drum compared to slamming the notes and dampening the sound. The concept design also has very few moving parts compared to the other concepts that have falling mallets and rotational mechanisms, making it much more stable and sturdy. However, due to use of solenoids, the design becomes one of the more expensive and heavy designs we have. Even though it has those cons, the difference in price and weight is not considerable enough to affect our decision, making it one of the lead concepts of our Pugh Chart.

3.7 Low-Resolution Prototype

For our low resolution prototype (Appendix N), we decided to pursue concept E as most of our questions pertained to the feasibility of dropping marbles onto a drum. Specifically, how high do we have to drop the marbles to create a sound and how will we collect the marbles after a note is played? Since we wanted a material that was cheap and easy to manipulate, we chose cardboard and tape as our construction media.

To start, we split up the concept into three (3) subsystems: the dropping mechanism, note selection system, and the catching/retrieval basket. In constructing our dropping mechanism, we hoped to achieve a consistent ball path and a mechanism that released one marble at a time. We found that dropping marbles led to large inconsistencies in landing zones. Dropping too high caused a sporadic trajectory and releasing too low meant double hits of the drum. Our solution to this was to design a release ramp to guide the marble and change the bounce angle (taken from Concept D). Added onto this was a marble deployment system modeled with a toothpick and cardboard gear, to control note tempo which will be actuated by continuous servo. For the second subsystem, we decided to model this with a large cardboard base that can house the drum and a motor. Finally for our catching and retrieval mechanism, we created a large funnel made of cardboard and paper that channeled the marbles underneath to a collection zone which will then be reloaded to the top.

Upon finishing our prototype, we wanted feedback from our prospective customers and robotics professionals. We demonstrated our design on video, as well as in person, showing how our product worked, and collected ideas and concerns they had with the prototype. Our responses were overwhelmingly positive, with many noting the marble drop design to be an intriguing concept and the ability to recycle the marbles to further enhance the novelty of our product.

Most of our concerns came from the robotics professionals. First, the delay of each note is heavily influenced by the angle and distance of the track. They suggested accounting for the time delay using kinematics equations and to consider releasing the marbles farther down the ramp, minimizing travel length. Another big concern was how fast and accurate we could actuate the instrument. Since there is only one dropping point, the drum has to rotate at a high angular velocity, posing problems of note speed and motor overshoot. Knowing this, we have to design a feedback control system for the drum motor and consider adding an additional ramp onto the design to cut the distance traveled by the drum in two.

3.8 Next Steps

Referencing our Pugh Chart, Concept E (free-falling marbles) and Concept F (solenoid actuated mallets) were our highest scoring concepts. The uniqueness of Concept E with its free falling marbles to actuate the different notes of the steel drum comes with certain drawbacks such as practicality. The high number of marbles necessary to play the instrument would require a mechanical recall mechanism or large quantities of marbles paired with a refill tray. However, our low resolution prototype highlights the novelty of an instrument played with marbles and would help achieve important customer needs such as aesthetics and performance. Items of concern regarding Concept E moving forward include recall mechanism, accuracy and consistency of falling marbles, and novelty.

Conversely, Concept F (solenoid actuated mallets) is a more practical way to play the steel drum. However, because of this practicality, the concept is not as novel and unique as Concept E (free-falling marbles). Looking forward, fine tuning the solenoids to actuate the mallets using the arduino board as the input signal function and designing the 3-D structure can be developed easily. In conclusion, Concept E and Concept F are our two leading designs based on the input of the pugh chart and low resolution prototype and our team will create and review new and existing designs to further lead us to the best design.

4 Final Prototype

4.1 Introduction

In our design review, we decided to pursue a design that utilized individual mallet assemblies to actuate a single note on the steel drum. The mallets were to be operated using solenoids and counterweights. Despite deciding on the basic functionality of the device, we still needed to generate ideas for exactly how the mallet/solenoid stands should be manufactured and assembled to reduce the possibility of failure and enhance the quality of performance. Within this chapter of the report, we will discuss how we arrived at our final design using our leading concept and Failure Mode and Effects Analysis (FMEA). We fine tuned the functionality of our product using Finite Element Analysis (FEA) and Design of Experiments (DoE) to guarantee our product would be able to repeatedly produce high fidelity sound with limited potential for failure. We considered the ease of use, assembly, and disassembly of the product as well as its environmental impact through Design of Manufacturing (DfM), Design of Assembly (DfA), and sustainability consideratranstions. Finally, we produced a working prototype of an automated steel tongue drum that resulted from the iterative design and prototyping process to be described in the following sections while also meeting the size, operation, and safety requirements set by the customer in chapter 2.

4.2 Leading Concept

Reflecting on the two leading concept designs, Concept E (free-falling marbles) and Concept F (multiple mallets & solenoid), we decided to move forward with Concept F. This design concept was simple, efficient, and reliable. We believed that the simplicity and reliability would satisfy the design requirements of being lightweight, compact, minimalistic aesthetically, and easy to assemble and disassemble. Conversely, Concept E would not be as compact and minimalistic due to the height required to drop marbles effectively. Concept E would also be reliant on a refilling mechanism that would resupply the marbles at the top of the steel drum to be able to actuate notes. This might lead to an issue where there may not be a large enough supply of marbles to quickly play a note multiple times repeatedly. The only moving piece in Concept F is the solenoid-mallet subsystem that simply actuates up and down to play the note. We also felt that using the mallets instead of the marbles to play the instrument would be a more intuitive way for a K-12 audience to learn how to play music, as in real life musicians use mallets and not marbles to play steel drums.

As shown in Figure O.1, the design uses eight (8) independent mallet-solenoid stands placed in a circular fashion around the steel drum. Each of the mallet-solenoid stands is aligned with a particular note. This design allows us to play multiple notes rapidly or even play multiple notes at one time since each of these notes have independent solenoids paired with each note. The most critical part of the design is the solenoid mallet subsystem. It was important to ensure that this system functions properly to guarantee a high fidelity sound with low amounts of operational noise. This design uses a pivot point that utilizes a 3D printed part that is friction fit to the mallet. This mallet is connected to the solenoid with hand-tied fishing line. Knowing that our solenoid was a pull solenoid it was important that we have the solenoid on the inside of the pivot point so that when the solenoid pulled downward it would also pull the mallet head downward. This distance helps create a moment around the pivot point when the solenoid is actuated and the tape acts as an adhesive to hold the fishing line in that one spot. Notice that in Figure O.1, on the opposite side of the pivot point exists a rectangular prism counterweight. This counterweight serves to rotate the mallet back to its resting position after the solenoid is actuated. This helps the steel drum continue to reverberate after the mallet head hits the note because the mallet head does not continue to rest on the steel drum but simply bounces off. The fishing line also helps serve this purpose because it is elastic and lightweight which allows the mallet to “jump” off the steel drum as opposed to an inelastic rod which would pause on the drum and kill the steel drum vibrations.

Now that we knew which concept we were moving forward with, we decided to start distributing tasks from the Gantt chart and making deadlines. Some of the tasks that we needed to complete included updating the Gantt Chart, creating CAD sketches of the prototype, producing a preliminary draft of the Failure Modes and Effects Analysis (FMEA) table, ordering parts, and building a functional prototype of at least one critical subsystem. During the entire process, our team was constantly updating our Gantt chart to ensure that the changes that we were making to our designs would continue to work with previous designs that we had made or parts that we had already purchased.

4.3 Preliminary FMEA

The Failure Modes and Effects Analysis (FMEA) table shown in Figure P.1 examines failure effects in some of the major design subassemblies and components and was conducted on the leading concept shown in section II of the final report. The modes of failure range from structural, timing, or electrical related issues. These failure modes result in failure effects which can be categorized into the following: mallet related and/or sound related. To assess the potential for risk, a risk priority number (RPN) was calculated for each mode by multiplying the degrees of severity, occurrence, and detection together.

Analyzing the FMEA table, many of the failure methods listed possessed relatively low risk (i.e. low RPN values). This stems from the simplicity of the design itself. With our design, many of these failure methods are easily detectable as they can be seen visually or heard audibly. The failure methods with comparatively high risk stem from high occurrence. The issues with high occurrence are related to the positioning of components and subassemblies relative to one another.

The component with the highest risk priority number value was the counterweight. The counterweight is integral to our design, and failure would effectively result in the device being dysfunctional, as our mallets would be immobile and incapable of pivoting with improper counterweight consideration. In our preliminary design, we had a system that allowed us to add or subtract weight as necessary to change the moment on the mallet pivot. This gave us a RPN of 140, meaning our current processes would not be sufficient for our final prototype. The suggested remedial measure to rectify this high failure risk was to implement a system or structure capable of being moved to a variable location along the mallet, effectively varying the moment on the mallet pivot. This reduced the amount of necessary components for this system, because only the location of the counterweight would change, not the counterweight itself. The component with the second highest RPN was the mallet, with the risk of the mallet sliding during operation being the most critical. In the same vein as the issue with the counterweight, when the mallet slides, it effectively changes the pivot location and therefore the moment on the mallet pivot. This does not always result in a dysfunctional product, but does lower the quality of sound to an unacceptable degree as the mallet can stop making sufficient contact with the steel drum at certain pivot locations. Our current process of wrapping the mallet pivot location in a high friction material at the pivot interface was not sufficient, so we suggested that we design a structure capable of attaching the mallet to the stand via a fastener assembly, allowing the mallet to be clamped into place using a tightening fastener. Additionally, the fastener, such as a screw, could act as a metal, low friction, pivot dowle for the mallet system.

The other systems analyzed in Figure P.1 showed RPNs that were insignificant compared to the counterweight and sliding mallet risks. This informed us that the majority of our design consideration should be focused on the counterweight and mallet pivot systems.

4.4 Design of Experiment

The goal of our experimental design was to determine how certain factors affect the sound quality and noise level of our instrument. The following factors, counterweight weight location, striking area, and string length were selected as they were hypothesized to possess the largest influence on sound quality and noise level. Each factor had an established low (-) and high (+). For the weight location, the low value refers to the counterweight, or battery in our design case, being flush with the weight holder. The high value pushes the battery toward the pivot point 6.50mm. The striking area low and high values were simply two distinct striking positions on the steel drum itself. As for string length, the low value was the minimum length required, 24.1mm, and the high value was an additional 10 mm of string, or about 34.2 mm.

The experiments were conducted in an isolated, quiet room to minimize any form of background noise. The experimental procedure was the following: the factors were first modified to respective high and low values, totaling eight different combinations. Once the combination was set, the solenoid activates to pull the mallet and strike the drum. The noise level is then instantaneously measured by a smartphone decibel meter application. The sound quality was qualitatively measured by the group on a one (1) to five (5) scale, with five (5) corresponding to a high quality sound. The procedure was repeated three times for every combination.

The resulting plots from the gathered data are shown in Appendix Q. From the main effects plot (Figure Q.1), the two main factors that influence noise level are weight location and string length. This is also supported by the regression as both factors are statistically significant as they possess a p value less than 0.05. As for sound quality, all factors are statistically significant and have some form of influence. These relationships can be seen visually in the cube plot (Figure Q.9). Since every factor is important, any parts that control these factors must be easy to fabricate and modify to allow for simple adjustments/fine tuning of these factors.

4.5 FEA Analysis

The constructed finite element analysis (FEA) model examines an extreme use scenario in which a K-12 audience member places their full weight on top of the acrylic platform. Since the acrylic platform is not supported centrally, it is important to determine if an extreme use case could potentially permanently warp the platform. To examine this, the results of interest are the maximum stress and displacement.

For the analysis, it was assumed the full weight corresponds to a load of about sixty (60) pounds. To produce the most accurate results, the finest quality mesh was utilized when conducting the simulation. As for boundary conditions, they were chosen to be fixed boundaries at the contact points between the two by fours and acrylic platform since they are joined together by an epoxy. In addition, it was assumed that the simulated load would be confined to the area in which the steel drum rests. This would mean that a student places their full force on the drum itself which is transferred to the acrylic material.

Analyzing the results from Figures R.1 and R.2, the maximum stress and displacement were within reason. The maximum stress experienced is less than that of the material's yield strength as shown in Figure R.1. This implies that, after experiencing the sustained load, the acrylic material will return to its original position. The simulated deflection was within reason and was on the same order of magnitude as the analytical calculations found in Figures R.3-R.5. From the FEA, it can be concluded that the current design is able to withstand the extreme case of a sustained sixty (60) pound load. If the design were not able to withstand the load or a heavier load was utilized, in other words, if permanent warping was an alarming issue, wooden braces could be implemented to reduce the stress experienced by the acrylic platform.

4.6 Updated Leading Concept

After completing the design and construction of our first prototype and completing our FEA analysis, two updates were made to our preliminary design. One of the updates made to our leading concept design was to add an extra level to the design. As shown in Figure S.3, the design consists of two levels: a bottom level made out of plywood and an acrylic top layer which are connected via wooden 2x4s. The first level houses the breadboard/circuitry and the Arduino microcontroller while the top level houses the steel drum and the surrounding mallet solenoid stands. The reason for utilizing differing layer materials is for educational benefits and to facilitate electronic cooling. The clear acrylic panel on the top layer allows for students to view the circuit board and the Arduino device to understand the engineering behind the instrument's electronics.

The other change made was to the mallet solenoid stand. We noticed during our initial critical subsystem test that the solenoid had a tendency to heat up and stop working due to repetitive use. This led us to create a design that allowed for air flow around the solenoid to cool it down. By doing this, we are ensuring that our instrument receives proper cooling to continue to function properly and produce high sound fidelity. This design is shown in Figure S.8.

4.7 Design of Manufacturing/Assembly

After researching and surveying a sample audience (K-12 focused), one of our design requirements was for the device to be easy to use, easy to assemble, and easy to maintain. During our design and manufacturing phase, we made sure to focus on designing components that were easy to manufacture and assemble, for us and for the customers. The three components that highlight these requirements were the mallet stand, the mallet holder, and the counter weight holder. Our final design concept involved the use of one mallet per note, so it was essential for our solenoid stand to be easy to manufacture and assemble. For this reason, our solenoid stands were made out of wood, laser-cut, and puzzle-piece assembled. The manufacturing and assembly was quick, simple, and consistent throughout all solenoid stands, adhering to the rule of standardizing to reduce part variety. We used wood glue to keep the solenoid stand together, but it used a friction fit to slide into the acrylic base, allowing us to pull it out and repair it if needed. The acrylic slots were also a built-in alignment feature.

The 3D printed mallet holder was designed to have a friction fit towards the center of the mallet since the mallet had a slight angle to its body; however, there was a gap in the bottom to allow the mallet holder to expand to accommodate a thicker diameter in case we needed to move the pivot point farther down the mallet. With every note on the drum differing in size, it was important for us to have the ability to vary the pivot point of the mallet to ensure the best sound quality. Also, as the part is 3D printed, it is easy to manufacture and replace if needed. Furthermore, our mallet holders doubled as the housing for our fastener assemblies, which attached the mallet holders to the solenoid stands and acted as the pivot dowels for our mallets. This allowed us to minimize the need for additional parts but incorporating several functions into the mallet holder.

Similar to the mallet holder, the counterweight holder is 3D printed and friction fit for ease of assembly when attaching the counterweight holder to the mallet. While the counterweight holder's position on the mallet was more consistent, it allowed for us to change the position of the counterweight (a AAA battery). The counterweight was responsible for pulling the mallet back up after striking the drum, yet allowing the solenoid to pull it down when actuated, so it was important that we had the ability to manipulate the counterweight's position for repair and functionality.

4.8 Sustainability

Aspects that enhance the sustainability of the device include the use of a wood base and polylactic acid (PLA) for our 3D printed parts. We used ordinary plywood as the bottom base of our device to hold the electrical components. Wood is a natural, renewable, and sustainable material which helps contribute to the sustainability of the device. We mainly used PLA plastic for our mallet stands in our device ie. mallet holder and counterweight holder. Like wood, PLA is also biodegradable and recyclable which reduces plastic waste and CO2 emissions. Not only is the use of wood and PLA sustainable, but it was also cheap and comfortable to work with.

On the other hand, aspects that detract from its sustainability are the use of electricity and the acrylic base. For the power source for our device, we used an AC power supply for our Arduino. One of the main sources of the electrical power is from the electric power sectors which burn fossil fuels or materials made from fossil fuels. The electric power sector is one of the leading sources behind the U.S. CO2 emissions thus detracting from the device's sustainability. One thing that can be changed would be to exchange the source of power with a more renewable energy source such as a solar powered source. While it may not be as efficient, it will be more sustainable in the long run. For the top panel of our assembly, we used an acrylic material which was not only sturdy, but also see-through, enhancing the visual aspects of the device. Acrylic is ideal for design requirements of our device, but is not recyclable or biodegradable. We could replace the acrylic, and cover up the entire base for a more sleek design. While it won't be clear and see-through, it will make the device more eco-friendly.

4.9 Final Design

Our final design addresses our previously stated design requirements of a high sound fidelity, a compact form factor, a minimalistic design, that is safe and easy to use, while also staying within a \$250 budget to cater towards a niche audience. Figures S.1-S.4 depict our final CAD design in an isometric, front, side, and top view, utilizing solenoids as our mechanical actuation source. Starting with the overall design, one of the most important characteristics derived from our customer needs is the compact nature of our final device. Figure S.5 depicts the bounding dimensions of the automated instrument fitting within a 17" x 17" x 9.5" space when completely set up. This can further be broken down in disassembly by sliding and removing the mallet stands from the base. By fitting within this confined volume, it allows the user to store our instrument in small cubbies or closets within the classroom when not in use.

Price was also a main concern for our automated instrument, as we set aside a \$250 budget to accomplish our task. From our Bill of Materials (Table T.1), a portion of our budget was taken up by the solenoids. As we designed our instrument to utilize one solenoid per note, we needed eight (8) in total, taking up approximately \$53 of our budget. Another large portion of our budget was set aside for the Arduino Uno and the Breadboard. This took up another \$70 from our total. To help keep costs down, we chose to use cheap construction materials for the mallet stands and electronics base, using a variety of thin plywood sheets and 2x4s to make up the majority of our structure. Overall we met our goal and undercut our budget by \$5 with the total price of the project being \$245. Moving on to how our instrument works, there are four notable design aspects that enable us to play our steel tongue drum: the Mallet/Solenoid stand, the Mallet/Counterweight Assembly, the Electronics Base, and the Electronics/Arduino.

4.9.1 Mallet/Solenoid Stand

The Mallet/Solenoid Stand (Figure S.8) was designed with ease and quickness of manufacturing in mind. By designing our stand with one-eighth inch plywood, we were able to create a design that fits together like a puzzle and allows us to print quickly using laser cut manufacturing. One defining feature of our mallet/solenoid stands are the holes located on the top of the stand (Figure S.8, Label A) used to attach the mallet holder to the base with M3 hardware. This enables us to translate the linear motion of the solenoid to a rotational movement of the mallet about the pivot. Our second feature (Figure S.8, Label B) enables us to hold the solenoid body in place only allowing the plunger to move up and down freely. Our last feature of the stand is the set of "L" attachment points (Figure S.8, Label C) which mesh to the slots located on the electronics base, both holding our mallet assemblies in place and allowing back and forth movement to find the optimal striking zone of each note on the drum.

4.9.2 Mallet/Counterweight Assembly

The Mallet/Counterweight Assembly (Figure S.6) was designed with 3D printing in mind. Starting with the mallet holder (Figure S.7), due to the wide manufacturing tolerances of the mallet shafts, it was important to have the ability to change the mallet holder's diameter. In our design, we have an open slot that allows for the manipulation of the holder diameter by tightening or loosening the inner nuts of the assembly. This worked well, as we were able to keep a constant lever distance even with the high variability of the mallet shaft diameter. The other part of this assembly is our counterweight holder. The idea of the counterweight was to use a AAA battery to pull back on the mallet and release the note. Our design not only accomplishes this goal, but also allows the user to manipulate the pull back force of the counterweight by moving the battery back and forth, ultimately changing the moment arm.

4.9.3 Electronics Base

The Electronics Base, the layered structure shown in figure S.1, holds and orients all the mallet assemblies towards the steel tongue drum and provides storage for the electronics. The base consists of two laser cut layers separated by four 2"x 4" wooden stands. The top layer consists of eight (8) pairs of rails to attach the mallet assemblies in place, and eight holes to route the solenoid wires to the breadboard in the bottom layer. The top layer was manufactured with $\frac{1}{4}$" acrylic to mitigate bending under load and, more importantly, to show the electronics in the bottom. The bottom layer has the same overall shape as the top layer to keep the same bounding dimensions, but is manufactured with $\frac{1}{4}$" Plywood as it has a high yield strength combined with a low cost of material.

4.9.4 Electronics/Arduino

To actuate the solenoids, we decided on using the circuit shown in Figure I.1. This circuit was copied eight times for each solenoid and connected in parallel to enable us to actuate one mallet at a time. We used eight transistors to act as a switch which were connected to separate digital pins on the Arduino Uno. We then used the transcribed version of the online sheet music to create a 2-D array of the music notes and another 2-D array for the length of the notes. These were played using a for loop, where the first array tells the Arduino which solenoid to actuate and the second array tells it how long to delay until the next note is played. When the pause button is pressed, it starts a while loop with a set delay that does not break until the button is pressed again. The second button changes the index of the 2-D array to play the next song in the array. Finally to actuate a song, we used physical buttons underneath the drum to play, pause, and skip each song.

4.10 Final FMEA

While redesigning our product, we referenced the preliminary FMEA table given in Appendix P, Figure P.1, considering our suggested remedial measures to revise our design. With our final prototype produced as detailed in Section IX. Final Design, the FMEA table was updated to include the revisions we implemented into our functional prototype and new RPN values were calculated (see Figure P.2, Appendix P). The revisions we made to our final product successfully mitigated the risk factor of both the counterweight system and mallet pivot system described in section 3 of this chapter.

Beginning with the counterweight, we used the suggested remedial measure to design the 3D printed counterweight holder as part of the Mallet/Counterweight Assembly described in the previous section. This assembly allowed us to slide the battery counterweight forward or backward as needed to produce the desired moment about the pivot point. We were able to detect and mitigate failure to a better degree than the initial design concept, reducing the RPN to almost one-third of the initial value. Still, our design could be improved upon as the occurrence of failure because of the counterweight position is still relatively high. The batteries slide within their holders and we noticed we have to "retune" and reposition the counterweights before we can begin to use the product. For the showcase, we refined this design by placing electrical tape around the back portion of the battery to prevent slippage, but if given more time, the counterweight holder could be reprinted with a marginally smaller diameter to prevent sliding.

With regards to the failure method of the mallet sliding along the pivot point, we incorporated the 3D printed mallet holder, described as part of the Mallet/Counterweight Assembly detailed in the previous section. This piece connects the mallet to the pivot point via the fastener assembly, allowing the mallet to pivot about the screw while preventing it from sliding through the friction fit 3D holder and the tightening fastener. Conveniently, the fastener assembly also allows us to fix the mallet holder in place to prevent interference between the 3D printed plastic holder and the wooden inner walls of the solenoid stand. This limited the frictional forces experienced by the mallet assembly during operation, ensuring a stronger strike force and a higher quality note. Consequently, not only did we mitigate the risk of the mallet sliding, but we also reduced the risk of insufficient strike force. Leading up to the showcase, the mallet sliding continued to be a fairly high occurrence issue and would result in inadequate moment arms and frictional interactions between the mallet holder and the solenoid stands. We noticed some of the mallets had significantly smaller diameters than the others, meaning our designed mallet holders were insufficiently dimensioned, allowing slippage. To mitigate this problem, we used electrical tape to thicken the diameter of the mallet at the pivot location, preventing excess sliding during use. In the future, we would purchase higher quality mallets with more manufacturing uniformity so that our mallet holders would be adequately sized.

Other notable risk factors like movement of the solenoid stands or of the steel drum were mitigated using the acrylic base described in the Electronic Base subsection of the Final Design section. The acrylic was designed with slotted cut-outs that the solenoid stands could be slid into, ensuring the direction and location of the mallets relative to the steel drum. The acrylic also proved high-friction enough relative to the rubber legs of the steel drum that movement of the instrument was of no issue. Hand-tied fishing line connected the mallet to the solenoid at the proper location and provided enough strength and elasticity for high-fidelity sound actuation, reducing the risk of string detachment. As expected in the preliminary FMEA, very little risk was associated with the solenoid functionality, mallet strength, power distribution, or speed of operation.

4.11 Operating and Repair Instructions

Instructions for constructing and repairing our autonomous steel drum instrument are outlined in Appendix U.1. They are composed of simple steps which essentially mirror the same process we used to construct the device. Each individual step explains what materials a user needs and the process required to complete that portion of the device manufacturing and assembly. An itemized bill of materials is given in Table T.1, but it should be noted that these materials constitute all eight (8) solenoid/mallet assemblies, so the final design models in Appendix S should be referenced to determine the necessary components for the repair. Because of the relative simplicity of our design, any major repairs to the device will most likely require reprinting of the 3D printed mallet/counterweight holders, recutting and reassembling of the wooden solenoid stands, and/or retying the fishing line attachments. Fortunately, the .STL files for the 3D printed parts and the .PNG files for the laser-cut solenoid stand assembly can be used to remake components relatively quickly and repeatedly, reducing the amount of required hand manufacturing. In this way, the assembly instructions for our device also double as repair instructions. Minor repairs for issues such as replacing a solenoid, adjusting a mallet that is not bouncing back after a strike, that is immobile, or that is not hitting the drum adequately during actuation are detailed in Appendix U.2.

For repairs of the electronic wiring of the system, Figure I.1 should be referenced. It is important to remember that the circuit given in Appendix I is for one solenoid, and that the circuit is repeated eight (8) times on our device's breadboard. Following the wiring given, though, repairs and maintenance should be manageable. In the case that a solenoid must be replaced, the old solenoid wires may be cut from the jumper wires of the breadboard and the new solenoid wires can be soldered directly to the open jumper wires, negating the need for any rewiring on the breadboard.

Operation instructions are given in Appendix U.3, but due to the lack of assembly required of our device, the operation of it is relatively simple. Our device utilizes an Arduino microcontroller, so a user may freely download the Arduino software and using the code we have created for our three songs, may upload that code to the instrument's Arduino. Assuming that all repairs detailed in Appendices U.1 and U.2 are completed properly, the operation instructions in Appendix U.3 may be followed to use the device.

5 Final Discussion and Recommendations

Our design process began with collecting customer needs and requirements through analysis of customer interviews. With these requirements as guidelines, we generated multiple different concepts using idea generation techniques to have a variety of system subfunctions and multiple methods of device operation. Compiling and comparing these solutions on the basis of our design requirements, we settled on a leading concept that used individual mallets actuated by solenoids. Over time, we built upon this basic concept to implement laser-cut, wooden, jiggle-saw type solenoid stand assemblies that held the mallet at the desired pivot location through a 3D printed mallet holder and paired fastener assembly. A counterweight holder was designed and 3D printed to hold a AAA battery at the end of the mallet with the option to change the battery location depending on the mallet system's needs. Each of the eight (8) solenoids were wired into a breadboard and were controlled by an Arduino program that used the relationship between each solenoid and its relevant note to play three (3) songs. After including a button within the electrical system to start and pause songs, we implemented a second button to allow users to skip between songs.

One of the strongest aspects of our product is its light weight and compactness, especially considering the amount of mechanical components contained within our device. The main reason for its compactness is the small size of our steel tongue drum. The use of a steel drum is in itself a selling point as it is a fairly unique instrument and many kids may not have real-life experience with one. Furthermore, the design and operation of our automated instrument is simple enough that, in theory, no assembly or disassembly should be required. As long as the coding for the songs has previously been uploaded onto the Arduino, the device only needs to be plugged into a power source to function. With only two buttons, the operation of our device is extremely straightforward and only takes a few seconds to figure out. As far as repairs go, the eight (8) solenoid stands are identical, and once one understands how to repair one stand, they understand how to repair the entire device. The stands slide out of the acrylic base in the case that repairs are needed, and they can therefore be replaced very easily without destroying or disassembling the entire device.

This device can also be marketed as a learning device as the transparent acrylic base and electrical work on the breadboard allows viewers to look down into the instrument to see how the solenoids are wired into the Arduino and connected to the power source. Students could use this device to learn about electrical circuits and could replicate the wiring of one solenoid to learn the basics of a breadboard and Arduino hardware. Furthermore, the variability in the location of the counterweight and mallet pivot point can be used as a visual tool to teach students about the basic physics principle of moments and the relationship between the length of the moment arm and the resulting force on the steel drum. Weaknesses of our device include the difficulty of repair of the electronic wiring. While the wiring is currently well-organized and neat, if all of the jumper wires were removed from the breadboard, it would be difficult to tell which solenoid wire went to which row on the breadboard. The device could benefit from clear labeling at plug points, either through colors, letters, or numbers for ease of reassembling or repairing the electronic subsystem. The device also lacks significant user interaction beyond the initial play, pause, and skip inputs. An array of buttons could be implemented into the wiring of the device, with each button actuating an individual mallet/solenoid assembly. This would allow the user to manually play the steel drum, a function that would be particularly useful for people with disabilities who aren't able to play percussive instruments in the traditional way.

As for the manufacturing of the device, future work on the prototype could include adding a removable, transparent, acrylic casing around the multi-platform base to allow users to still look into the device while providing a protective barrier between the user and the electrical components. This would reduce the risk of damage to the electronics while also decreasing the risk of accidental electrocution due to interaction with the device wiring. Furthermore, with an increased budget, a future prototype could utilize a chromatic tongue drum for enhanced musical sound and higher quality mallets for standardized manufacturing and ensured uniformity of materials. We also noticed one weakness of the device was that the fishing line stayed tied onto the solenoid, but tended to slide backwards and forwards along the length of the mallet, affecting the moment on the mallet. Currently, our prototype uses electrical tape to secure the fishing line in place, but in the future, notches could be cut into the mallet for the string to "nestle" into, disallowing movement during operation. The fishing line could also be melted together to eliminate the need for hand-tied knots and standardize the string length from solenoid to attachment point on the mallet.

Despite our prototypes' weaknesses and potential for improvement, it does currently fulfill all of the design requirements specified at the beginning of this project. It is visually appealing, but could be more so if the improvements specified in the previous paragraph were made, eliminating the need for electrical tape on the mallet. Higher quality materials would also improve the aesthetics as well as printing all of the 3D parts with the same color PLA. As discussed, the device is also compact enough to fit on a shelf when in storage and fit on a table while in use. It is lightweight enough to be easily carried by the average person and is easy to hold. Our product also meets the budget requirements and costs less than $250 to manufacture. The device is easy to use with only two (2) user inputs available and takes very little time to assemble and disassemble, with no significant assembly required after the initial manufacturing of the product.

As for the musicality of the device, our prototype is able to produce sound automatically through mechanical means and is currently equipped with the necessary coding to play three (3) distinct songs. The songs are clearly audible with relatively little background noise, though the device could benefit from producing louder sound. This could be accomplished simply by buying a higher quality steel drum, such as a chromatic steel drum as mentioned, or by using higher quality solenoids that produce smoother, less noisy linear motion. One of our songs, 'Jingle Bells', meets the requirement of being recognizable over a broad range of ages, while the other two songs 'Carry on My Wayward Son' and 'Thriller' cater to an older subsection of users. More universally recognizable tunes and/or songs could be programmed to further meet this requirement.

The device is also safe for all age ranges to use, although its safety could be increased with the acrylic casing suggestion previously described. This would also increase the overall robustness of the product by decreasing the potential for damage of the electrical components. Currently, the device is fairly robust with the one poignant weakness being the propensity of the counterweight, mallet, and fishing line to slide out of location, producing undesirable moments about the pivot point. If the manufacturing improvements described in this section were adhered to, the robustness of the device would greatly improve, further meeting the design requirement. Lastly, as explained, the device is quick and easy to repair with regards to the components above the acrylic base. Labeling of plug points in the breadboard would make maintenance and repair of the electrical wiring much simpler, and even users with no circuitry knowledge could assemble and disassemble the wiring of our prototype. Overall, our automated steel tongue drum fulfills all design requirements to an acceptable degree, performs the necessary operations in an efficient and repeatable manner, and shows potential for great improvement if given a more generous time and cost allowance.

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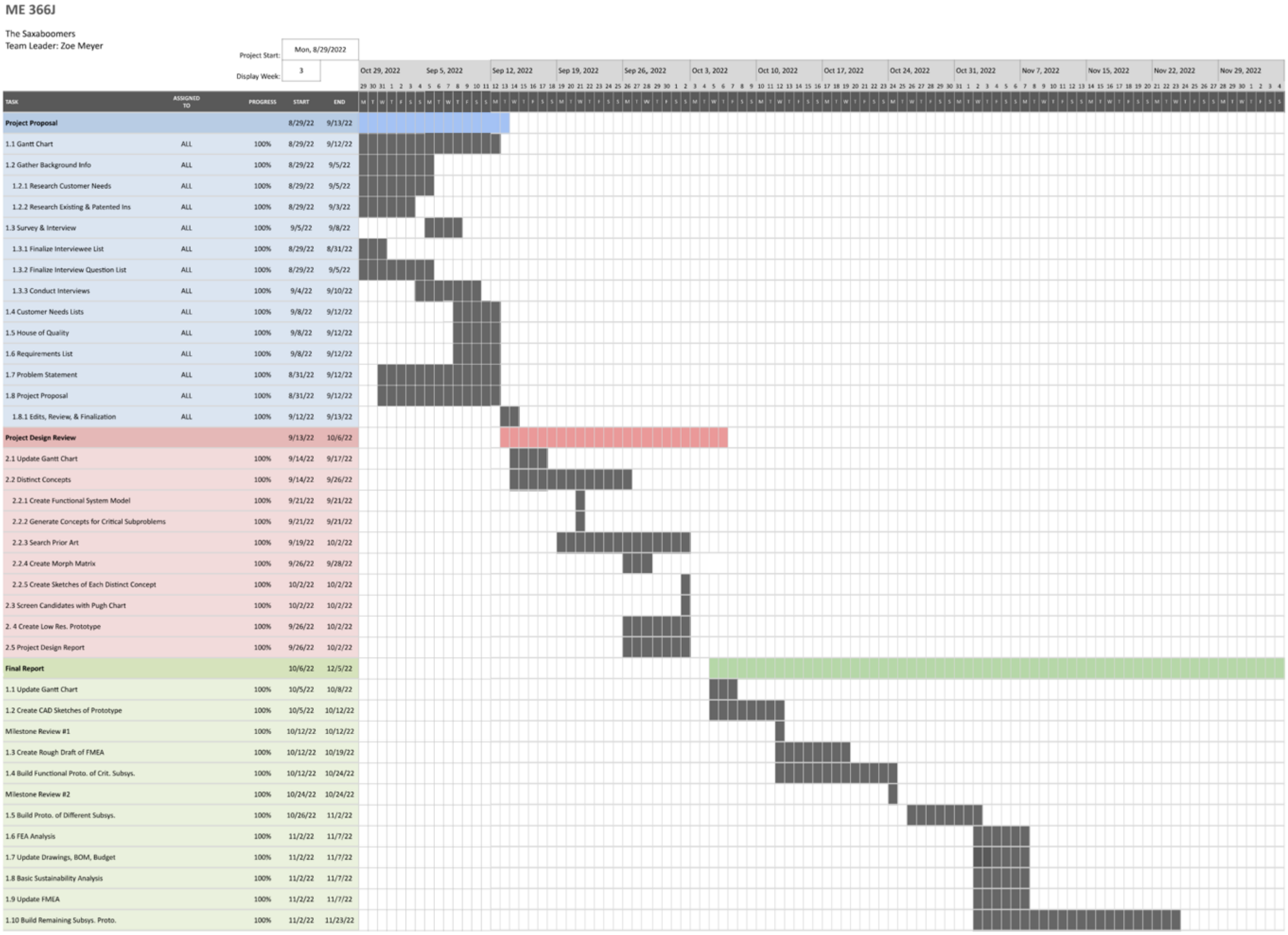
7 Appendix

7.1 Appendix A: Gantt Chart & Task List

Table A.1. Gantt Chart



ME 366J

The Saxaboomers
Team Leader: Zoe Meyer

Project Start: Mon, 8/29/2022
Display Week: 3

TASK	ASSIGNED TO	PROGRESS	START	END
Project Proposal			8/29/22	9/13/22
1.1 Gantt Chart	ALL	100%	8/29/22	9/12/22
1.2 Gather Background Info	ALL	100%	8/29/22	9/5/22
1.2.1 Research Customer Needs	ALL	100%	8/29/22	9/5/22
1.2.2 Research Existing & Patented Ins	ALL	100%	8/29/22	9/3/22
1.3 Survey & Interview	ALL	100%	9/5/22	9/8/22
1.3.1 Finalize Interviewee List	ALL	100%	8/29/22	8/31/22
1.3.2 Finalize Interview Question List	ALL	100%	8/29/22	9/5/22
1.3.3 Conduct Interviews	ALL	100%	9/4/22	9/10/22
1.4 Customer Needs Lists	ALL	100%	9/8/22	9/12/22
1.5 House of Quality	ALL	100%	9/8/22	9/12/22
1.6 Requirements List	ALL	100%	9/8/22	9/12/22
1.7 Problem Statement	ALL	100%	8/31/22	9/12/22
1.8 Project Proposal	ALL	100%	8/31/22	9/12/22
1.8.1 Edits, Review, & Finalization	ALL	100%	9/12/22	9/13/22
Project Design Review			9/13/22	10/6/22
2.1 Update Gantt Chart		100%	9/14/22	9/17/22
2.2 Distinct Concepts		100%	9/14/22	9/26/22
2.2.1 Create Functional System Model		100%	9/21/22	9/21/22
2.2.2 Generate Concepts for Critical Subproblems		100%	9/21/22	9/21/22
2.2.3 Search Prior Art		100%	9/19/22	10/2/22
2.2.4 Create Morph Matrix		100%	9/26/22	9/28/22
2.2.5 Create Sketches of Each Distinct Concept		100%	10/2/22	10/2/22
2.3 Screen Candidates with Pugh Chart		100%	10/2/22	10/2/22
2. 4 Create Low Res. Prototype		100%	9/26/22	10/2/22
2.5 Project Design Report		100%	9/26/22	10/2/22
Final Report			10/6/22	12/5/22
1.1 Update Gantt Chart		100%	10/5/22	10/8/22
1.2 Create CAD Sketches of Prototype		100%	10/5/22	10/12/22
Milestone Review #1		100%	10/12/22	10/12/22
1.3 Create Rough Draft of FMEA		100%	10/12/22	10/19/22
1.4 Build Functional Proto. of Crit. Subsys.		100%	10/12/22	10/24/22
Milestone Review #2		100%	10/24/22	10/24/22
1.5 Build Proto. of Different Subsys.		100%	10/26/22	11/2/22
1.6 FEA Analysis		100%	11/2/22	11/7/22
1.7 Update Drawings, BOM, Budget		100%	11/2/22	11/7/22
1.8 Basic Sustainability Analysis		100%	11/2/22	11/7/22
1.9 Update FMEA		100%	11/2/22	11/7/22
1.10 Build Remaining Subsys. Proto.		100%	11/2/22	11/23/22

7.1.1 Task List

Gather Background Information

Task	Responsibility
Gather information on automated wind instruments	Quaid
Gather information on automated percussion instruments	Neil
Gather information on automated string instruments	Steven
Gather information on brass instruments	Frank
Gather information on random instruments (accordion)	Zoe
Gather information on patents	Zoe
Gather information on the history of automated instruments	Christian

Gather Background Information

Task	Responsibility
Finalize Interview Questions	All
Conduct Interviews	All
Compile Interviews	All
Transcribe Interviews	All
Create Customer Needs List	All

House of Quality/Requirements List

Task	Responsibility
Analyze Customer Needs List	All
Compile Most Important Needs	All
Assign Weighting to Each Important Need	All
Create Requirements List	All
Create Metrics for Each Need	All
Create House of Quality	All

Project Proposal

Task	Responsibility
Introduction	Francisco
Background Research	All
Customer Needs Analysis	Steven & Neil
House of Quality	Zoe
Engineering Requirements/Specifications	Quaid
Problem Statement	All
Closure	All

Functional System Model

Task	Responsibility
Create Template	All
Identify Subsystems	All

Concept Generation

Task	Responsibility
Identify sub-problems	All
Create mind-map template	All
Generate Ideas to Solve Sub-Problems	All
Fill template	All

6-3-5

Task	Responsibility
Create 3 design distinct concepts	All
Edit concepts	All

Prior Art

Task	Responsibility
Research existing solution to critical subsystems	All

Morphological Matrix

Task	Responsibility
Identity Sub-functions	All
Identify Methods	All
Create Chart Template	All
Fill Chart	All
Generate 6 distinct sketches	All

Pugh Chart

Task	Responsibility
Create 3 different pugh chart templates	All
Select baseline designs	All
Generate Appropriate metrics	All
Compare 6 different designs	All
Compare Results	All
Screen Candidates	All

Design Review

Task	Responsibility
Introduction	All
Functional Model	Christian
Creative Idea Generation	Zoe
Morph Matrix	All
Prior Art	All
Pugh Chart	Steven, Francisco
Low Res Prototype	Neil
Conclusion	Quaid

Create CAD Sketches and Prototype

Task	Responsibility
Create CAD Models	Neil, Christian
Create Drawings	Neil
Create Assembly	Neil

Rough Draft of FMEA

Task	Responsibility
Establish Failure Locations	All
Specify Failure Modes	All
List Effect of Failure	All
Explain How Failure is Caused	All
Specify Current Process Controls	All
Give S/O/D Ratings	All

Build Functional Prototype of Critical Subsystem

Task	Responsibility
Create bill of materials	All
Laser Cut Components	Neil
3D Print Components	All
Assemble Prototype	All

FEA Analysis

Task	Responsibility
Conduct FEA	Christian
Establish Analytical Equivalent	Christian
Analyze Results	Christian

Update FMEA

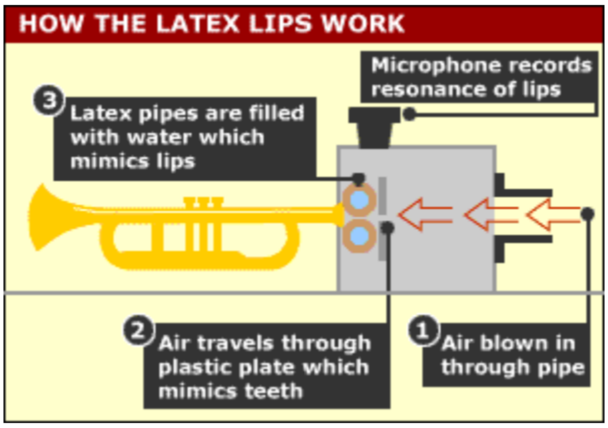
Task	Responsibility
List Possible Revisions	Zoe
Provide Modified S/O/D Score	Zoe

Final Report

Task	Responsibility
Introduction	Zoe
Leading Concept	Quaid
Preliminary FMEA	Christian
DOE	Christian
FEA	Christian
Updated Leading Concept	Quaid
Design of Manufacturing/Assembly	Steven
Sustainability	Steven
Final FMEA	Zoe
Final Drawings/ BOM/ Budget	Neil
Operating/Repair Instructions	Frank
Final Discussions & Recommendations	Zoe

7.2 Appendix B: Background Information

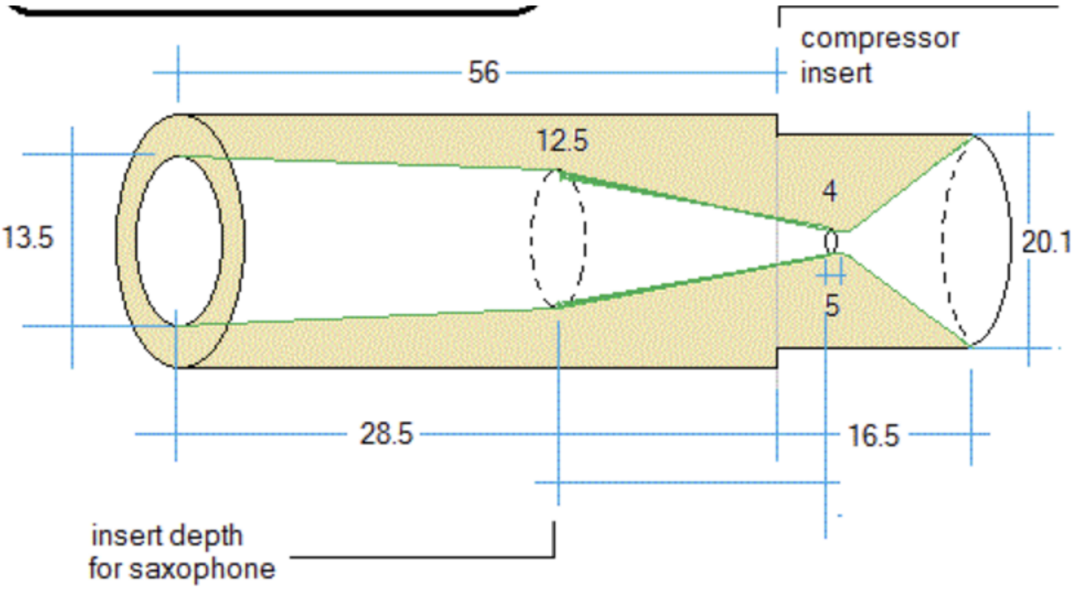
Figure B.1. Latex Tips



BBC News. (1999). *Latex Lips Blow Own Trumpet* [Diagram].
BBC News. http://news.bbc.co.uk/2/hi/science/nature/467244.stm

Note: Configuration to create buzzing lips for accurate sound out of trumpet. 1. Air blown in through pipe 2. Air travels through a plastic plate which mimics teeth 3. Latex pipes are filled with water to mimic lips.

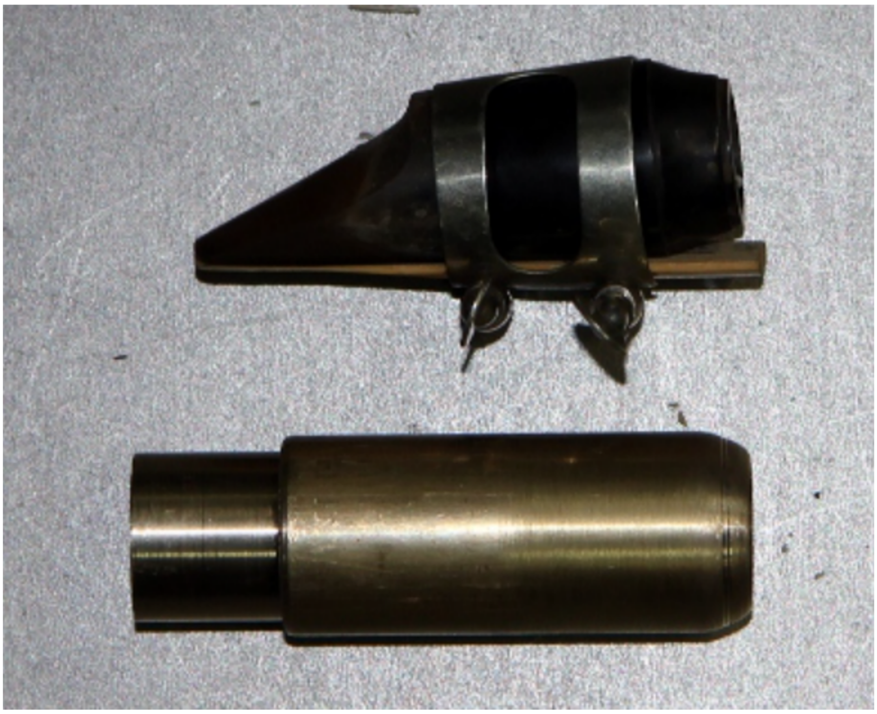
Figure B.2. Saxaphone Impedance Converter



Raes, G.-W. (2014). *Microtonal Musical Robot* [Drawing]. University College Ghent.
https://www.logosfoundation.org/instrum_gwr/asa.html

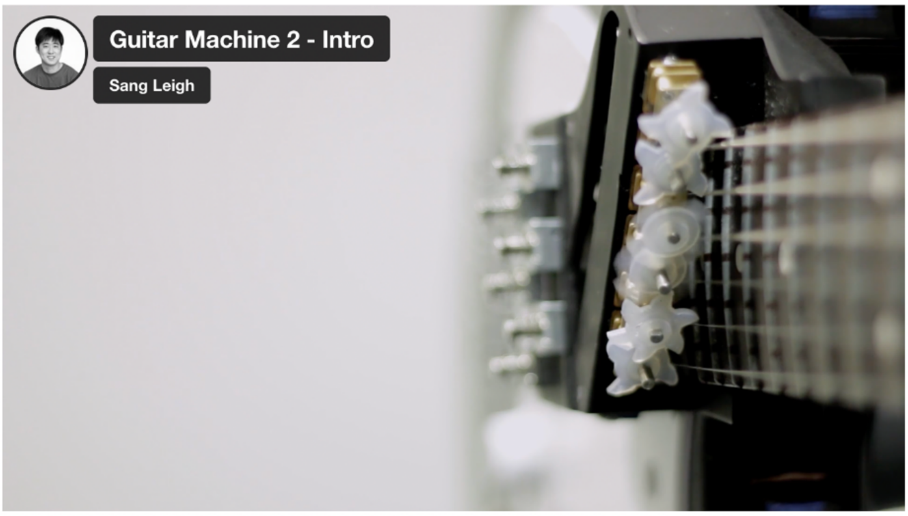
Note: Acoustic impedance converter used to imitate embouchure on saxophone (alto).

Figure B.3. Acoustic Impedance Converter vs. Typical Alto Saxophone Mouthpiece



Raes, G.-W. (2014). *Microtonal Musical Robot* [Drawing]. University College Ghent.
https://www.logosfoundation.org/instrum_gwr/asa.html

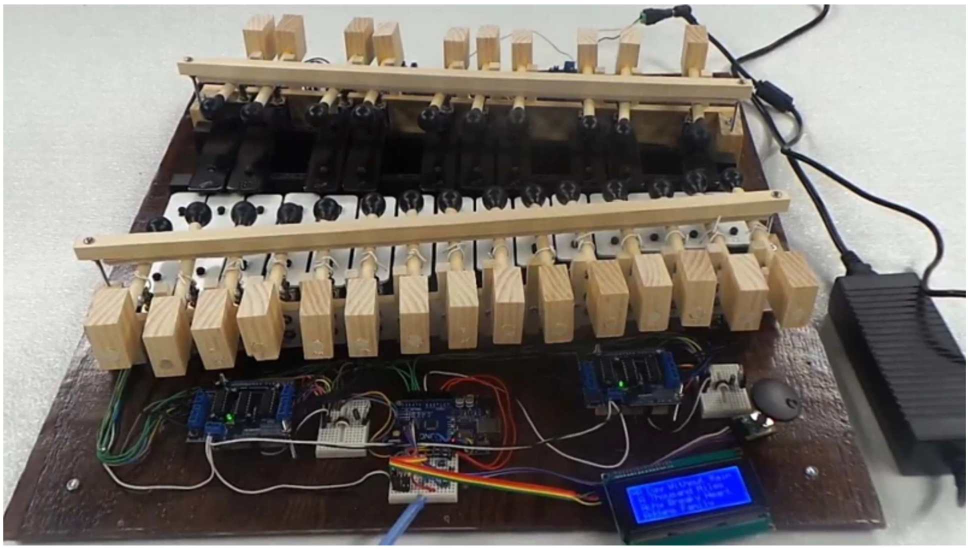
Figure B.4. Automated Plucking of a Guitar



Leight, S. (2019). *Guitar Machine* [Photograph]. MIT Media Lab.
https://www.media.mit.edu/posts/guitar-machine/

Note: The compact device that is attached to the strumming side of the guitar uses 6 motors that are used to strum/pluck the guitar strings. The user holds the notes down while the device plays the right side of the guitar. The device allows the guitar player to create sounds that are otherwise very difficult to do if the user plays without the device.

Figure B.5. Robotic Xylophone



Wilkinson, C. (2022). *Robotic Xylophone* [Photograph]. Hackaday. https://hackaday.com/2022/01/27/robotic-xylophone-makes-music-with-midi-magic/

Note: A solenoid and mallet are attached to individual notes on the xylophone. This enables the device to have the ability not only to play fast, but play chords. Each mallet is pulled down by the solenoid and is retracted via a counter-weight in a seesaw mechanism.

Figure B.6. Wintergatan Marble Machine

Lewis, D. (2016). *Wintergatan Marble Machine* [Photograph]. Smithsonian.com. https://www.smithsonianmag.com/smart-news/machine-makes-music-marbles-180958293/

Note: Machine is hand-cranked to actuate the controlled release of around 2,000 marbles onto specific keys of the vibraphone below. Marbles are circulated throughout the machine. Fully wooden.

7.3 Appendix C: Customer Interviews

7.3.1 Interviewee List

Educators:

1. High School Physics Teacher (Interviewed by Zoe)
2. Middle/Elementary School Music Teacher (Interviewed by Quaid)
3. Middle School Music Teacher (Interviewed by Quaid)
4. Elementary Music Teacher (Interviewed by Neil)

K-12 Students:

5. 7-year Old Student (Interviewed by Zoe)
6. High School Student (Interviewed by Christian)

Robotics Professionals:

7. High School Robotics Teacher (Interviewed by Francisco)

Musicians:

8. Ex High School Band Member (Interviewed by Neil)
9. Ex High School Band Member (Interviewed by Steven)
10. Longhorn Marching Band/ UT Orchestra Member (Interviewed by Steven)

7.3.2 Interview Questions

Educators:

- What type of students do you teach?
- What type of students do you teach?
- What musical instruments do you teach with?
- Do you have any children with disabilities that want to learn music?
- What instruments do these children best respond to?
- Instrument; where do students struggle?
- Any music in class?
- What physics concepts do you think could be best demonstrated?
- What musical concepts could be demonstrated through an instrument that we design?
- How to keep kids engaged? Hardware specific
- What would you like out of a self playing educationally designed instrument?
- Accommodations for different abilities
- Mechanical systems/physics principles/experience?
- What instruments do most children learn to use in K-12 schools?
- How much time are you willing to spend on maintenance?
- How much are you willing to pay for the product?

Students:

- What instruments are badass?
- What song do you like?
- Time/space of setup/how complicated is tech? -¿ “comfort level”
- Safety/Robustness
- What kind of music do you listen to?
- Who are your favorite artists?
- What instruments do you want to learn how to use?
- What fine art do you take in school?

Robotics Professionals:

- Lowest barrier to entry?
- What safety precautions do you believe are needed?
- What are the essential tasks you expect the machine to do?
- How long should it take to set up?

7.3.3 Interview Transcripts/Notes

1. Zoe – 7-year Old Student Audio Transcription

Zoe: So I just have a couple of questions, it shouldn't take too long. And it should just be about stuff that you like, basically.
Rose: Okay, okay.
Zoe: So the first question is, what are your favorite instruments to play: ones that you hit, ones with strings, or ones that you blow into?
Rose: My favorite is playing ukulele.
Zoe: Oh, ukulele? Okay, So ones with strings. Then, like guitars and stuff like that?
Rose: I like ukuleles the most.
Zoe: Why?
Rose: Because it's like it's funner than a guitar for a reason, because, I, my ukulele has different color strings, so that's why I like it a whole bunch.
Zoe: Okay, so you like the way it looks?
Rose: Yes
Zoe: And is it easier to play than a guitar, do you know?
Rose: Yeah, it is easier to play than the guitar.
Zoe: Okay, What's your favorite instrument to listen to?
Rose: My favorite instrument to listen to would be piano.
Zoe: The piano? Why?
Rose: Because um it's it's sound makes it makes you like calm, and it makes you soothing.
Zoe: I agree, I like piano, too. And then are there any instruments that you wanna learn to play, but they look really hard?
Rose: Yes, a saxophone.
Zoe: It does look really hard.There's too many buttons.
Rose: I know it's like which button do I press?
Zoe: Yeah, and you have to blow into it? It's too much.
Rose: Yes, it is.
Zoe: Okay, what are some of your favorite songs?
Rose: I like, I like, so what I like is, I like, like, I can't remember the name of it. Zoe: Is it from a movie?
Rose: No, it it's like a, um I know, making a purple stew.
Zoe: Making a Purple Stew? I've never heard of that.
Rose: I listened to it when I was a baby, and I like it.
Zoe: What do you like about it?
Rose: It's like, I get, um, I like it because it's funny, and then you get to choose whatever food you want and it's gotta be purple.
Zoe: Okay, that sounds fun.
Rose: Purple's my favorite color.
Zoe: That makes sense. Okay, Are you taking a music class right now?
Rose: No. Right now I'm in science.
Zoe: Have you ever taken a music class?
Rose: I go to music class at school, like we play instruments. Like we play boomwhackers, we play ukuleles, we play different things like that.

Zoe: Do you ever get bored in music class or frustrated by anything?

Rose: I'll get frustrated at a friend cause they annoy me in the class.

Zoe: But never frustrated with the instruments?

Rose: Sometimes like when I'm like I don't know how to play this instrument, even though I was listening. It's like I don't know how to play this but I was listening.

Zoe: Yeah, it's just like too complicated? Okay, that makes sense and we kind of already talked about this, but do you like instruments that look a certain way or that are certain colors? I know you said purple. You like purple instruments

Rose: Yeah, I don't have a purple instrument. My ukulele strings are the 3 primaries and the green string.

Zoe: And you like whenever your instruments are colorful?

Rose: Yes,

Zoe: Makes sense. Do you ever listen to music in classes that aren't your music class?

Rose: Yeah, we listen to music. We listen to the guitar.

Zoe: In what class?

Rose: In music class.

Zoe: Do you ever listen to music in like your other classes?

Rose: In chapel, too.

Zoe: Okay, that makes sense. Do you know what engineering is?

Rose: No.

Zoe: Have you ever seen any kind of like engineering demonstrations?

Rose: No.

Zoe: Do you know what coding is?

Rose: I don't know.

Zoe: Do you think that you would be interested in learning what those were if we were able to like, demonstrate what they were with the project?

Rose: Maybe.

Zoe: Maybe? Is there anything about the demonstrations that could be boring like, do you ever have demonstrations in class where maybe your science teacher shows you something, and they're just really boring, and you can't pay attention.

Rose: No, not that much.

Zoe: Not that much? What's something that keeps your intention in those demonstrations like colors, sounds, reactions?

Rose: The one thing that does happen that I get bored in would be like our teachers talk about like things a whole bunch like they repeat like they repeat, like it like 3 times, just so people can like get, know it, but I don't think we need it because like we listen to it the first time, and then um she repeats it and it's like, okay, you can stop saying it we know it.

Zoe: Right, like you don't need to hear it that many times?

Rose: Yeah, I listened to it the first time, and if I had trouble the first time I ask a second time, Zoe: Gotcha. Okay. So nothing repetitive. I think that might be all of my questions. You answered them really well. Let me think, are there any times in class when you're really excited about what you're doing.

Rose: Yes, I get really excited when doing a craft.

Zoe: Okay. So things that you can do like with your own hands?

Rose: Yeah

Zoe: You like to be hands on?

Rose: I like, I also get really excited when we do like math sheets and language arts worksheets. I do. I do get really excited.

Zoe: I liked math sheets when I was a kid, too.

end of interview

2. Zoe - High School Physics Teacher

Z: Thank you for joining me today.

D: Hi! How are you?

Z: Okay, we'll just go question 1 through 12 I guess. What aspects of demonstrations, of physics demonstrations, keep students engaged versus disengaged things like color, sounds, reactions of some sort.

D: Yeah. So they're usually engaged when you ask them a question, and they think they know the answer, but then they're not quite sure they know the answer so some of those thinking questions, and of course anything that makes noise, and you know, has some sort of reaction. A surprising reaction is always engaging.

Z: What would you consider a demonstration failure to be?

D: A demonstration failure is something that either doesn't do what it's supposed to do, or they're just like meh, okay, we've seen that before or you know our second grade teacher did that, or just you know, when when it's something really cool and it just doesn't work, that's always, they're always disappointed.

Z: Do you think an aspect of disengagement is if the demonstration doesn't have some sort of novelty.

D: Yeah, it has to be something that they're curious about if it's, you ask them a question, and they aren't curious about it, or don't care anything about it then they're not going to be very engaged. Z: So in the scope of like an engineering project it can sometimes be a little bit out of the realm of like normal High schooler knowledge. Do you think that that could be a pitfall to the demonstration, like it being too complicated?

D: So I mean, yeah, I mean it has to be something that they can relate to, or see a use for or you know it kind of it has to peak their interest or peak their their wondering I mean, you, if you showed them something that's too complicated that they completely can't understand, not so much why, but you know, it's just too complicated it's above their head. But if it's something, it can be complex, but if it's something that in the real world that they know, but they're not quite sure why it does that they just know it does, something complex like that. it can still be complex. but it's still within their their scope of the real world.

Z: So maybe we could relate to them like with the songs that we choose, or the tunes that are recognizable. That could be the relatable part?

D: Oh definitely, well, and then music is relatable to everyone, so anything with music that hits across all cultures and ages is music. But definitely if it's music that they're interested in they'll be they'll be more engaged.

Z: That makes sense. Do you ever play music in class for any reason?

D: Yeah, so in some of my classes if it's a high energy day like we have pep rallies, or there's you know it's the day before holidays or anything or if it's just a class that's always high energy I always have classical music, playing as soon as they walk in. And that seems to have a little bit of a calming effect on the class. Or if they're working in group projects where they could get a little too involved or too loud, that classical music since just seems to bring the volume of the room down and then we also play music we have it's a called a Brain Break, and it's called "Bop or Flop", and you play a snippet of a song, and they actually get up and vote if they like if they think it's a a bop which means they like it they go to one side of the room. If they think it's a flop. they go to the other side of the room, and so you can play all kinds of snippets of whatever kind of music, and they get to vote So that's always kind of fun.

Z: What physics principles do you believe could be best demonstrated, or that have a need to be demonstrated?

D: Well, obviously, anything with sound is a physics concept that you know, they they hear the sound, but they can't always see how it how it acts, or how it interacts. So waves and wave interactions and sound and stuff like that would definite be with music.

Z: Any of the other, not even music related, but any other like base topics within the physics level that you teach?

D: Kinematics and dynamics, obviously mechanics, and then electricity. That comes into play also.

Z: And then what accommodations for differently abled people or students can you think of? Maybe like vision, hearing, something physical?

D: Yeah. So I mean, if it if it has to do with sound, maybe have an oscilloscope, so they can see, at least to see the sound wave and see the peaks in the the amplitude and frequency and all that good stuff, so that would be one if you had a hearing impaired person. They may not get as much out of it because they can't hear what it's doing, but if they could see what it's doing.

Z: Oh, that's a great idea. How would you plan to implement this kind of musical demonstration into relevant coursework? You sort of already talked about it with the waves.

D: Yeah definitely with waves and even I mean if we're talking, you know, I don't know kinematics it would, it would depend on you know how we could use it if we could you know, demonstrate equations, or use it to demonstrate certain principles.mStuff like that. so even it could be, you know, free fall. If you have things falling, making noise, it may be a free fall demonstration.

Z: Okay, do you ever have issues like translating demonstrations into relevant coursework? Like, do you ever sometimes do a demonstration or a project and you're like, well, that was cool but did that actually work the way we wanted it to?

D: No, so that's kind of the little thing whenever you kind of when you're planning you plan okay, these are the principles we're going to we want them to know and then you pick your demonstrations to actually demonstrate the principles you don't, you know, pick a demonstration that's cool, and then somehow make it work into.

Z: So it's just like teacher planning then?

D: Yeah, unless it's like during an advisory, or a home room, sometimes, or if it's, you know just a thinking, hey? Here's something that we will get to eventually think about it because I'm not gonna tell you why. But what would you think about it?

Z: And like you said I could even be used as like a brain break, or just a way to peak interest.

D: Definitely.

Z: How much time are you as an educator willing to spend on maintenance of the device?

D: I guess it would depend on how complex the maintenance is, if it just needs like oiled or adjusted, or you know, tightened up, and you know, an hour or 2 before an demonstration, is you know about the maximum. but if it's like it's gotta be you know completely taken apart and put together, and you know, major maintenance done and that's that that would be a hassle that it would never get used,

Z: And how much would you or I guess technically, the school or the department be willing to spend on this instrument or how much would you pay for the product?

D: So the thing we get into is if it was a really cool demonstration that had some valid purposes we might spend \$150 maybe \$200. But we like to all be kind of on the same page. So ideally, we would have enough of the instrument for the teachers to all have one to do at the same time. So then, that would definitely drop the price to you know, \$25-\$50 bucks. Unless like I said, it's very relevant. And it's like oh, this is so cool you do it one day and I'll do it one day. But yeah, that's the drawback is if you've got multiple teachers now like AP physics, there's only 2 of us. So we could definitely get by with 1. But when you have subjects you got 5 teachers, then by the time the teacher gets to it, then, you know, the demo is irrelevant, because they already have learned all the concepts.

Z: Kind of in the same vein. What is the maximum amount of technology that you are comfortable with in terms of operation of the device?

D: Yeah. So myself, I think I could probably get by with quite a bit of technology. I'm i'm fairly tech savvy or can at least pick up on how to do it. Unfortunately, not all teachers are that way. So I know we have a couple of teachers in our department that have trouble with email, so any technology would be out of their scope.

Z: Do they have trouble following tutorials, like if we were to include a tutorial for the instrument?

D: No, they probably could, I mean, with some help, they could probably do it if it was a step by step with pictures. As long as it didn't get too complicated, yeah the average physics teacher probably could .

Z: Hopefully. it won't be too complicated? Oh, what safety precautions would you like us to be aware of well,

D: Well, obviously I mean if it has flame, obviously there would there would have to be some sort of shielding, or if there is a possibility of things flying away from the thing, you would definitely have to, it would have to have some sort of plexiglass shielding to protect the kids. And it would have to come with, you know it has moving parts, it would have to come with signage and or guarding so there's no pinch points or you know a place where someone gets their finger chopped off because they poked at something they shouldn't have been poking at but other than that, I mean the obvious things, you know moving parts, things that fly off open flame stuff like that. Just, you know, make sure that kids that are standing and watching the demonstration are safe.

Z: Okay makes sense. Do you believe that your students at your specific school would benefit from exposure to engineering, robotics, and coding,

D: Oh, definitely. Especially if it's if it's not the typical engineering if it's kind of an interesting turn, or an interesting look at engineering it's like okay, hey you could do this, and this is not what people normally think of as engineers, or you know you could code this, and that's really cool. So it takes it more to the more kids than just the science math typical kids.

Z: Yeah, it also kind of draws on the art kids.

D: Yeah, your art kids, your music kids, your fine art kids, yeah.

Z: Okay, I think that was the last question. The last one is just any other thoughts or suggestions that you thought of while we were talking.

D: The one thing, storage, whatever it is, Yeah. Cause I mean storage space gets tight, so it needs to be able to, without taking it completely apart, maybe fold down or not be huge, so that it can fit on the shelf.

Z: Okay, yeah, just like a regular lab shelf.

D: Yeah, just a regular, just a regular shelf or in a cabinet or some place, you know, just didn't need to take up a huge amount of space, so that, and then it needs to be durable, so that it can be used over and over.

Z: Yeah, especially if you have to assemble and reassemble over a bunch of years or through a bunch of teachers. And then, when it is fully assembled, do you have like maximum dimensions in mind of where you would set it up?

D: Usually a a lab demo table, or a regular old lab table. So maybe you know, 3 feet by 2 and a half feet maybe.

Z: Okay

D: And, you know, and not so heavy that a person a regular teacher can't pick it up and move around.

Z: Okay, so portable, compact, and durable.

D: Yes.

Z: Makes sense. Glad you brought those up. I did not think of them. Well thank you, those were all of my questions.

D: Thank you, Zoe.

end of interview

3. Christian - High School Student Interview Notes

Q: What instruments look cool?
- The Harp, violin, organ, and maybe the piano but it's big.

Q; What are some instruments you find ugly?
- The bagpipe.

Q: What types of songs do you like?
- My favorite genres are Spanish, R&B, Pop, and Christmas jingles. In general though, I like catchy and chill music.

Q: Do you think your friends would be interested in this?
- My friends like guitars. Maybe they'd think an automated instrument is cool.

Q: What instruments do you want to learn how to use?
- I'd like to learn the Guitar, keyboard, violin, and bass.

Q: What fine art do you take in school?
- I've participated in the arts, choir, and a little bit of the violin.

Q: How good are you with technology?
- Not great but not bad.

Q: Have you played instruments before?
- I've played violin before. I have some experience with the piano.

Q: What are some features that might be cool?
- If the instrument could automatically tune itself. It would be cool if it could play any song I wanted.

Q: Would little kids you know enjoy it?
- Little kids might get scared. Some kids would be cool with it though.

Q: How long do you think it should take to set up?
- I think the time it takes to set up will depend on the size. The bigger the instrument, the longer it's going to take. If it's a smaller instrument, it should be portable. At the very most, it should take 20 minutes

Q: What should it look like? (i.e. aesthetic)
- I think a sleek, minimal aesthetic would be the best.

Q: Should it be fully automatic?
- It should be fully automatic. It shouldn't be semi automatic as most people would buy it since it's automatic.

Q: How should it be controlled? (i.e. push button, app, etc.)
- It should be controlled by a controller or a smartphone app.

4. Francisco – High School Robotics Teacher Interview Notes

Q: Do you have any children with disabilities that want to learn music?
- No

Q: What instruments do these children best respond to or you think they would respond to the best?
- Piano, organ, keyboard. It engages both sides of the brain

Q: What physics concepts do you think could be best demonstrated?
- Sound waves an explanation for the kids. How a certain wavelength creates a certain sound

Q: What would you like out of a self playing educationally designed instrument?
- Use it to calm students down. People destress with music so it can help in the classroom Q: Accommodations for different abilities
- Simple design so it's easier for kids with disabilities to use the instrument

Q: How much time are you willing to spend on maintenance?
- Hour/ day

Q: What safety precautions do you believe are needed?
- Couldn't think of anything

Q: What are the essential tasks you expect the machine to do?
- Ability to record sounds and playback. Ideally, like a sort of demo for the kids, where they learn how to use it.

5. Neil – Ex High School Band Member (Nathanael) Interview Notes

Q: What musical instruments do you play?
- Saxophone, trombone, bass

Q: What instruments do these children best respond to or you think they would respond to the best?
- Trombone (sliding action), guitar (poplar)

Q: What physics concepts do you think could be best demonstrated?
- Lengthening and shortening of a tube (sound waves?)

Q: What musical concepts do you think could best be demonstrated through an instrument that we could design?
- Pitch, Timing, and rhythm

Q: What instruments did you first learn on?
- Recorder, piano

Q: What instruments are badass?
- Guitar, Xylophone, Piano, Hard wind instrument

Q: What song do you like or to play
- Baby shark, Amongus remix, Africa

Q: What kind of music do you listen to?
- Metal, rock, game soundtracks

Q: Who are your favorite artists?
- Metallica, muse

Q: What fine art do you take in school?
- Marching band, Concert band

Q: What safety precautions do you believe are needed?
- Keep kids away from instruments or moving parts (maybe encapsulated)

Q: What are the essential tasks you expect the machine to do?
- Play the instrument, sound like the tune its playing

Q: How long should it take to set up?
- 10 minutes or less

Q: How much to buy
- $50 to $100

Q: Fully automated
- PLAY SOMETHING PHYSICALLY IMPOSSIBLE BY HUMAN WOULD BE COOL

Q: Aesthetic
- WOOD AESTHETIC OR METAL,

Q: How should it be controlled
- Play button, easy interface, maybe a piano feature (semi automated)

6. Neil – Music Teacher (Mike) Interview Notes

Q: What type of students do you teach?
- 3rd-6th

Q: What instrument do you primarily play?
- Guitar

Q: What musical instruments would be cool?
- Guitar, or any Instrument that will help sing at the same time (sync to him playing). Something that tunes guitar when playing

Q: Do you have any children with disabilities that want to learn music?
- No just kids that have no passion or are distracted

Q: What instruments do these children best respond to or you think they would respond to the best?
- Guitar, Piano, Xylophone, recorder

Q: Instrument; where do students struggle?
- Reading music, No interest/ passion

Q: Any music in class?
- Music books, kPOP, baby shark catchy

Q: What physics concepts do you think could be best demonstrated?
- Maybe levers, things dropping

Q: What musical concepts do you think could best be demonstrated through an instrument that we could design?
- Timing, staying on rhythm

Q: How to keep kids engaged? Hardware specific
- Colorful, Instrument that everyone likes

Q: What would you like out of a self playing educationally designed instrument?
- Able to play with group of students or with the teacher

Q: Accommodations for different abilities
- some sort of interface that excites and helps maybe repeat directions

Q: Mechanical systems/physics principles/experience?
- No

Q: What instruments do most children learn to use in K-12 schools?
- Hand percussion, Recorder, Violin, Guitar, Piano, ukulele

Q: How much time are you willing to spend on maintenance
- 10-15 min before and after class, Very Little on maintenance

Q: How much are you willing to pay for the product?
- Less than a couple hundred for in class usage, but if it was used for parents to teach their kids, maybe under a hundred (depends if school's money)

7. Quaid – Music Educator (Mr. Kingston) Interview Notes

Q: What type of students do you teach?

- Mr Kingston is currently a vice principal at a middle school however he graduated with a degree in music as well as taught band to middle schoolers for a number of years.

Q: What musical instruments do you teach with?

- Mr. Kingston teaches with woodwinds, percussion, and brass to middle schoolers.

Q: Do you have any children with disabilities that want to learn music?

- One student and it was a learning disability not a physical disability. Did not have the cognitive skills to be able to read music or ability to learn that type of thing. Having a robot to manipulate a keyboard would make a student with a disability feel more of a sense of belonging. Percussion instruments would be easiest to use for children with disabilities.

Q: What instruments do these children best respond to or you think they would respond to the best?

- Percussion instruments would be able to manipulate. Takes a lot less skill to play initially. Tapping a bar with a mallet, barrier to entry is much lower that instrument.

Q: What musical concepts do you think could best be demonstrated through an instrument that we could design?

- Keyboard concept. Music notation program on the computer (finale: writes music). Can have the musical instrument to play the keyboard for you. Every band director has a different strength and this it could be helpful to teach a different instrument in case you cannot do it yourself.

Q: How to keep kids engaged?

- We want the instruction to be the main attraction so do not make the instrument super colorful so that the kids do not lose sight of the lesson.

Q: What would you like out of a self playing educationally designed instrument?

- Accommodations for different abilities
- ORF instruments.

Q: How much time are you willing to spend on maintenance? How much are you willing to pay for the product?

- Not much and this is a very niche instrument to help a children out with this. Budgets are extremely tight when it comes music. This is something that would come out of a different department.

Q: Do you think your students could benefit from robotics coding and engineering?

- Find music that is public domain when it comes to copyright and find music that can be helpful to children.
- Special needs kids could find an advantage in this to manipulate an instrument to be able to play an instrument. Specifically designed
- Band instructor; testing coordinator and assistant principal.
- Band instruments, flute clarinet saxophone. Teach percussion as well.

8. Steven – Ex High School Band Member (Julia Le) Interview Notes

Q: What is your background with musical instruments?
- Piano for 13 years, flute 8 years, self-taught ukulele and guitar 3 years, choir since 4th grade

Q: What did you find difficult when learning how to play?
- Fingerpicking for guitar
- Getting both hands in sync
- Piccolo was difficult because of breath control (needs more air)
- Flute has less breath control

Q: Do you have experience with any disabled musicians?
- Euphonium musician (one arm)
- She only needed one hand to play it

Q: What would you say other people struggle on when playing instruments?
- The typical difficulties stated above
- Tempo and dynamics

Q: Easiest band instrument to play?
- Saxophone

Q: What do you think is the easiest instrument to autotomize?
- Xylophone
- Drums

Q: What musical concepts do you think could best be demonstrated through an instrument that we could design?
- Tempo and dynamics could be demonstrated

Q: What would you like out of a self playing educationally designed instrument?
- Piano or guitar where the device can play one side of the instrument
- Piano where 4 hands are needed

Q: How do you play the flute/saxophone?
- Hotter breath when doing a lower octave (Want the air to spin slower/back of your throat)
- Colder breath when doing a higher octave (Want the air to spin faster)

Q: Easiest breath control instrument?
- Saxophone

Q: How would you compare listening live to listening online?
- Listening live is much better
- Live has differences that make the song sound cooler
- Listening online is always the same

Q: What instrument would you make your kid learn?
- Piano/Guitar. Different performance styles. You can sing or just play it.
- Playing with both hands are transferable to other instruments
- Rhythm and dynamics (music theory that is learned)

Q: Future instruments?
- Drums and harp

9. Steven – Andrew Dang Interview Notes

Q: What is your background with musical instruments?
- Piano at 11 years old, Cello a year later. Both instruments ever since. Dabble in other instruments

Q: What did you find difficult when learning how to play?
- Since starting on piano, it was a lot easier to learn other instruments. Knowing what to do with both hands

Q: Do you have experience with any disabled musicians?
- Heard of a violinist with three fingers. Uses three fingers to play the bow

Q: What would you say other people struggle on when playing instruments?
- Hand coordination (Piano and cello)
- Active listening to their instruments

Q: Easiest band instrument to play?
- Saxophone

Q: What do you think is the easiest instrument to autotomize?
- Couldn't imagine a robot playing wind instrument
- More percussion instrument
- Drums, xylophones

Q: What musical concepts do you think could best be demonstrated through an instrument that we could design?
- Visualization of sound waves
- Sound is a physical thing. A machine that can replicate that would be instrument

Q: What would you like out of a self playing educationally designed instrument?
- Seen a lot of robots playing instruments
- Very robotic and metronomic
- A robot cant have nuances of playing with emotions
- Knowing when to play soft and loud
- Add emotion or color to the music

Q: Easiest breath control instrument?
- Recorder
- Saxophone

Q: How would you compare listening live to listening online?
- Nowadays, all the best recorded interpretations are recorded. Past the curve of bad recording.
- More about seeing someone perform
- Can't replicate the feeling alone

Q: What instrument would you make your kid learn?
- Piano

Q: Future instruments?
- Guitar
- Violin

10. Quaid – Music Educator Interview Notes

Q: Tell me about yourself?

- Education degree; music has always been part of her life; Family was drawn to music and she got her son into music. She found kinder music. Specifically, from 0 to 7 ages. She teaches babies with their parents' toddlers and babies. She plays guitar she sings and was in the band. Talks about how she does not play all the instruments but would be helpful to have a robot play an instrument. Starts them on a Glock and shpiel. Younger kids are still developing coordination and motor skills for the Xylophone and violin.

Q: What type of students do you teach?

- Ages 0-7

Q: What musical instruments do you teach with?

- Hand drums, shakers, jingle bells, rhythm sticks, sound blocks, zig zag blocks, balls, ribbons, glock and shpiel(5-7 year olds), (all percussion), recorder a little bit and the dull simmer

Q: Do you have any children with disabilities that want to learn music?

- Kids who had sensory issues that were not able to participate. Kids who are blind, autism. Another with cerebral paulsy (motor skills were fine, limitation was walking).

Q: What instruments do these children best respond to or you think they would respond to the best?

- Most children are drawn to the drums and they love the drum set. Up tempo music gets them really excited, quite music for quiet time. Creative music for creative portion of class. Q: Instrument; where do students struggle?
- Not a lot of struggle in some of the instruments. Only difficulty is on the glock and spiel and the recorder and being able to move the hands correctly.

Q: What musical concepts do you think could best be demonstrated through an instrument that we could design?

- Concepts – pitch high and low are concepts that we teach. The small keys are high pitched and the bigger keys are low pitched. Tempo is something as well. Allegro would be fast.

Q: How to keep kids engaged? Hardware specific

- Color coated for a xylophone for each note would be really cool. Have a reoccurring notes to have the same color.

Q: What would you like out of a self-playing educationally designed instrument?

- Accommodations for different abilities

Q: How much are you willing to pay for the product?

- Small business owner – couple hundred dollars.

Q: Do you think it would be helpful to have some kind of immersive?

- Having a button that would allow the student to play the instrument and hit the mallet and allow the student a more dynamic environment

7.4 Appendix D: Customer Needs List

Prompt	Customer Statement	Interpreted Need	Weight
Aesthetics	”I think a sleek, minimal aesthetic would be the best” “We want the instruction to be the main attraction so do not make the instrument super colorful so that the kids do not lose sight of the lesson.”	The visual design should be attractive and not overly visually complex.	2
	“Should be something colorful so that kids are interested.” “My ukulele has different color strings, so that’s why I like it a whole bunch.”	The visual design should be colorful.	4
Performance	“Piano or guitar where the device can play one side of the instruments. So you can learn one side at a time. Also a good use when a piano song requires 4 hands.”	Device that can be used as a training tool for instruments that require two hands.	2
	“Special needs kids could find an advantage in this to manipulate an instrument to be able to play an instrument. Specifically designed.”	Assisted device that can be used to play an instrument another way.	3
	“Find some way to play this instrument in a physically impossible way.”	Play an instrument in a unique way.	5
	“I would like to see a robot adding emotion or color to the music it’s playing. Knowing when to play soft and loud. Adding nuances to the music. This is the difference between listening live and listening online.”	Add dynamics to the automated instrument playing (i.e. intensity of sound).	4
Music	“My favorite genres are Spanish, R& B, Pop, and Christmas jingles. In general though, I like catchy and chill music.” “Baby Shark, Among Us remix, Africa, kpop”	The songs should be recognizable across a broad range of ages.	5
	“Find music that is public domain when it comes to copyright and find music that can be helpful to children.”	The songs should be catchy and musically interesting to children.	3
	”A demonstration failure is something that either doesn’t do what it’s supposed to do, or they’re just like meh, okay. . . ”	The song should be clearly audible.	5
Cost	“I am a small business owner – so maybe a couple hundred dollars.”	Cost of instrument should be minimal	2
	“Not much and this is a very niche instrument to help children out with this. Budgets are extremely tight when it comes to music. This is something that would come out of a different department.”	Cost of instrument should be minimal	5
	“So the thing we get into is if it was a really cool demonstration that had some valid purposes we might spend \$150 maybe \$200.”	The maximum price for the product would have to be less than a few hundred dollars.	4

Prompt	Customer Statement	Interpreted Need	Weight
User Interface	"Maybe should have a piano feature." "Special needs kids could find an advantage in this to manipulate an instrument to be able to play an instrument. Specifically designed." "Having a button that would allow the student to play the instrument and hit the mallet and allow the student a more dynamic environment."	Robot has inputs for the user to actuate each note.	4
	"It should be controlled by a controller or a smartphone app."	Device can be controlled remotely.	1
	"It should have a playback function that can record and play sounds that the kids create, and for there to be a step-by-step tutorial for the kids to follow."	Robot can have a record and playback function.	1
Size/Shape	"And, you know, and not so heavy that, a person, a regular teacher can't pick it up and move around."	Instrument must be compact and under 25lbs.	5
	"Cause I mean storage space gets tight, so it needs to be able to, without taking it completely apart, maybe fold down or not be huge, so that it can fit on the shelf."	Instruments should be compact enough to fit on a shelf when not in use.	5
	"...a lab demo table, or a regular old lab table. So maybe you know, 3 feet by 2 and a half feet maybe."	Instrument should be compact enough to fit on a table top.	5
Time & Maintenance	"Setup and Clean up should be within the time of switching classes. About 10 min each." "I think the time it takes to set up will depend on the size. The bigger the instrument, the longer it's going to take. If it's a smaller instrument, it should be portable. At the very most, it should take 20 minutes."	The automated instrument should take no longer than 20 minutes to set up.	5
	"Should be able to be replaced for cheap if broken."	Parts should be cheap and easily replaceable.	1
	"If it's like it's gotta be you know completely taken apart and put together, and you know, major maintenance done and that would be a hassle, then it would never get used."	The device should be robust, easily maintained, and should be easy and simple to utilize.	5
Safety	"... And it would have to come with, you know it has moving parts, it would have to come with signage and or guarding so there's no pinch points."	The product should be equipped with the proper safety labels and equipment.	5

7.5 Appendix E: House of Quality

			How													
			Volume	Mass	Boundary Dimensions	Amount of Parts	Cost	Aesthetics Rating	Song Recognizability	Time	Noise	Safety Factor	Force	Risk	Required Inputs	Signal to Noise Ratio
Direction of Improvement			↓	↓	↓	↓	↑	↑	↑	↓	↓	↑	↓	↓	↓	↑
Units			m^3	kg	m	#	$	-	-	s	dB	#	N	-	#	dB
What	Aesthetics	Attractiveness						✓								
	Performance	Assembly Time				✓			✓							
		Robustness										✓				
		Repairability				✓				✓						
	Music	Music Choice							✓							
		Sound Quality									✓					✓
		Ambient Noise									✓					
	Size/Shape	Compactness	✓		✓											
		Portability	✓	✓	✓											
		Weight		✓												
	Cost	Device Cost				✓	✓									
	U. Interface	Usability													✓	
	Safety	Safeness											✓	✓		
Target			0.28	11.3	3x3x2.5	15	250	4	5/5	1200	40	2	25	1/5	3	80

7.6 Appendix F: Requirements List

Date	Demand or Wish	Customer Need	Design Requirement	Verification
9/11/22	W	The design should be visually appealing	Attractiveness rating of at least 4/5.	Customer survey
9/11/22	D	The song should be clearly audible	The automated instrument should have a signal to noise ratio of 80dB	Decibel meter
9/11/22	W	The maximum price a customer may pay for the product would have to be less than a few hundred dollars.	Product must not exceed $250	Bill of Materials
9/11/22	W	Device should be lightweight enough to be carried by a single person (the average woman).	Total weight of the device should not exceed 11.3 kg (25lbs). Have handles or holding points if large.	CAD/Weighing of Product
9/11/22	W	Instruments should be compact enough to fit on a shelf.	Limit the volume of the device to 0.28 m^3.	CAD
9/11/22	D	Instrument, when in use, should be compact enough to fit on a table top.	Limit the size of the device to 3 x 3 x 2.5 meters	CAD
9/11/22	D	The device should be easy to learn and use.	Device should have a minimum of 3 inputs to streamline speed of operation.	Testing of product
9/11/22	D	The device should play at least 3 tunes/rhythms directly from a digital file.	. Device should be capable of playing 3 separate tunes/rhythms	Amount of tunes/rhythms & testing of product
9/11/22	W	The tunes/rhythms should be recognizable across a broad range of ages.	. Recognizability rating of 5/5	Customer Survey
9/19/22	D	Device, when in use, should be safe to use for all age ranges and certifications.	Maximum force output of 25 Newtons.	Customer Risk Survey and Testing product
9/11/22	D	The device should not take too long to set up or disassemble.	Set up and disassembly time does not exceed 20 minutes.	Testing of Product
9/19/22	D	Sound should be created acoustically through mechanical means.	Use of a percussion, strumming, or airflow mechanism to produce sound.	Prototyping

Date	Demand or Wish	Customer Need	Design Requirement	Verification
9/11/22	D	Device should produce minimal background noise.	Maximum decibel output when the device is on but not playing should be 40 dB.	Decibel meter
9/11/22	D	Device should be robust enough to withstand normal handling.	All components of the device should maintain a safety factor of at least 2 during normal handling conditions.	FEA and Calculations
9/11/22	W	Device should be quick and easy to repair.	Minimal repairs should be able to be made within 20 minutes and the number of components should be minimized to reduce failure points.	Prototype and Bill of Materials

7.7 Appendix G: Functional Models

7.7.1 Blackbox Diagram

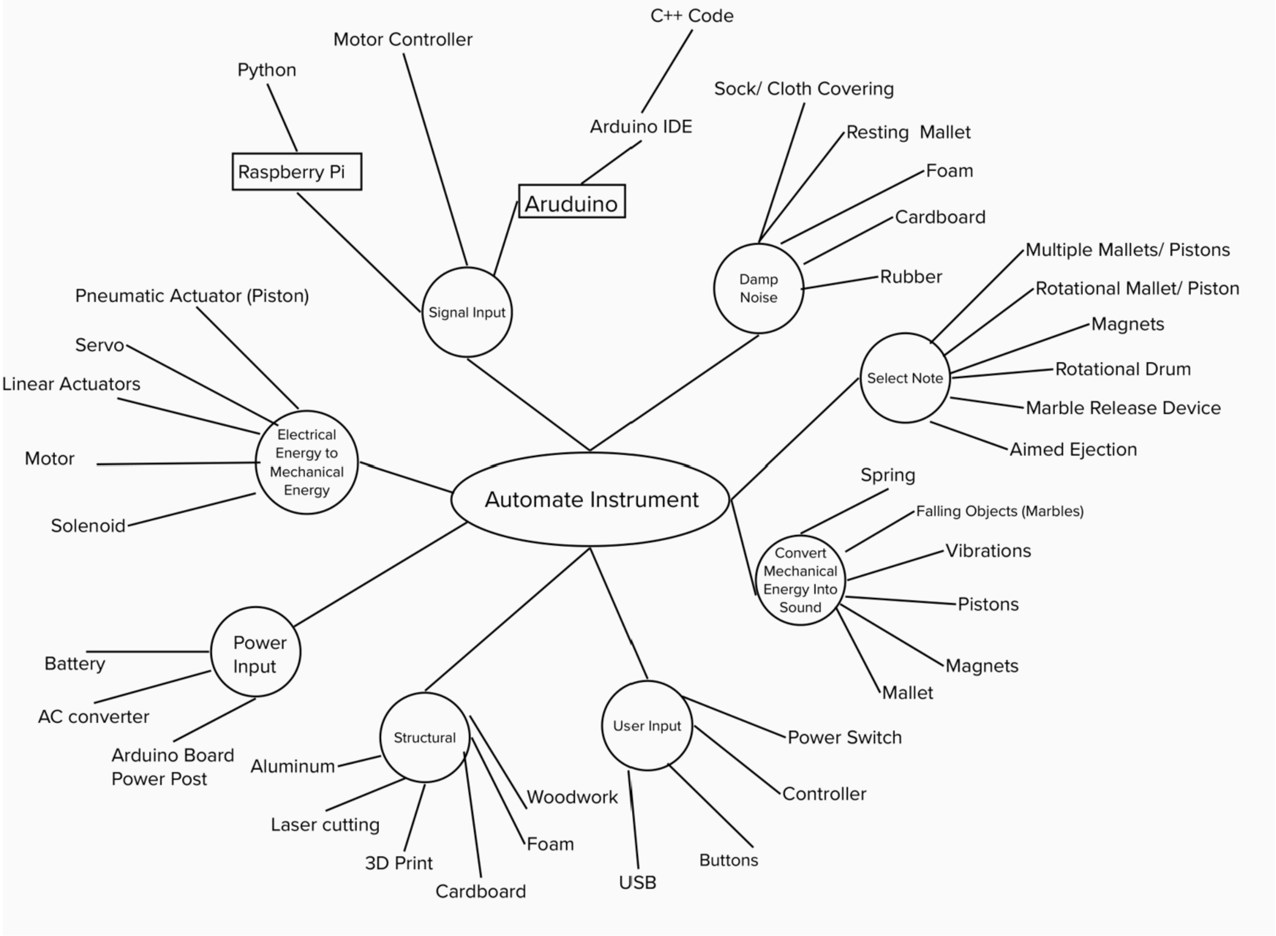


Figure H.1. Mind Map

7.8 Appendix H: Concept Generation

7.8.1 Mind Map

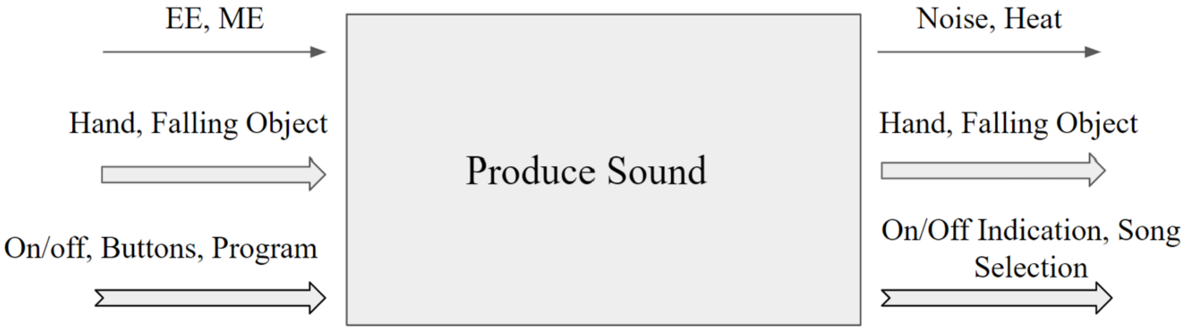


Figure G.1. Black Box Diagram

7.8.2 Functional Model

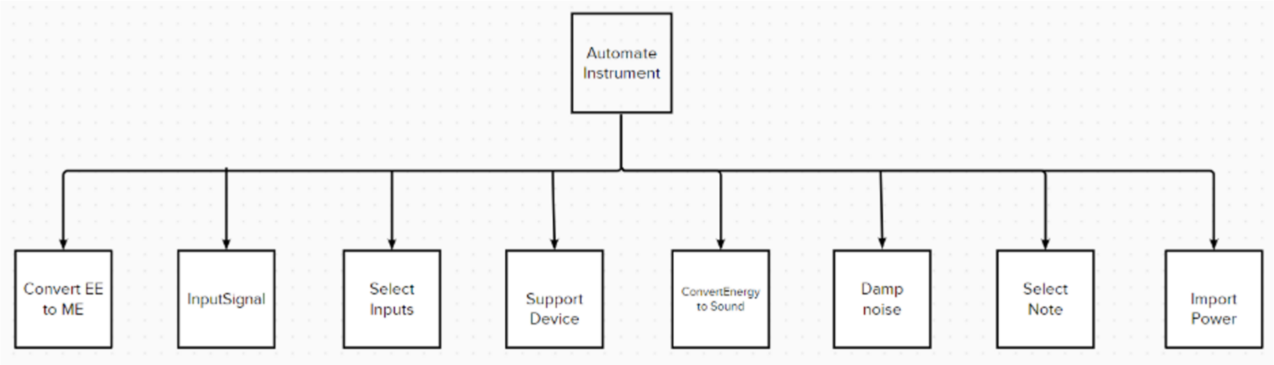
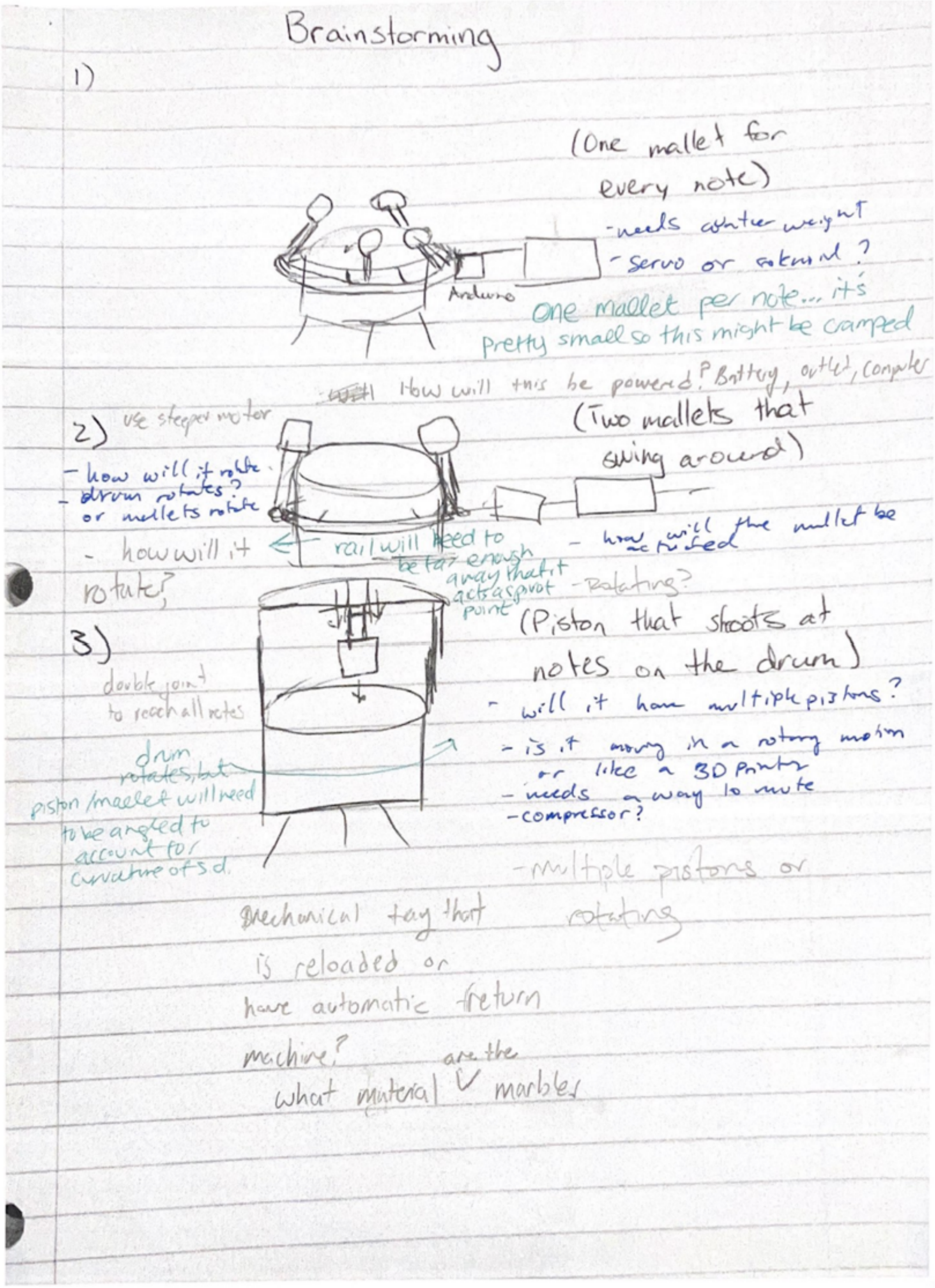


Figure G.2. Functional Model

7.8.3 6-3-5



Brainstorming

1)

(One mallet for every note)
- needs counter weight
- servo or solenoid?

Arduino

one mallet per note... it's pretty small so this might be camped

How will this be powered? Battery, outlet, Computer

2) use stepper motor

(Two mallets that swing around)

- how will it rotate.
- drum rotates? or mallets rotate

- how will it rotate?

rail will need to be far enough away that it acts as pivot point

- how will the mallet be actuated
- Rotating?

3)

(Piston that shoots at notes on the drum)
- will it have multiple pistons?
- is it moving in a rotary motion or like a 3D Printer
- needs a way to mute
- compressor?

double joint to reach all notes

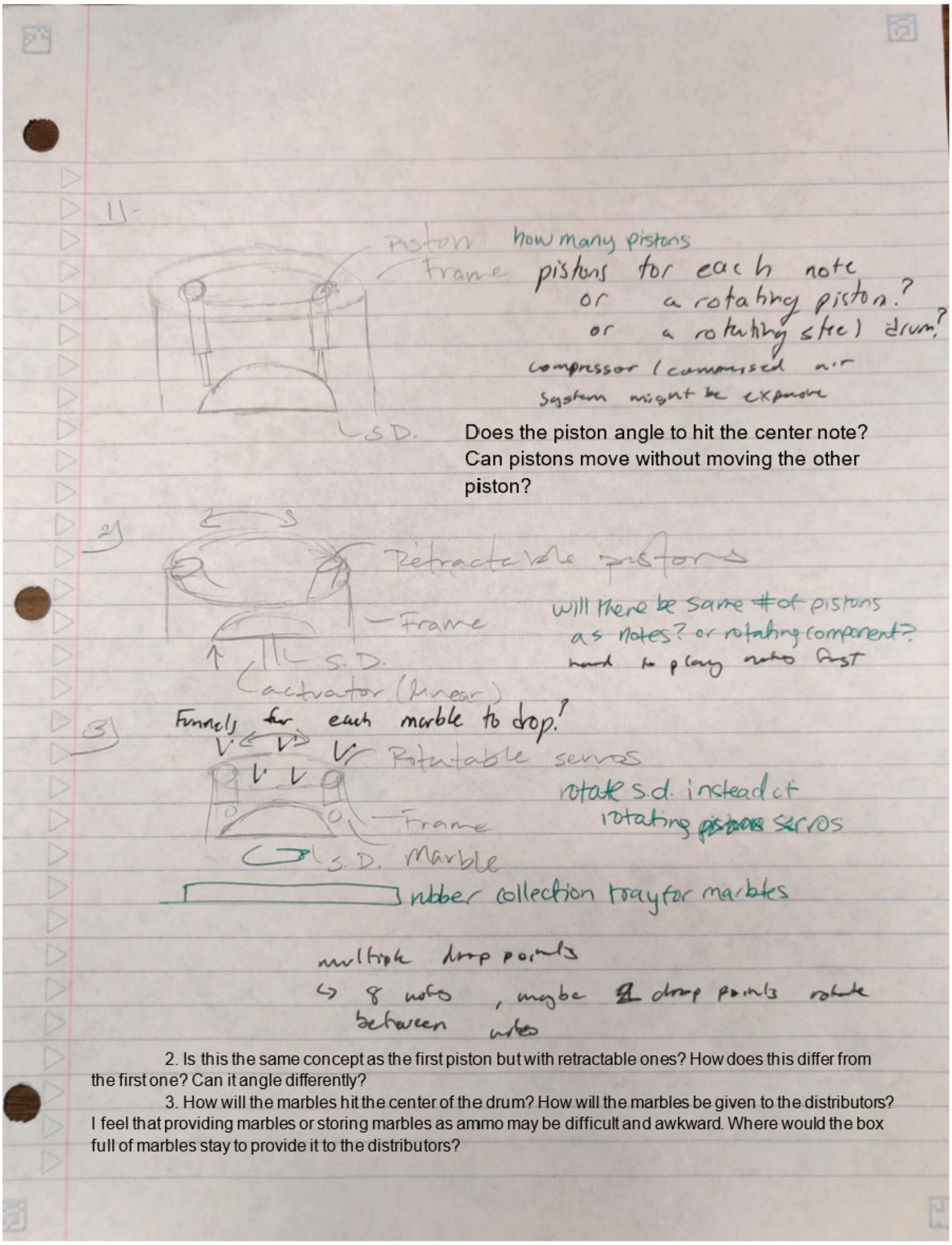
drum rotates, but piston/mallet will need to be angled to account for curvature of s.d.

- multiple pistons or rotating

mechanical tray that is reloaded or have automatic return machine?

what material are the marbles

Figure H.2. Steven 6-3-5 Concepts



how many pistons

pistons for each note
or a rotating piston?
or a rotating steel drum?

compressor / compressed air
system might be expensive

Does the piston angle to hit the center note?
Can pistons move without moving the other piston?

will there be same # of pistons
as notes? or rotating component?
hard to play notes fast

Funnels for each marble to drop?

rotate s.d. instead of
rotating ~~pistons~~ servos

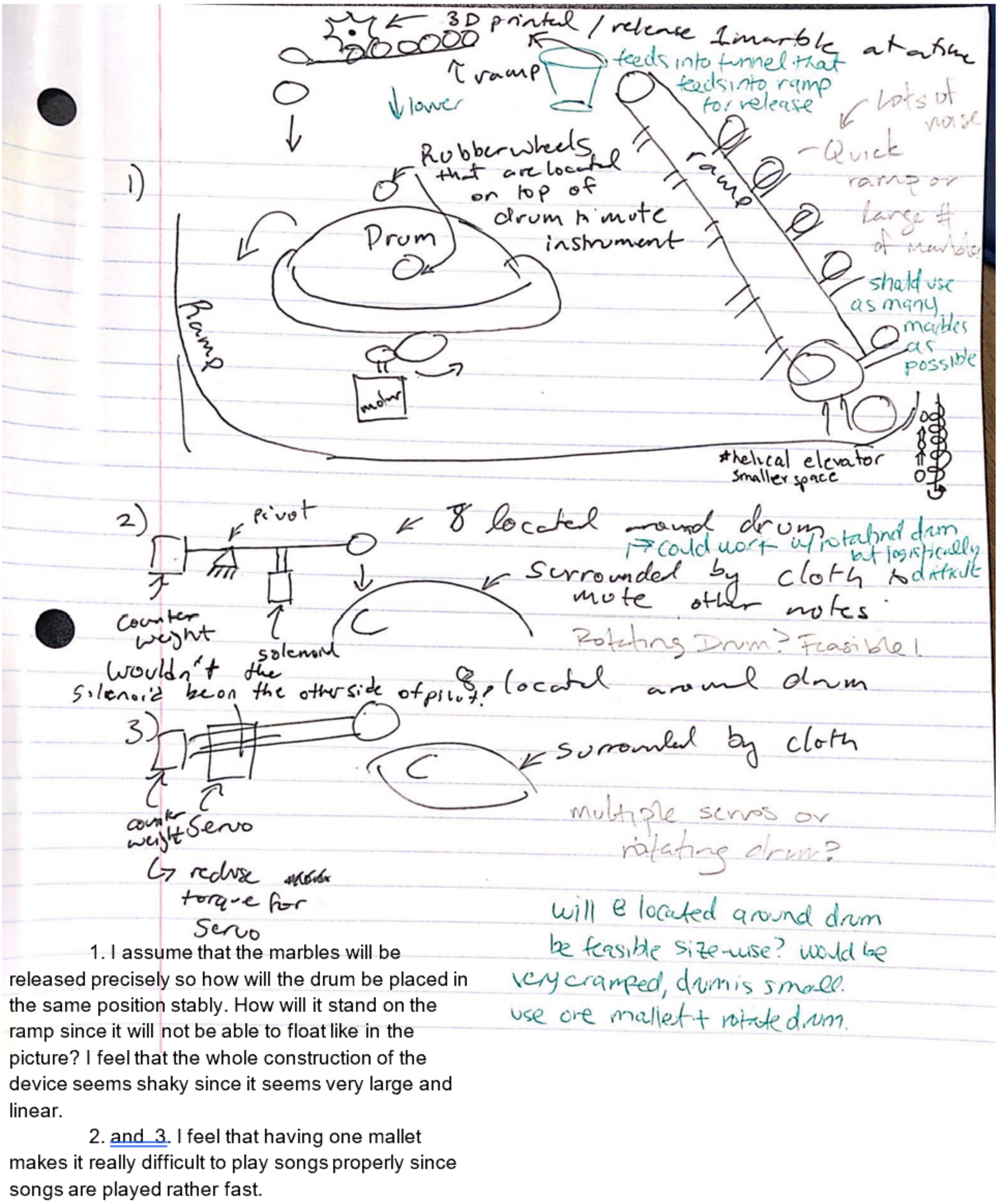
rubber collection tray for marbles

multiple drop points
↳ 8 notes, maybe 4 drop points rotate
between notes

2. Is this the same concept as the first piston but with retractable ones? How does this differ from the first one? Can it angle differently?

3. How will the marbles hit the center of the drum? How will the marbles be given to the distributors? I feel that providing marbles or storing marbles as ammo may be difficult and awkward. Where would the box full of marbles stay to provide it to the distributors?

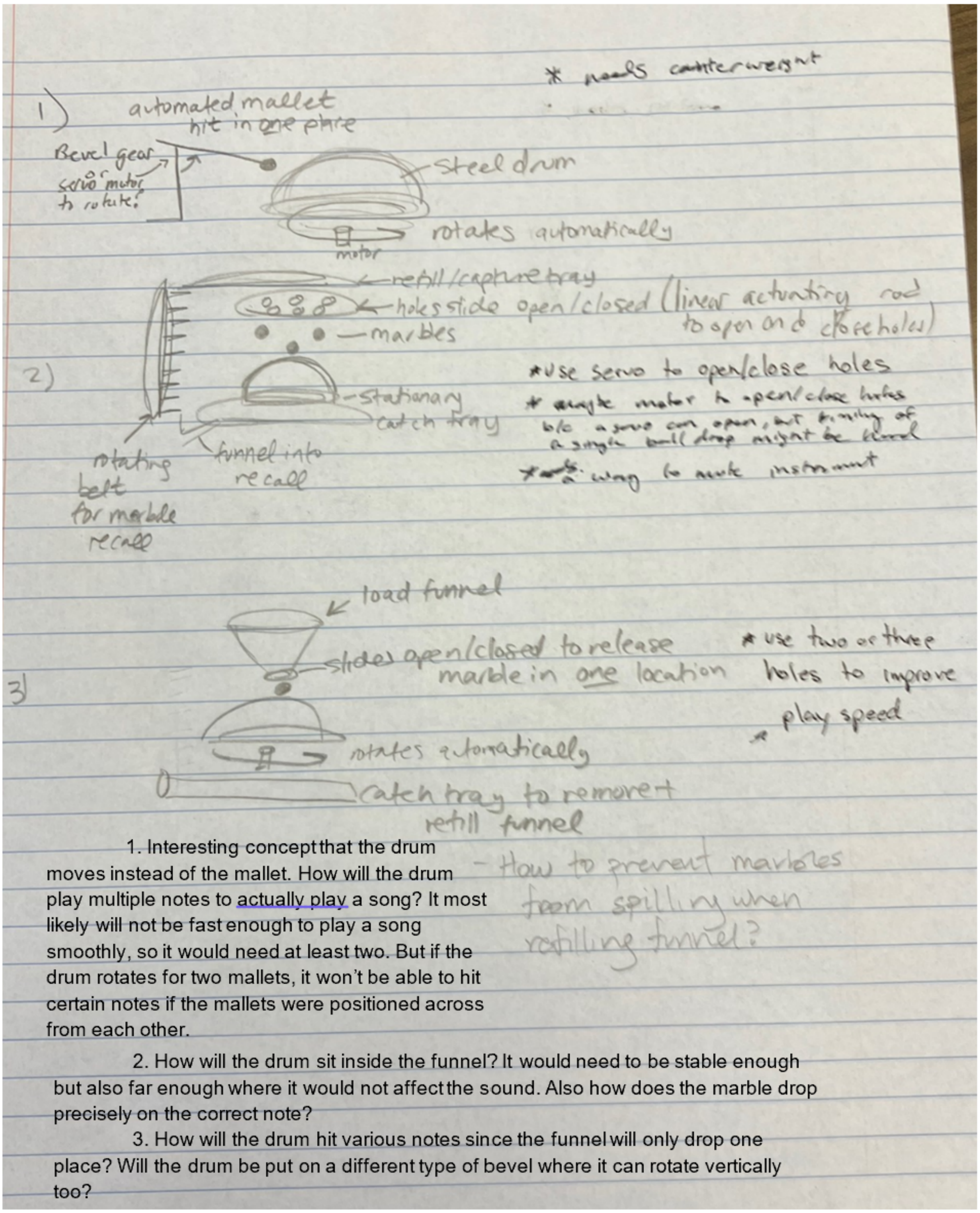
Figure H.3. Christian 6-3-5 Concepts



1. I assume that the marbles will be released precisely so how will the drum be placed in the same position stably. How will it stand on the ramp since it will not be able to float like in the picture? I feel that the whole construction of the device seems shaky since it seems very large and linear.

2. and 3. I feel that having one mallet makes it really difficult to play songs properly since songs are played rather fast.

Figure H.4. Neil 6-3-5 Concepts

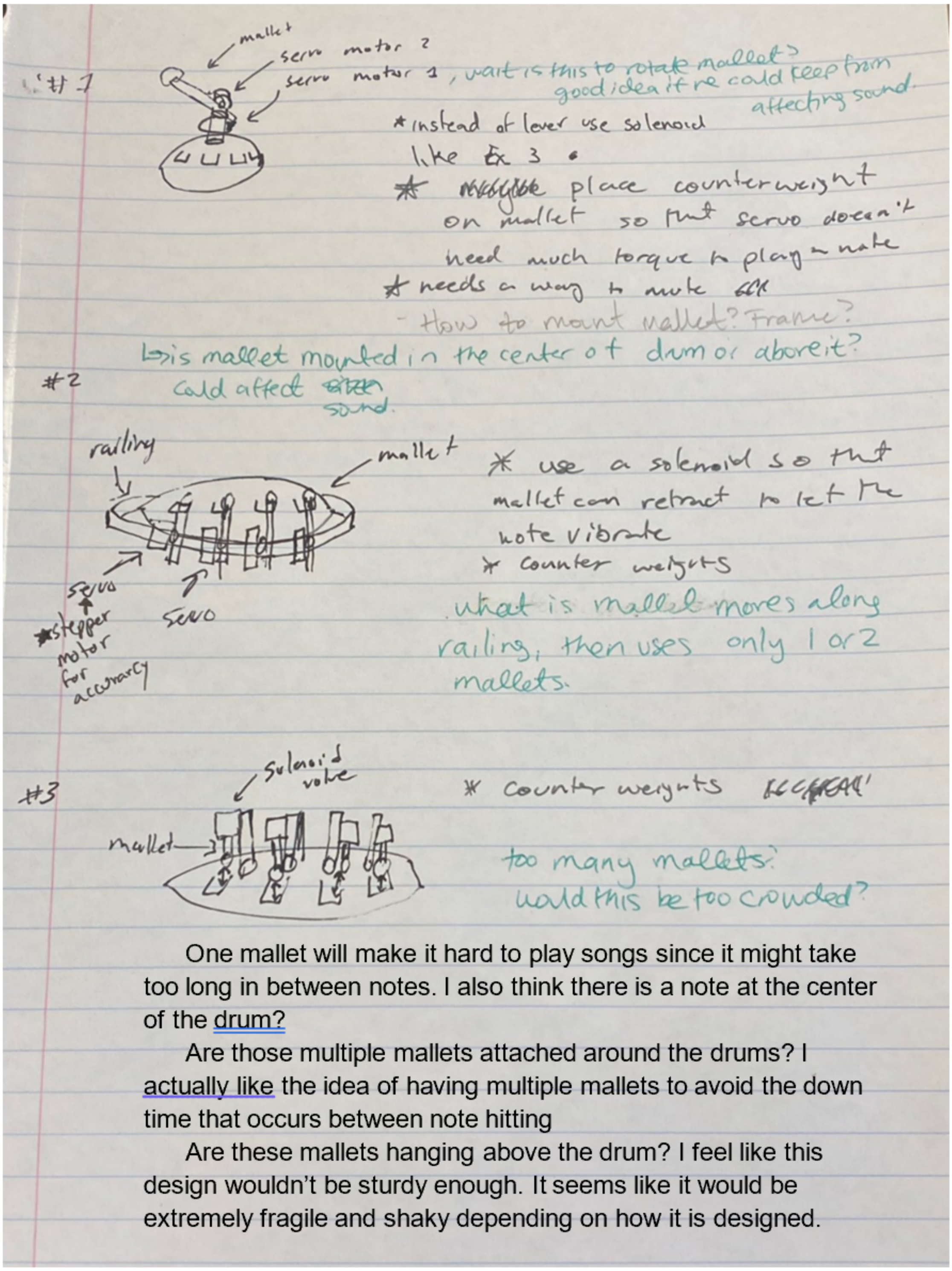


1. Interesting concept that the drum moves instead of the mallet. How will the drum play multiple notes to actually play a song? It most likely will not be fast enough to play a song smoothly, so it would need at least two. But if the drum rotates for two mallets, it won't be able to hit certain notes if the mallets were positioned across from each other.

2. How will the drum sit inside the funnel? It would need to be stable enough but also far enough where it would not affect the sound. Also how does the marble drop precisely on the correct note?

3. How will the drum hit various notes since the funnel will only drop one place? Will the drum be put on a different type of bevel where it can rotate vertically too?

Figure H.5. Zoe 6-3-5 Concepts



#1

, wait is this to rotate mallet? good idea if we could keep from affecting sound.

*instead of lever use solenoid like Ex 3

* ~~[illegible]~~ place counterweight on mallet so that servo doesn't need much torque to play a note

* needs a way to mute ~~[illegible]~~

- How to mount mallet? Frame?

↳ is mallet mounted in the center of drum or above it? Could affect ~~[illegible]~~ sound.

#2

* use a solenoid so that mallet can retract to let the note vibrate

* counter weights

*stepper motor for accuracy

what is mallet moves along railing, then uses only 1 or 2 mallets.

#3

* counter weights ~~[illegible]~~

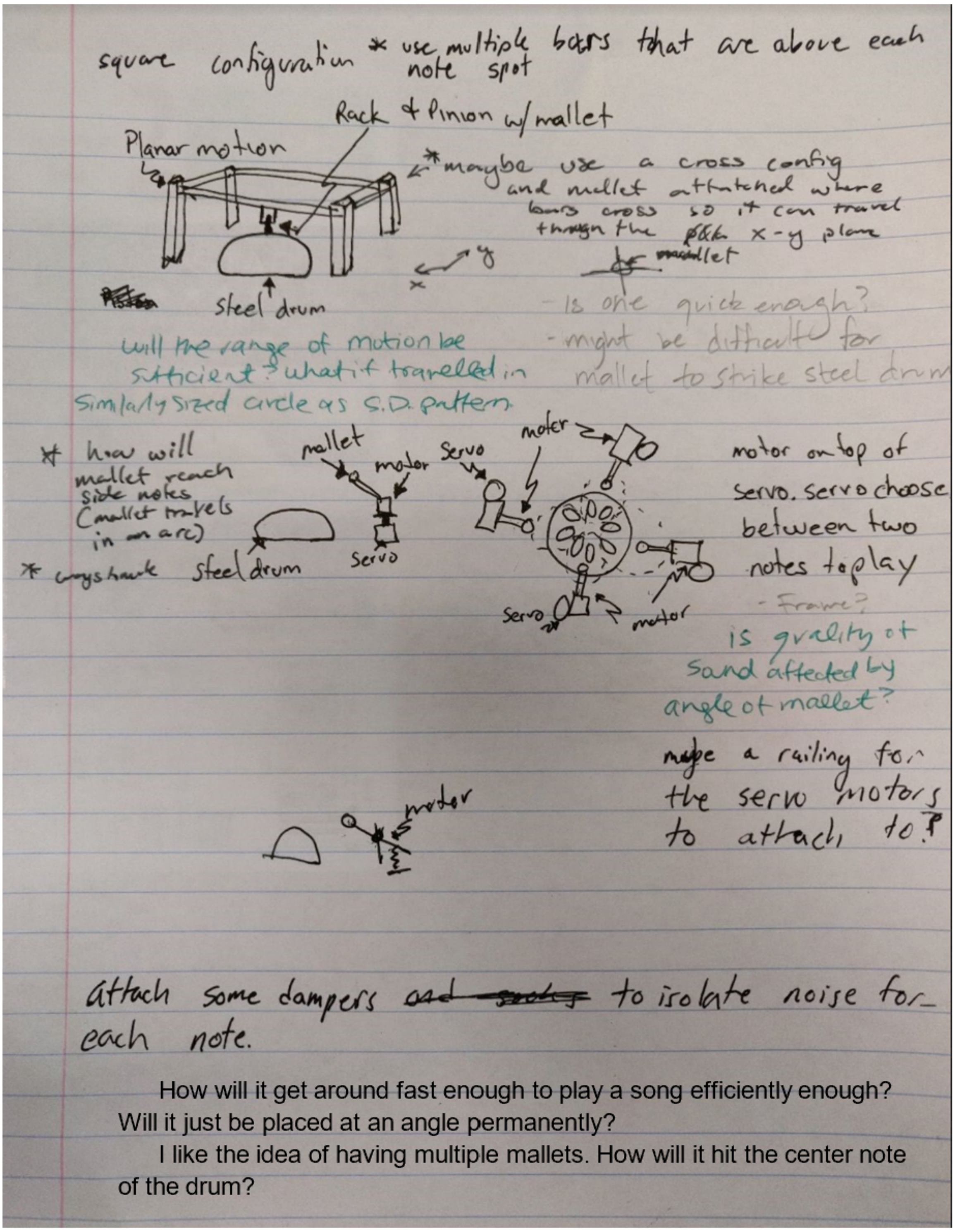
too many mallets? would this be too crowded?

One mallet will make it hard to play songs since it might take too long in between notes. I also think there is a note at the center of the drum?

Are those multiple mallets attached around the drums? I actually like the idea of having multiple mallets to avoid the down time that occurs between note hitting

Are these mallets hanging above the drum? I feel like this design wouldn't be sturdy enough. It seems like it would be extremely fragile and shaky depending on how it is designed.

Figure H.6. Quaid 6-3-5 Concepts


square configuration * use multiple bars that are above each note spot

*maybe use a cross config and mallet attatched where bars cross so it can travel through the x-y plane

- Is one quick enough?
- might be difficult for mallet to strike steel drum

will the range of motion be sufficient? what if travelled in similarly sized circle as S.D. pattern.

* how will mallet reach side notes (mallet travels in an arc)

* wayshack

motor on top of servo. servo choose between two notes to play

- Frame?

is quality of sound affected by angle of mallet?

maybe a railing for the servo motors to attach to?

attach some dampers ~~and springs~~ to isolate noise for each note.

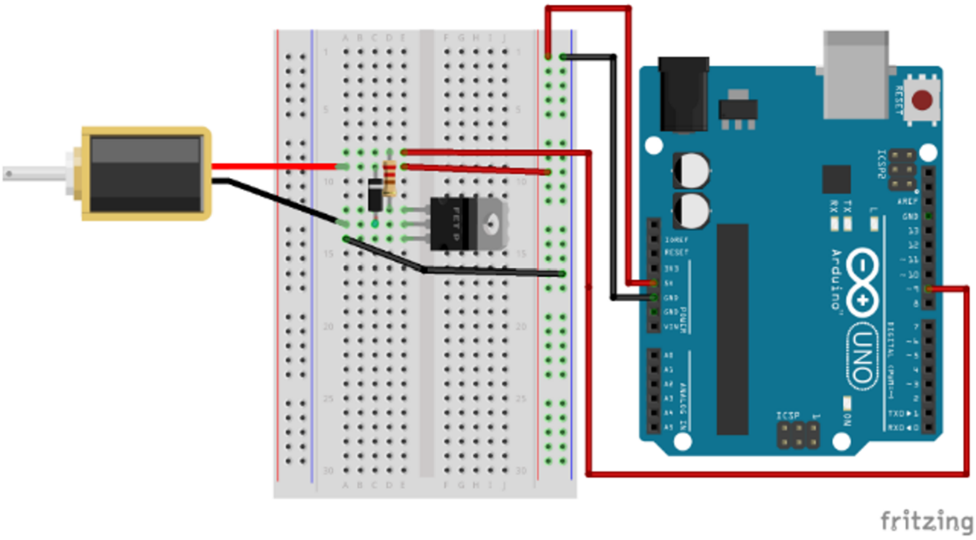
How will it get around fast enough to play a song efficiently enough? Will it just be placed at an angle permanently?

I like the idea of having multiple mallets. How will it hit the center note of the drum?

Figure H.7. Frank 6-3-5 Concepts

7.9 Appendix I: Prior Art

Figure I.1. Connecting a solenoid to an Arduino



Aiden. (2022) *Controlling a Solenoid with an Arduino* [Diagram]. Core Electronics.com. https://core-electronics.com.au/guides/solenoid-control-with-arduino/

Figure I.2. Marble Recall Conveyor Belt

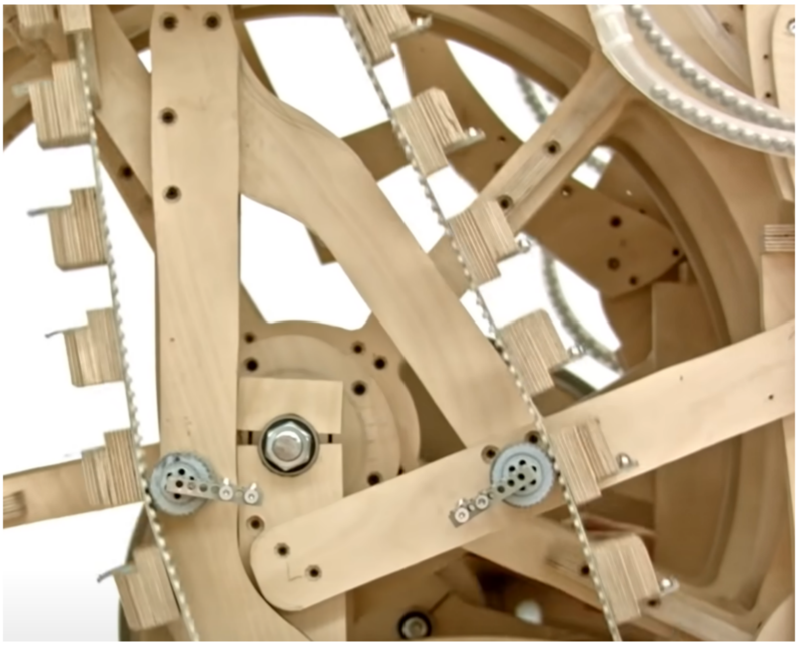
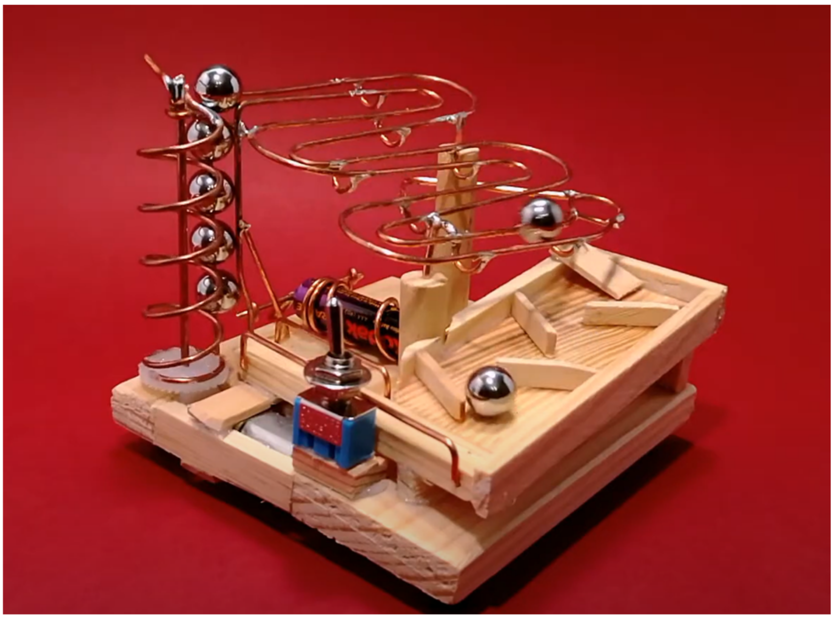


Figure I.3. Marble “Grabber” for Marble Recall

Lewis, D. (2016) *Wintergatan Marble Machine* [Photograph]. Smithsonian.com. https://www.smithsonianmag.com/smart-news/machine-makes-music-marbles-180958293/

Figure I.4. Helical Marble Lift



Frank, S. (2020). *Spiral Lifter Marble Machine* [Photograph]. https://www.youtube.com/watch?v=FgQfJPAGfws&list=LL&index=4

7.10 Appendix J: Morphological Matrix

Table J.1. Base Morphological Matrix

Sub-function	Solutions						
Import Power	Crank	AC Converter	Battery	Arduino 5V	Hydraulic	Wind Turbine	Solar Panel
Convert EE to ME	Servo	Motor	Piston	Linear Actuator	Solenoid		
Input Signal	Crank	Motor Controller	Arduino	Rasberry Pi	Button Input		
Convert E to Sound	Spring	Falling Objects	Amplifier	Vibrations	Pistons	Mallets	Magnets
Support Device	Woodwork	Cutting Process	3D Print	Laser Cutting	Machining	Foam	PVC
Support Device	Cardboard	Rubber	Plastic				
Select Inputs	Buttons	Controller	USB	Power Switch	Crank Handle	Computer Program	
Select Note	Mallets or Pistons	Rotational Mallets	Magnets	Rotating Drum	Marble Device	Aimed Ejection	
Damp Noise	Sock/Cloth Covering	Resting Mallet	Foam	Rubber	Cardboard		

Table J.2. Morphological Matrix Solution A

Sub-function	Solutions						
Import Power	Crank	AC Converter	Battery	Arduino 5V	Hydraulic	Wind Turbine	Solar Panel
Convert EE to ME	Servo	Motor	Piston	Linear Actuator	Solenoid		
Input Signal	Crank	Motor Controller	Arduino	Rasberry Pi	Button Input		
Convert E to Sound	Spring	Falling Objects	Amplifier	Vibrations	Pistons	Mallets	Magnets
Support Device	Woodwork	Cutting Process	3D Print	Laser Cutting	Machining	Foam	PVC
Support Device	Cardboard	Rubber	Plastic				
Select Inputs	Buttons	Controller	USB	Power Switch	Crank Handle	Computer Program	
Select Note	Mallets or Pistons	Rotational Mallets	Magnets	Rotating Drum	Marble Device	Aimed Ejection	
Damp Noise	Sock/Cloth Covering	Resting Mallet	Foam	Rubber	Cardboard		

Table J.3. Morphological Matrix Solution B

Sub-function	Solutions						
Import Power	Crank	AC Converter	Battery	Arduino 5V	Hydraulic	Wind Turbine	Solar Panel
Convert EE to ME	Servo	Motor	Piston	Linear Actuator	Solenoid		
Input Signal	Crank	Motor Controller	Arduino	Rasberry Pi	Button Input		
Convert E to Sound	Spring	Falling Objects	Amplifier	Vibrations	Pistons	Mallets	Magnets
Support Device	Woodwork	Cutting Process	3D Print	Laser Cutting	Machining	Foam	PVC
Support Device	Cardboard	Rubber	Plastic				
Select Inputs	Buttons	Controller	USB	Power Switch	Crank Handle	Computer Program	
Select Note	Mallets or Pistons	Rotational Mallets	Magnets	Rotating Drum	Marble Device	Aimed Ejection	
Damp Noise	Sock/Cloth Covering	Resting Mallet	Foam	Rubber	Cardboard		

Table J.4. Morphological Matrix Solution C

Sub-function	Solutions						
Import Power	Crank	AC Converter	Battery	Arduino 5V	Hydraulic	Wind Turbine	Solar Panel
Convert EE to ME	Servo	Motor	Piston	Linear Actuator	Solenoid		
Input Signal	Crank	Motor Controller	Arduino	Rasberry Pi	Button Input		
Convert E to Sound	Spring	Falling Objects	Amplifier	Vibrations	Pistons	Mallets	Magnets
Support Device	Woodwork	Cutting Process	3D Print	Laser Cutting	Machining	Foam	PVC
Support Device	Cardboard	Rubber	Plastic				
Select Inputs	Buttons	Controller	USB	Power Switch	Crank Handle	Computer Program	
Select Note	Mallets or Pistons	Rotational Mallets	Magnets	Rotating Drum	Marble Device	Aimed Ejection	
Damp Noise	Sock/Cloth Covering	Resting Mallet	Foam	Rubber	Cardboard		

Table J.5. Morphological Matrix Solution D

Sub-function	Solutions						
Import Power	Crank	AC Converter	Battery	Arduino 5V	Hydraulic	Wind Turbine	Solar Panel
Convert EE to ME	Servo	Motor	Piston	Linear Actuator	Solenoid		
Input Signal	Crank	Motor Controller	Arduino	Rasberry Pi	Button Input		
Convert E to Sound	Spring	Falling Objects	Amplifier	Vibrations	Pistons	Mallets	Magnets
Support Device	Woodwork	Cutting Process	3D Print	Laser Cutting	Machining	Foam	PVC
Support Device	Cardboard	Rubber	Plastic				
Select Inputs	Buttons	Controller	USB	Power Switch	Crank Handle	Computer Program	
Select Note	Mallets or Pistons	Rotational Mallets	Magnets	Rotating Drum	Marble Device	Aimed Ejection	
Damp Noise	Sock/Cloth Covering	Resting Mallet	Foam	Rubber	Cardboard		

Table J.6. Morphological Matrix Solution E

Sub-function	Solutions						
Import Power	Crank	AC Converter	Battery	Arduino 5V	Hydraulic	Wind Turbine	Solar Panel
Convert EE to ME	Servo	Motor	Piston	Linear Actuator	Solenoid		
Input Signal	Crank	Motor Controller	Arduino	Rasberry Pi	Button Input		
Convert E to Sound	Spring	Falling Objects	Amplifier	Vibrations	Pistons	Mallets	Magnets
Support Device	Woodwork	Cutting Process	3D Print	Laser Cutting	Machining	Foam	PVC
Support Device	Cardboard	Rubber	Plastic				
Select Inputs	Buttons	Controller	USB	Power Switch	Crank Handle	Computer Program	
Select Note	Mallets or Pistons	Rotational Mallets	Magnets	Rotating Drum	Marble Device	Aimed Ejection	
Damp Noise	Sock/Cloth Covering	Resting Mallet	Foam	Rubber	Cardboard		

Table J.7. Morphological Matrix Solution F

Sub-function	Solutions						
Import Power	Crank	AC Converter	Battery	Arduino 5V	Hydraulic	Wind Turbine	Solar Panel
Convert EE to ME	Servo	Motor	Piston	Linear Actuator	Solenoid		
Input Signal	Crank	Motor Controller	Arduino	Rasberry Pi	Button Input		
Convert E to Sound	Spring	Falling Objects	Amplifier	Vibrations	Pistons	Mallets	Magnets
Support Device	Woodwork	Cutting Process	3D Print	Laser Cutting	Machining	Foam	PVC
Support Device	Cardboard	Rubber	Plastic				
Select Inputs	Buttons	Controller	USB	Power Switch	Crank Handle	Computer Program	
Select Note	Mallets or Pistons	Rotational Mallets	Magnets	Rotating Drum	Marble Device	Aimed Ejection	
Damp Noise	Sock/Cloth Covering	Resting Mallet	Foam	Rubber	Cardboard		

7.11 Appendix K: Morphological Matrix Design Concepts

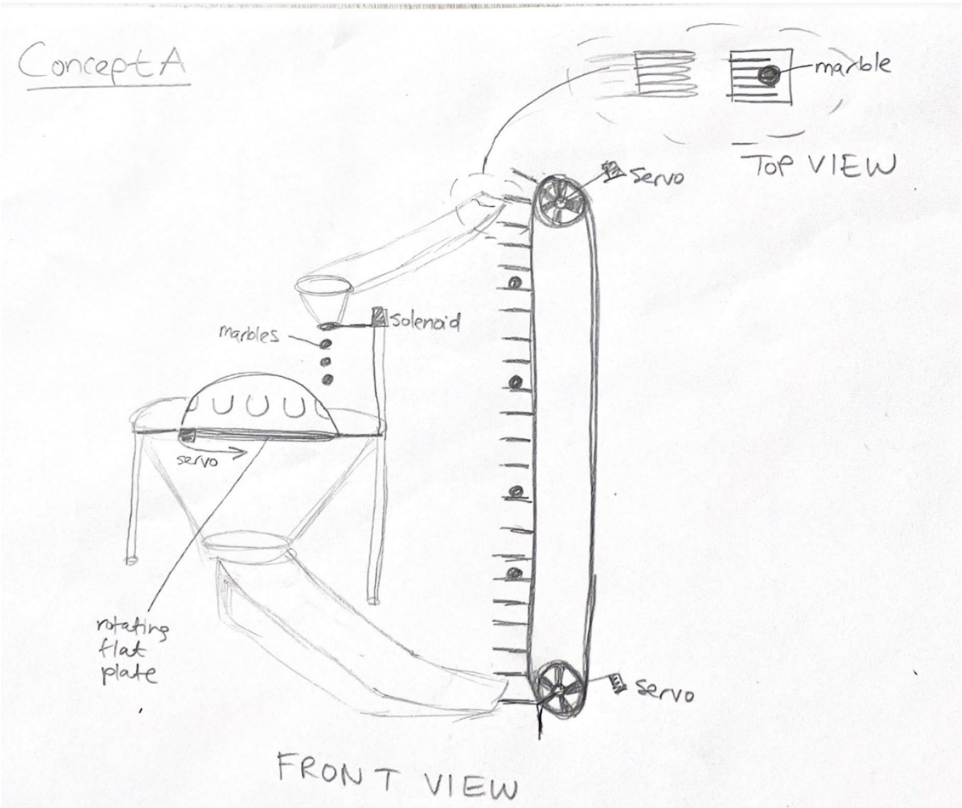


Figure K.1. Morph Matrix Falling Marbles Concept (Concept A)

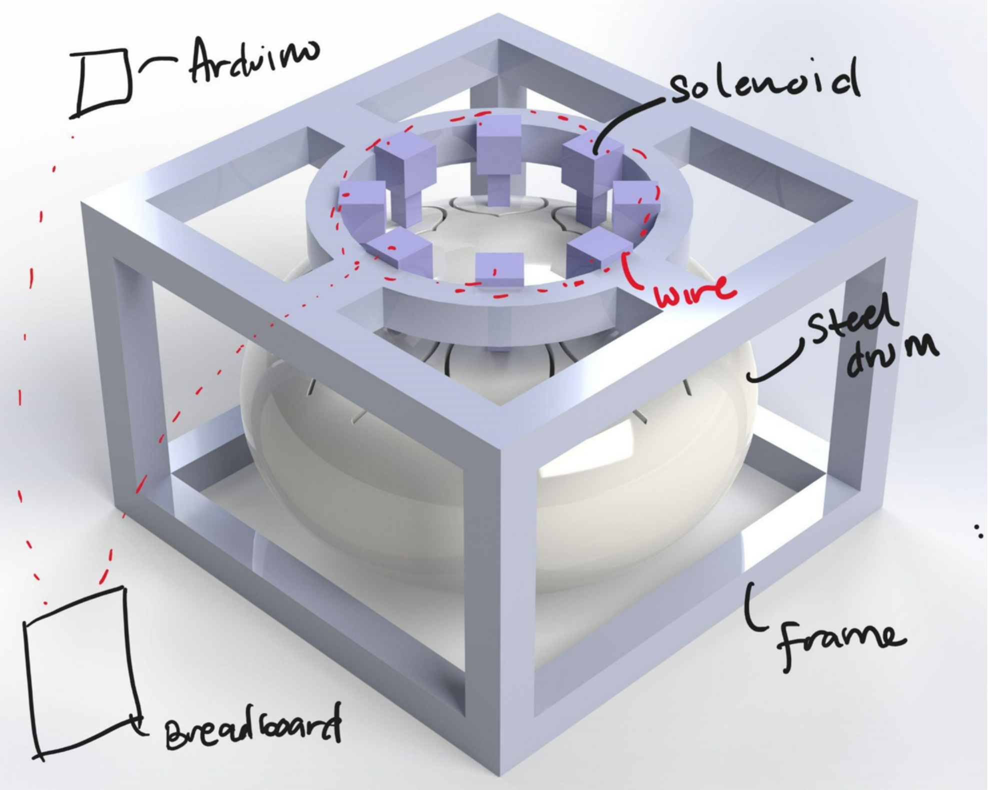


Figure K.2. Morph Matrix Piston Concept (Concept B)

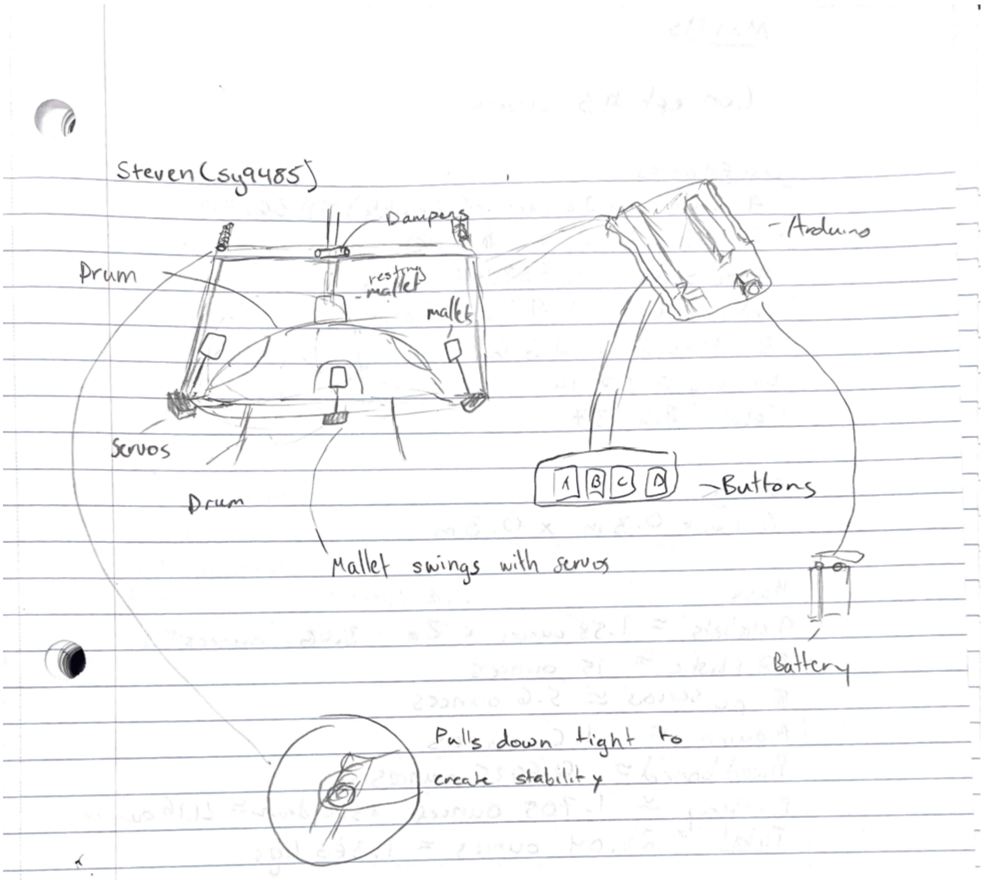


Figure K.3. Morph Matrix Multiple Mallets w/ Servos (Concept C)

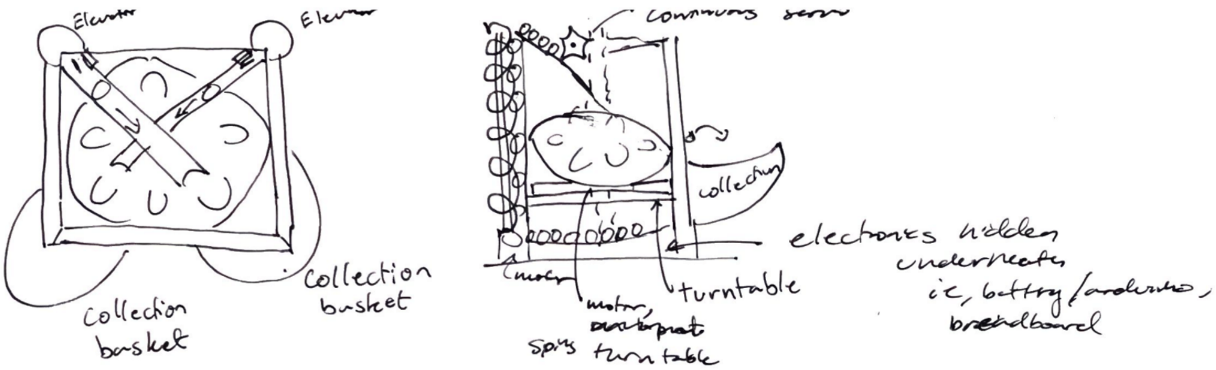


Figure K.4. Morph Matrix Slide Concept (Concept D)

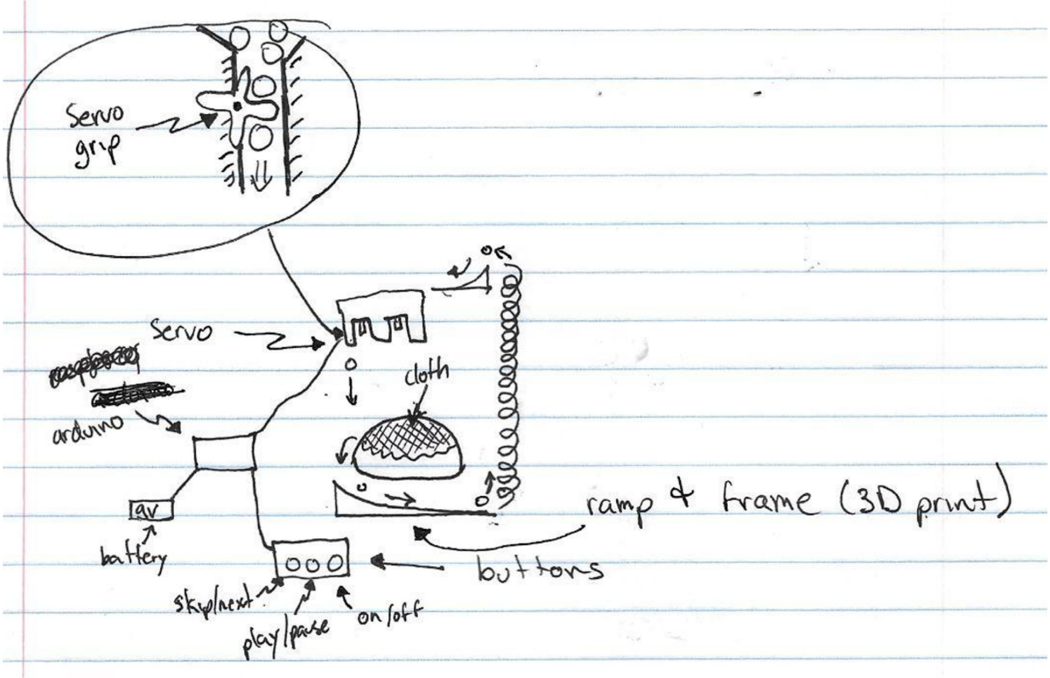


Figure K.5. Morph Matrix Slide Concept (Concept E)

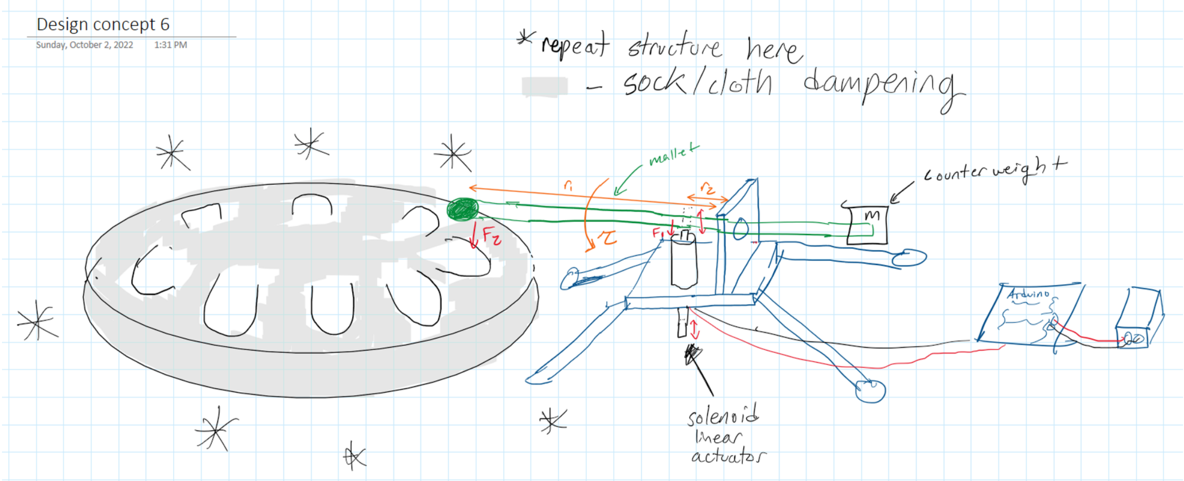


Figure K.6. Morph Matrix Slide Concept (Concept F)

7.12 Appendix L: Pugh Charts

Table L.1. Marble Datum Pugh Chart

Criteria	**Concept A**	Concept B	Concept C	Concept D	Concept E	Concept F
Cost	0	+	+	+	+	-
Sizing	0	-	+	-	+	+
Mass	0	+	+	+	+	+
Assembly Time	0	-	-	0	0	-
Force Estimate	0	-	-	0	-	-
# of Parts	0	+	-	-	+	-
$\Sigma+$	0	3	3	2	4	2
$\Sigma-$	0	3	3	2	1	4
Σ_{NET}	0	0	0	0	3	-2

Table L.2. Mallet Datum Pugh Chart

Criteria	Concept A	Concept B	**Concept C**	Concept D	Concept E	Concept F
Cost	-	+	0	+	-	-
Sizing	-	-	0	-	0	0
Mass	-	-	0	-	-	-
Assembly Time	+	+	0	+	+	0
Force Estimate	+	-	0	+	+	+
# of Parts	+	+	0	+	+	-
$\Sigma+$	3	3	0	4	3	1
$\Sigma-$	3	3	0	2	2	2
Σ_{NET}	0	0	0	2	1	-1

Table L.3. Piston Datum Pugh Chart

Criteria	Concept A	**Concept B**	Concept C	Concept D	Concept E	Concept F
Cost	-	0	-	+	-	-
Sizing	-	0	+	-	-	-
Mass	+	0	-	-	+	+
Assembly Time	+	0	+	+	+	+
Force Estimate	+	0	+	+	+	+
# of Parts	-	0	-	-	+	-
$\Sigma+$	2	0	3	3	4	3
$\Sigma-$	4	0	3	3	2	3
Σ_{NET}	-2	0	0	0	2	0

7.13 Appendix M: Pugh Chart Metric Calculations

Concept A:

Components	Cost ($)
3 Servos	12
1 Solenoid	5.50
Rubber belt w/ tread & gears	75
Metal frame & Plate	13
Rubber marbles	13
Conveyor belt metal frame	4
Rubber ramps & funnels	5
Arduino & breadboard	40

Factor	Value
Mass estimate	10.45 [kg]
Force estimate	0.045 [N]
Disassembly time	2 [min]
Size footprint	0.5 x 0.5 x 0.3 [m^3]

Concept B:

Components	Cost [$]	Mass [g]
8 Solenoids	44	400
Cardboard	30	1820
Arduino & breadboard	40	250
Total	115	3000

Factor	Value
Force estimate	2.5 [N]
# of parts	11
Disassembly time	5 [min]
Size footprint	6.5 x 6.5 x 6 [in^3]

Concept C:

Components	Cost [$]	Mass [g]
9 Mallets	37	87
3D printed structure	0	425
Arduino & breadboard	40	250
Battery	7	48
Total	121	1366

Factor	Value
Force estimate	1 [N]
# of parts	2
Disassembly time	6 [min]
Size footprint	0.2 x 0.2 x 0.3 [m^3]

Concept D:

Components	Cost [$]	Mass [g]
Servo	37	87
3 stepper motors	36	2325
Arduino & breadboard	40	250
Turntable	4	100
Wires & Buttons	5	-
Marbles	5	260
Total	95	5500

Factor	Value
Force estimate	0.45 [N]
# of parts	14
Disassembly time	1 [min]
Size footprint	24 x 24 x 18 [in^3]

Concept E:

Components	Cost [$]
Battery	25
8 Servos	40
Arduino	28
15 Buttons	8
Al Wire	15
Cloth	5
Marbles	9
Total	120

Factor	Value
Force estimate	0.45 [N]
Mass estimate	1.5 [kg]
# of parts	10
Disassembly time	1 [min]
Size footprint	0.38 [m^3]

Concept F:

Components	Cost [$]	Mass [g]
8 Solenoids	88	182
Battery	3.5	46
Arduino & breadboard	40	250
8 Mallets	36	72
8 Counterweights	5	23
Cloth	5	8.5
32 fasteners	6	-
1.5" plywood	20	-
Total	146	1500

Factor	Value
Force estimate	0.5 [N]
# of parts	28
Disassembly time	6 [min]
Size footprint	0.2 x 0.3 x 0.2 [m^3]

7.14 Appendix N: Low-Resolution Prototype

Figure N.1. Low Resolution Prototype (Marble Drop Design)

Figure N.2. Low Resolution Prototype Single Drop Mechanism

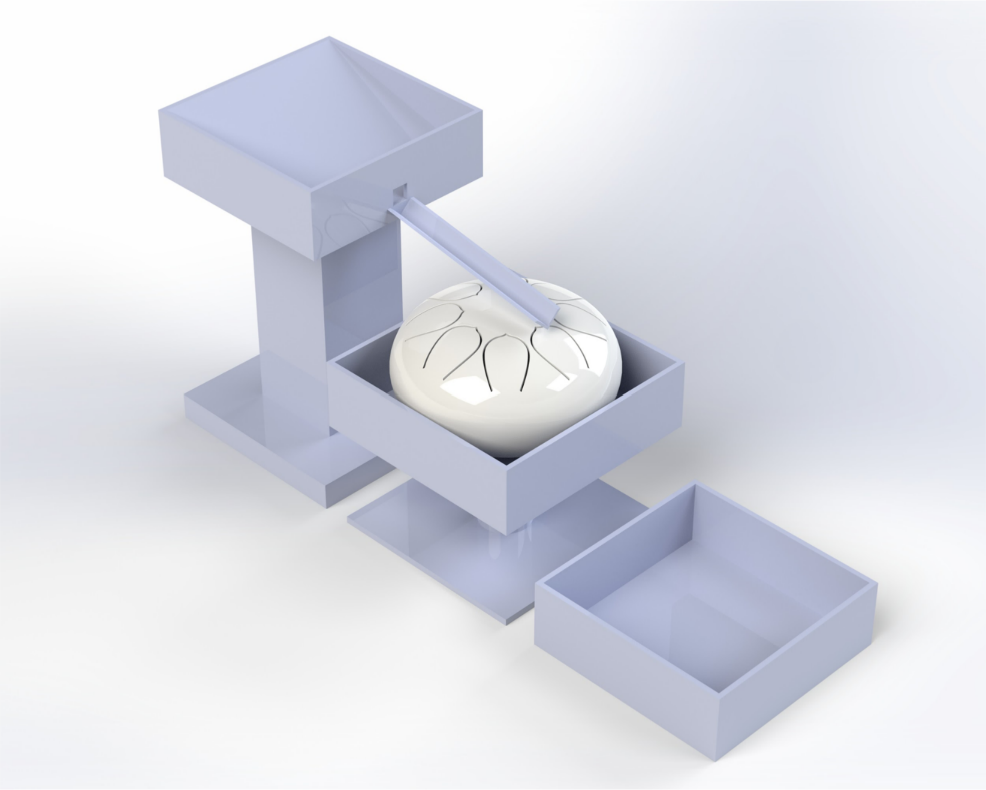


Figure N.3. CAD Low-Resolution Prototype

NOTE: The CAD version of the low resolution prototype is functionally identical to the physical prototype. There are small differences due to having no material limitations in CAD.

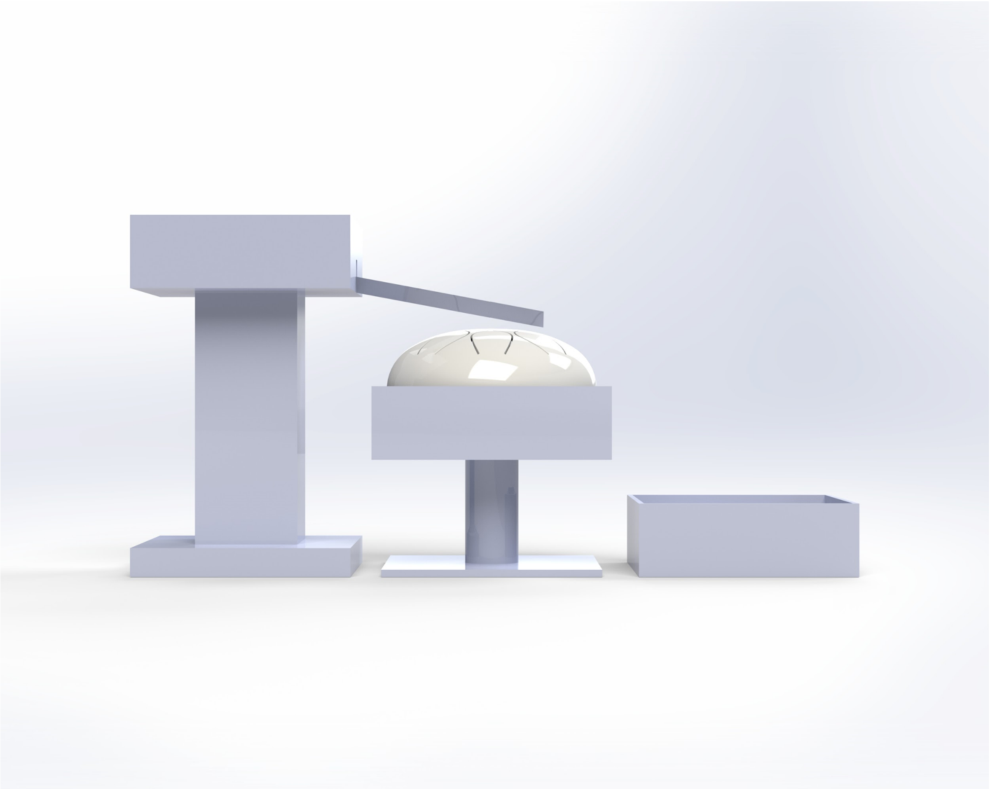


Figure N.4. CAD Low-Resolution Prototype Side View

7.15 Appendix O: Initial Design

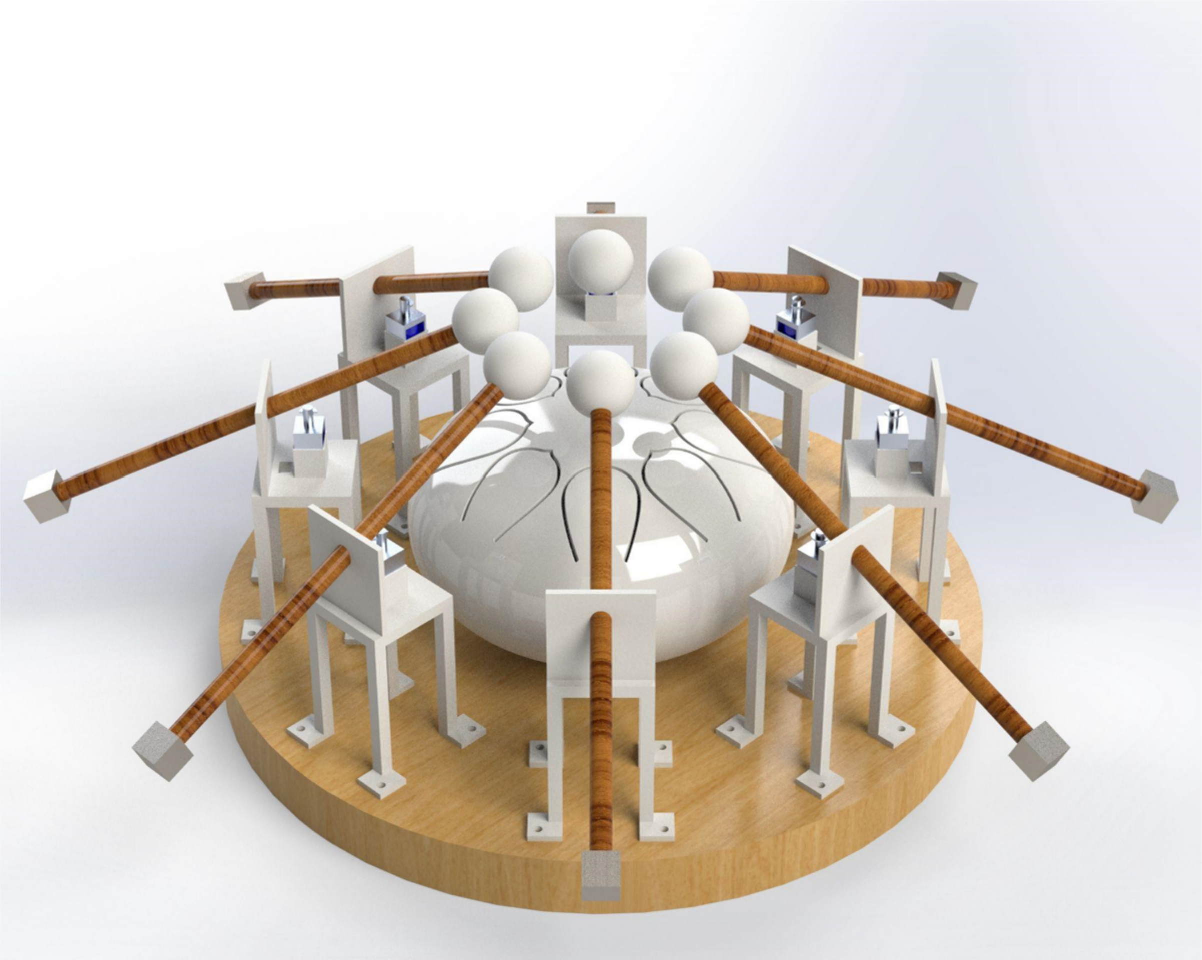


Figure O.1. CAD Model of Initial Design

7.16 Appendix P: FMEA

Failure Location	Failure Mode	Failure Effect	Failure Cause	Current Process Controls	S	O	D	RPN	Suggested Measures
Counterweight	Counterweight	Immobile mallet	Counterweight improper weight	Implement a system of a variable counterweight to end of mallet	10	7	2	140	Implement a variable location system for the counterweight on the mallet to vary the moment on the pivot.
Note Actuation	Miss strike zone	Poor sound quality	Incorrect setup/poor structure	Ensure structure is aligned with steel drum with fixed structure and a narrow pivot that allows only vertical mallet movement.	4	3	2	24	Redesign structure to increase strike accuracy.
	Insufficient Strike Force	Muted sound quality	Weak solenoid	Adjust mallet or solenoid position with respect to the pivot point to vary the moment	6	8	1	48	Decrease friction force on the axial force rod by using graphite or other lubricant to increase efficiency of strike.
	Speed of operation	Mistimed note	Programming error or incorrect wiring	Utilize multisim to check wiring	5	1	1	5	Use multimeter to check the actual current running through device.
Solenoid	Solenoid fails	Missing note	Incorrect wiring/broken solenoid	Test each solenoid individually to ensure functionality.	10	1	1	10	Re-wire solenoid or replace solenoid.
	String detachment	Mallet does not pivot	Lack of structural attachment	Compare string yield stress to experienced force.	10	1	1	10	Use a stronger string.
Mallet	Mallet sliding	Poor sound quality	Lack of structural attachment	Use high friction material between mallet and pivot.	7	4	3	84	Utilize an attachment which clamps the mallet to a pivot rod.
	Mallet breaking	Safety hazard & poor sound quality	Excessive solenoid force	Vary weight of counterweight.	10	1	1	10	Use solenoid with less force or lower steel drum.
Structure	Structure failure	Detached mallet	Poor build & structural integrity	Conduct FEA simulation on structure.	10	1	2	20	Utilize stronger material than PLA.
	Steel drum movement	Poor sound quality	Lack of friction	Use high friction materials to keep steel drum in place.	7	2	2	28	Modify base design to hold steel drum in place.
Electrical	Power distribution	Notes not actuated	Insufficient current	Compare current values to expected values with an ammeter.	10	1	1	10	Replace power supply with one that delivers more current.

Figure P.1. Preliminary FMEA

Failure Location	Failure Mode	Failure Effect	Failure Cause	Current Process Controls	S	O	D	RPN	Suggested Measures	Revisions	S	O	D	RPN
Counterweight	Counterweight	Immobile mallet	Counterweight improper weight	Implement a system of a variable counterweight to end of mallet	10	7	2	140	Implement a variable location system for the counterweight on the mallet to vary the moment on the pivot.	Rather than adjust weight, the counterweight position is manually changed.	10	5	1	50
Note Actuation	Miss strike zone	Poor sound quality	Incorrect setup/poor structure	Ensure structure is aligned with steel drum with fixed structure and a narrow pivot that allows only vertical mallet movement.	4	3	2	24	Redesign structure to increase strike accuracy.	Slots in the acrylic base were cut to fit mallet and pivot structure.	5	1	1	5
	Insufficient Strike Force	Muted sound quality	Weak solenoid	Adjust mallet or solenoid position with respect to the pivot point to vary the moment	6	8	1	48	Decrease friction force on the axial force rod by using graphite or other lubricant to increase efficiency of strike.	Mallets fixed to 3D printed piece via friction and fasteners. Fasteners minimize friction between 3D printed piece and structure.	6	5	1	30
	Speed of operation	Mistimed note	Programming error or incorrect wiring	Utilize multisim to check wiring	5	1	1	5	Use multimeter to check the actual current running through device.	Speed of operation using current process controls was satisfactory.	3	1	1	3
Solenoid	Solenoid fails	Missing note	Incorrect wiring/broken solenoid	Test each solenoid individually to ensure functionality.	10	1	1	10	Re-wire solenoid or replace solenoid.	Solenoids were tested individually to ensure functionality.	10	1	1	10
	String detachment	Mallet does not pivot	Lack of structural attachment	Compare string yield stress to experienced force.	10	1	1	10	Use a stronger string.	Fishing line provided sufficient strength and elasticity.	10	1	1	10
Mallet	Mallet sliding	Poor sound quality	Lack of structural attachment	Use high friction material between mallet and pivot.	7	4	3	84	Utilize an attachment which clamps the mallet to a pivot rod.	Mallet fixed in place by 3D printed piece and fastener.	7	2	3	42
	Mallet breaking	Safety hazard & poor sound quality	Excessive solenoid force	Vary weight of counterweight.	10	1	1	10	Use solenoid with less force or lower steel drum.	Mallet fixed in place by 3D printed piece and fastener.	10	1	1	10
Structure	Structure failure	Detached mallet	Poor build & structural integrity	Conduct FEA simulation on structure.	10	1	2	20	Utilize stronger material than PLA.	Structure was sufficiently strong; failure not a concern.	10	1	1	10
	Steel drum movement	Poor sound quality	Lack of friction	Use high friction materials to keep steel drum in place.	7	2	2	28	Modify base design to hold steel drum in place.	Rubber feet on the steel drum prevented slipping on the acrylic base.	7	1	1	7
Electrical	Power distribution	Notes not actuated	Insufficient current	Compare current values to expected values with an ammeter.	10	1	1	10	Replace power supply with one that delivers more current.	Sufficient current was provided by the power supply.	10	1	1	10

Figure P.2. Final FMEA

7.17 Appendix Q: Design of Experiment

7.17.1 Main Effect Plots

NOTE: Square - High (+) value, Circle - Low (-) Value

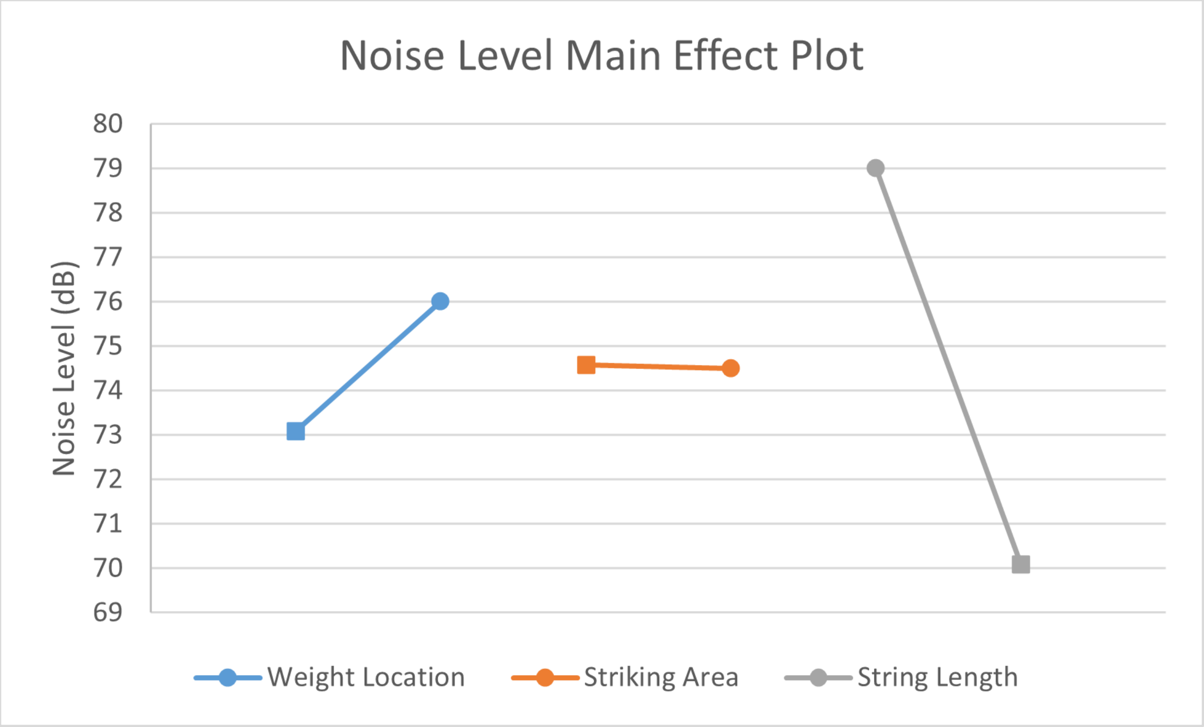


Figure Q.1. Noise Level Main Effect Plot

Figure Q.2. Sound Quality Main Effect Plot

7.17.2 Interaction Plots

NOTE: Square - High (+) value, Circle - Low (-) Value

Figure Q.3. Weight Location - Striking Area Noise Level Interaction Plot

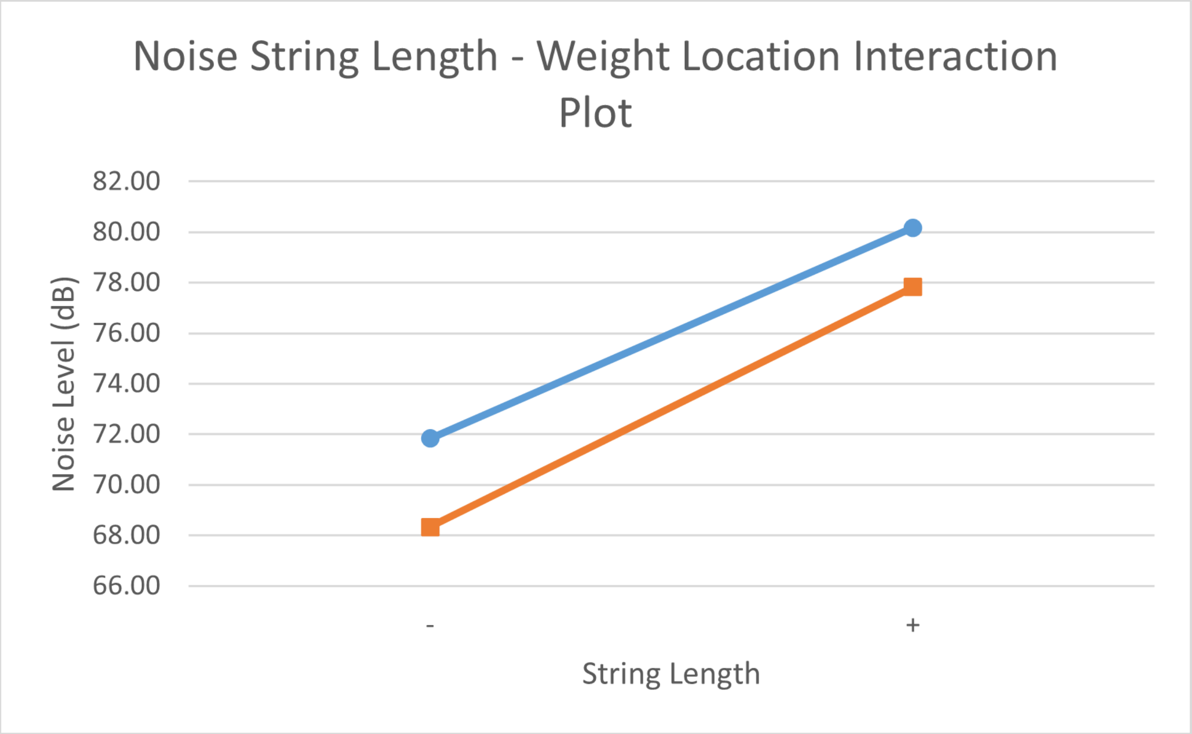


Figure Q.4. String Length - Weight Location Noise Level Interaction Plot

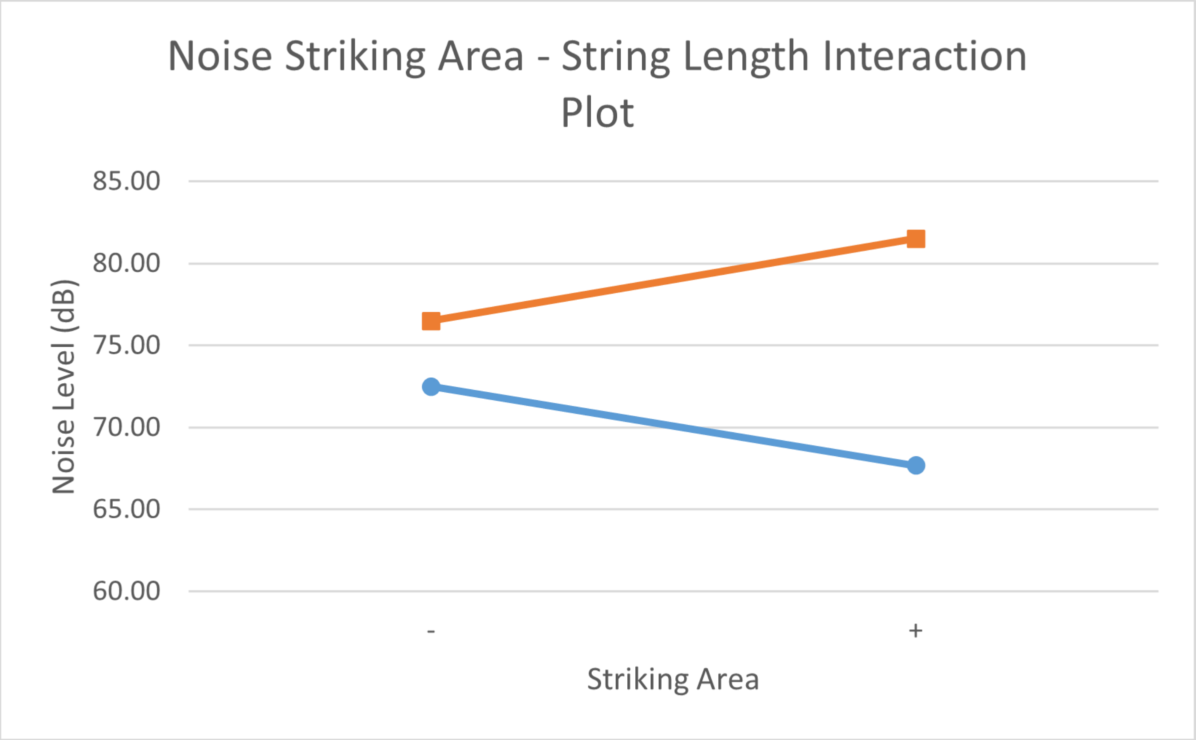


Figure Q.5. Striking Area - String Length Noise Level Interaction Plot

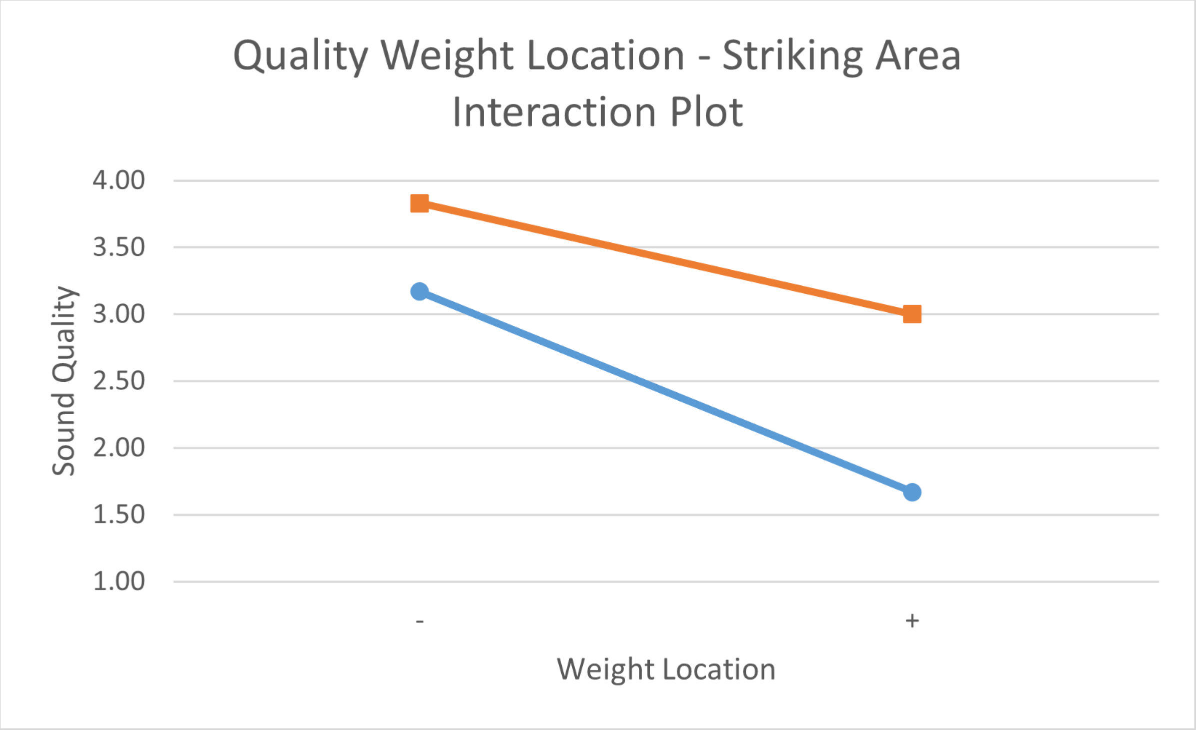


Figure Q.6. Weight Location - Striking Area Sound Quality Interaction Plot

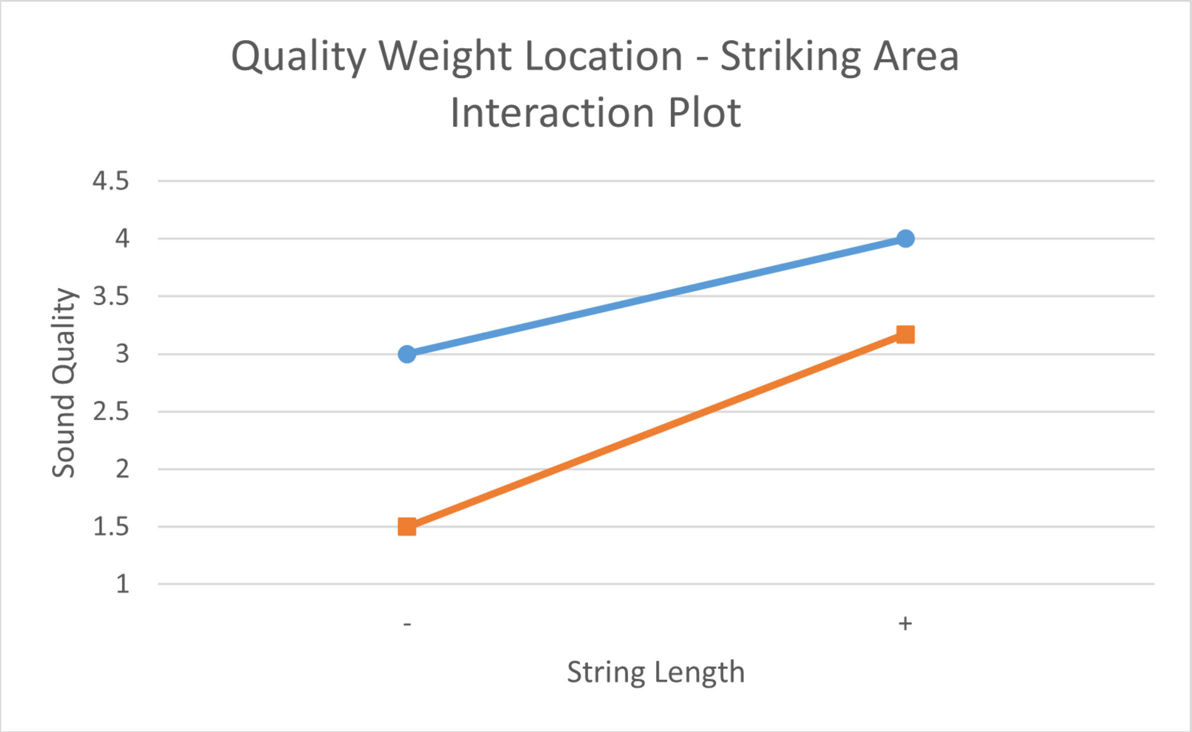


Figure Q.7. Weight Location - Striking Area Sound Quality Interaction Plot

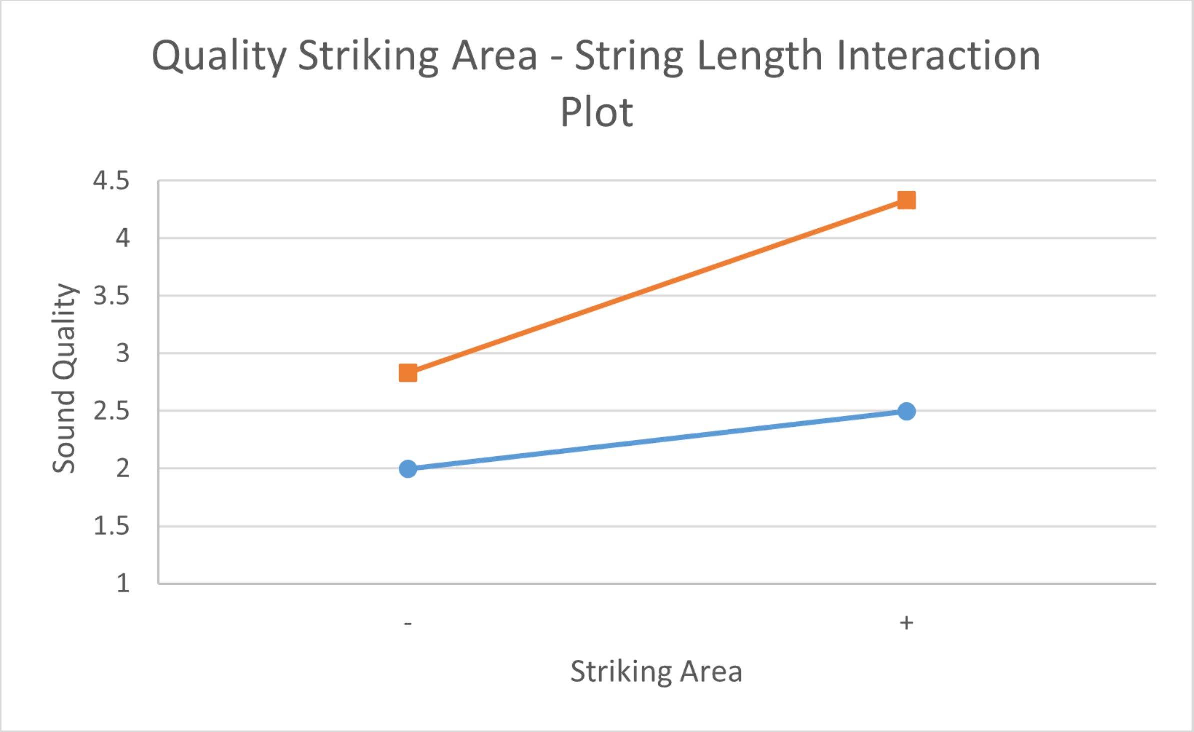


Figure Q.8. Striking Area - String Length Sound Quality Interaction Plot

7.17.3 Regression

Tables Q.1. Noise Level Regression

Regression Statistics	
Multiple R	0.920
R Squared	0.847
Adjusted R Squared	0.793
Standard Error	2.675
Observations	24

ANOVA					
	df	SS	MS	F	Significance F
Regression	6	676.250	112.708	15.742	4.255E-06
Residual	17	121.708	7.159		
Total	23	797.958			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	74.541	0.546	136.480	2.752E-27	73.389	75.693
Weight Location [x1]	-1.458	0.546	2.670	0.016	-2.610	-0.306
Striking Area [x2]	0.041	0.546	0.076	0.940	-1.110	1.193
String Length [x3]	4.458	0.546	8.162	2.771E-07	3.306	5.610
x1-x2	0.208	0.546	0.381	0.707	-0.943	1.360
x2-x3	2.458	0.546	4.501	0.0003	1.306	3.610
x1-x3	0.291	0.546	0.534	0.600	-0.860	1.443

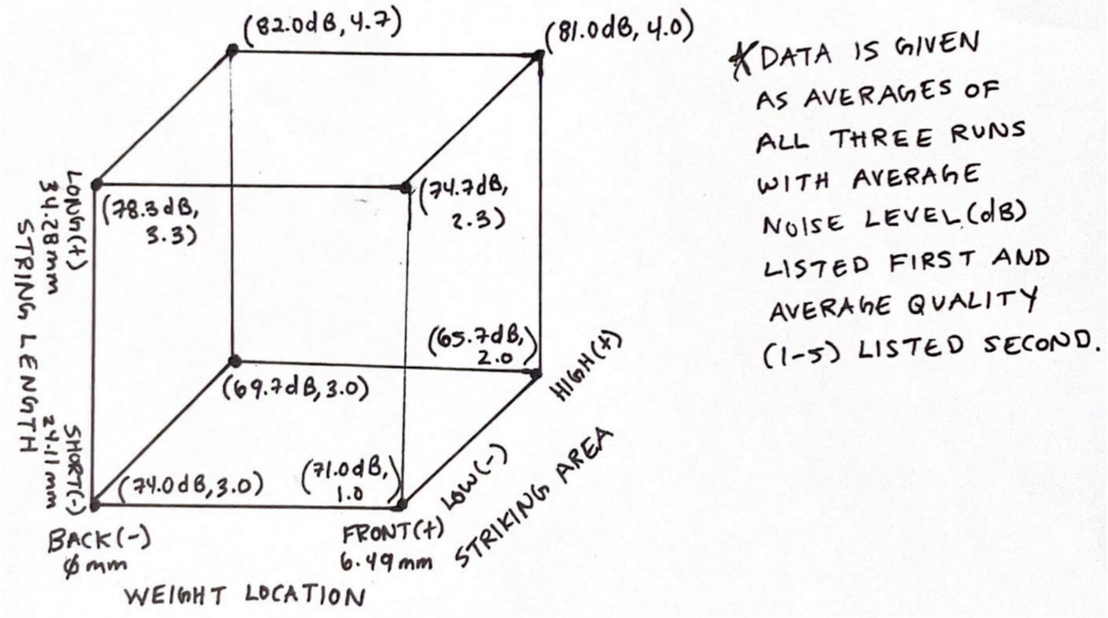
Tables Q.2. Sound Quality Regression

Regression Statistics	
Multiple R	0.879
R Squared	0.772
Adjusted R Squared	0.692
Standard Error	0.693
Observations	24

ANOVA					
	df	SS	MS	F	Significance F
Regression	6	27.667	4.611	9.599	1.10E-04
Residual	17	8.167	7.159		
Total	23	35.833			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	2.917	0.141	20.616	1.82E-1	3 2.618	3.215
Weight Location [x1]	-0.583	0.141	-4.123	7.10E-04	-0.882	-0.285
Striking Area [x2]	0.500	0.141	3.534	2.55E-03	0.202	0.798
String Length [x3]	0.667	0.141	4.712	2.01E-04	0.368	0.965
x1-x2	0.167	0.141	1.178	0.255	-0.132	0.465
x2-x3	0.250	0.141	1.767	0.095	-0.048	0.548
x1-x3	0.167	0.141	1.178	0.255	-0.132	0.465

7.18 Cube Plot



*DATA IS GIVEN AS AVERAGES OF ALL THREE RUNS WITH AVERAGE NOISE LEVEL (dB) LISTED FIRST AND AVERAGE QUALITY (1-5) LISTED SECOND.

Figure Q.9 Cube Plot of Collected Data from DoE

7.19 Appendix R: FEA Analysis

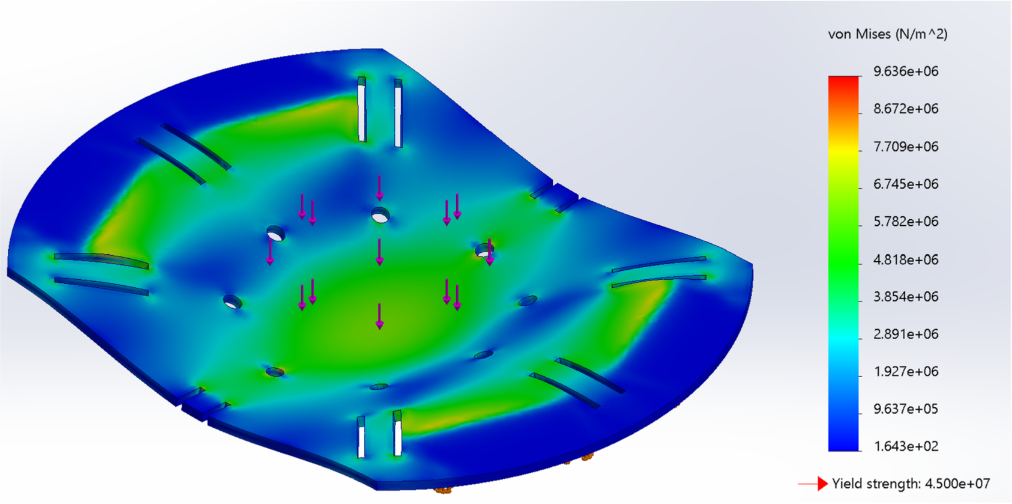


Figure R.1. Stress FEA Results

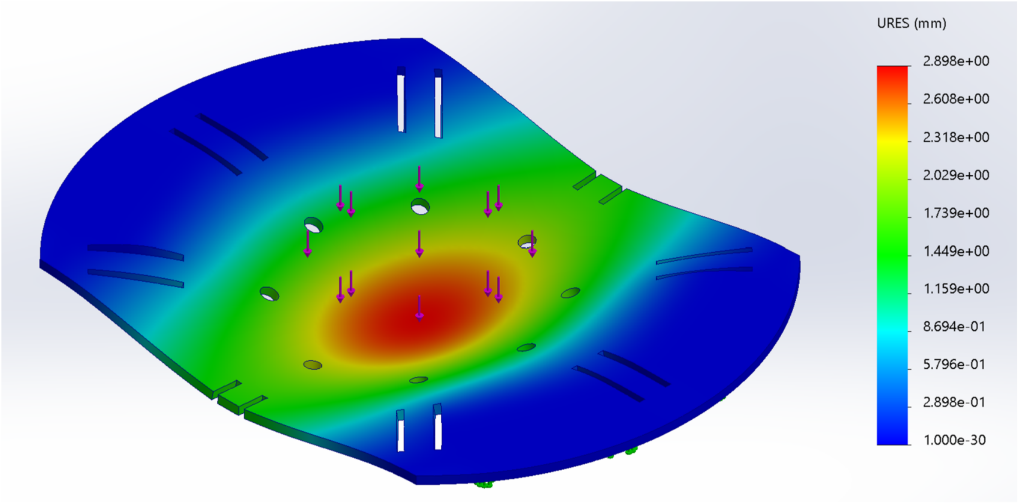


Figure R.2. Displacement FEA Results

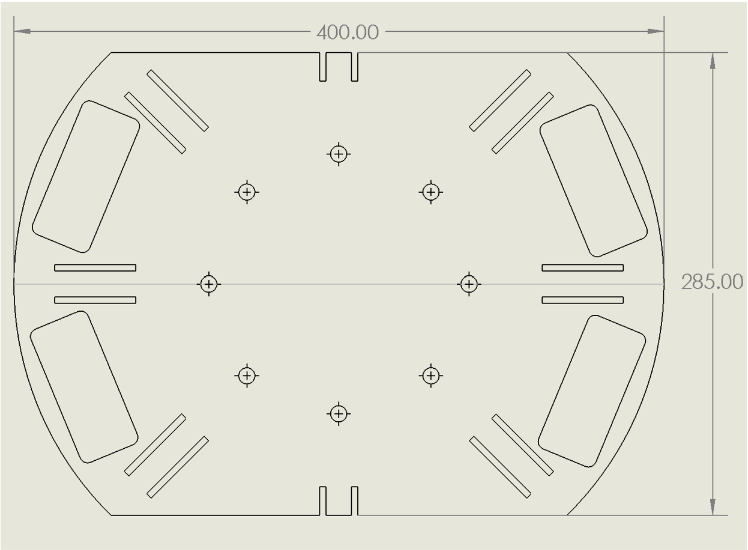
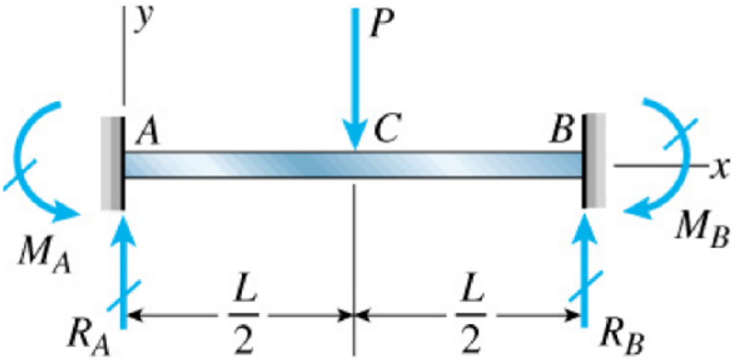


Figure R.3. Base and Length Dimensions of Acrylic Platform

Figure R.4. Beam Representation



Statically Indeterminate Beams. https://ocw.nthu.edu.tw/ocw/upload/8/259/Chapter_10-98.pdf.

NOTE: The FEA simulation loading and boundary conditions were approximated to the beam system shown above.

R.5. Analytical Solution for Maximum Displacement

$$\delta_{max} = \frac{PL^3}{384EI} \tag{1}$$

$$I = \frac{1}{12}bh^3 \tag{2}$$

$$I = \frac{1}{12}(0.285m)(5.55 \cdot 10^{-3}m)^3 \approx 4 \cdot 10^{-9}m^4$$

$$\delta_{max} = \frac{270N \cdot (0.4m)^3}{384(3GPa)(4 \cdot 10^{-9}m^4)} \approx 3.7mm$$

$$\rightarrow \boxed{\delta_{max} \approx 3.7mm}$$

The following parameters were used for the maximum deflection calculation. Acrylic elastic modulus (E) ≈ 3GPa, L = 0.4m (figure R.4), b = 0.285m (figure R.4), h = 5.55E-3m (thickness of acrylic platform), P = 60 lb load equivalent.

7.20 Appendix S: Final Design

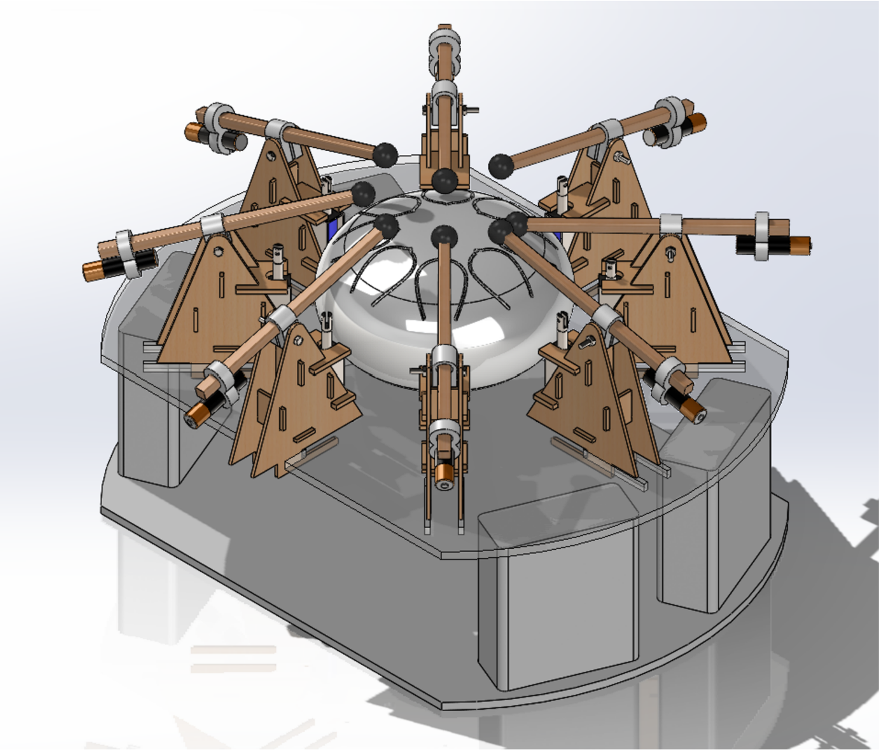


Figure S.1. Isometric View

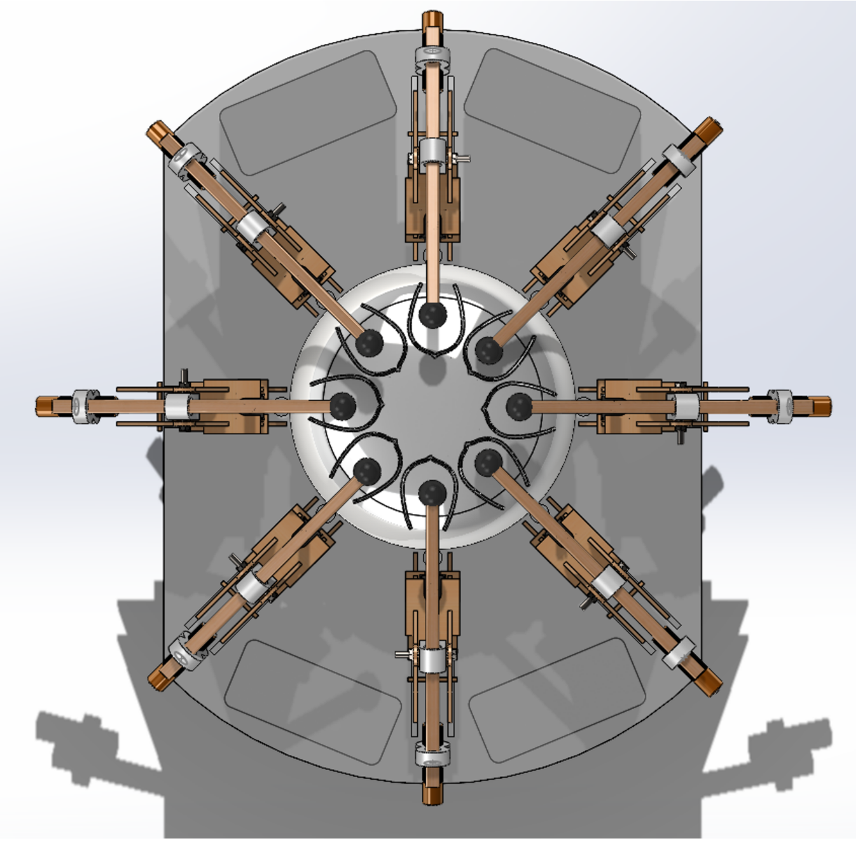


Figure S.2. Top View

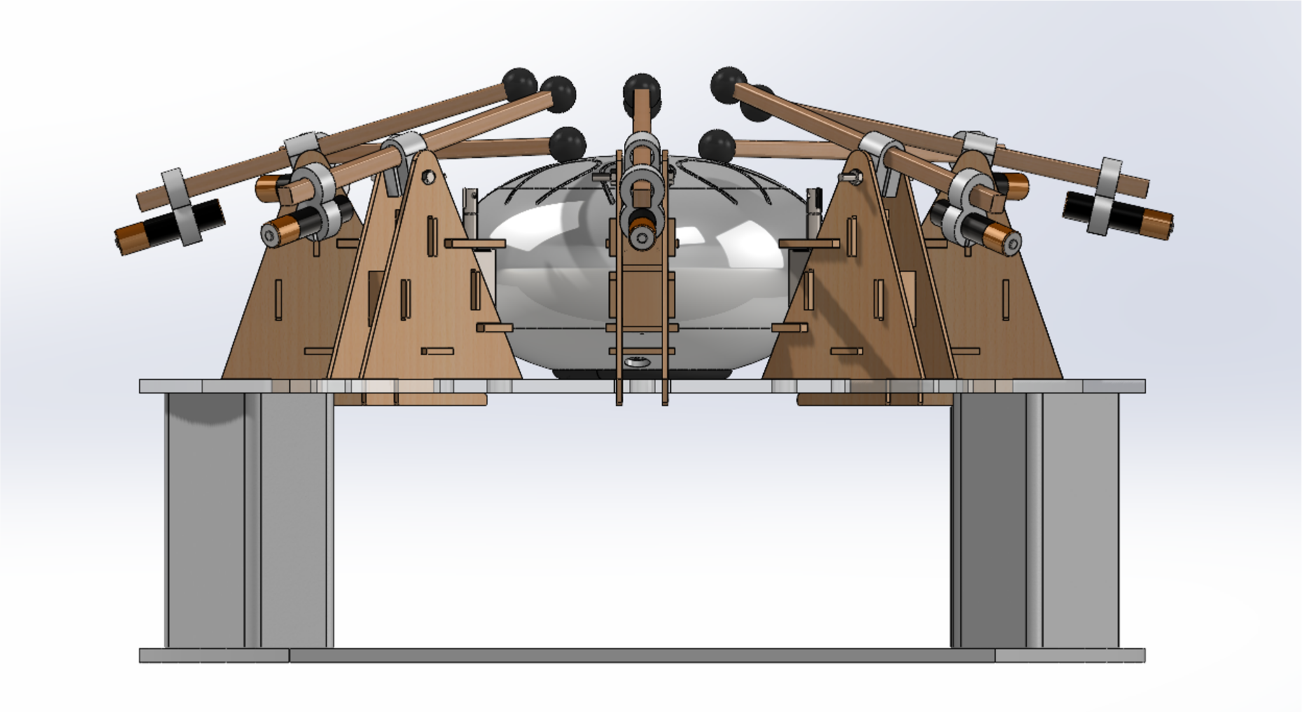


Figure S.3. Front View

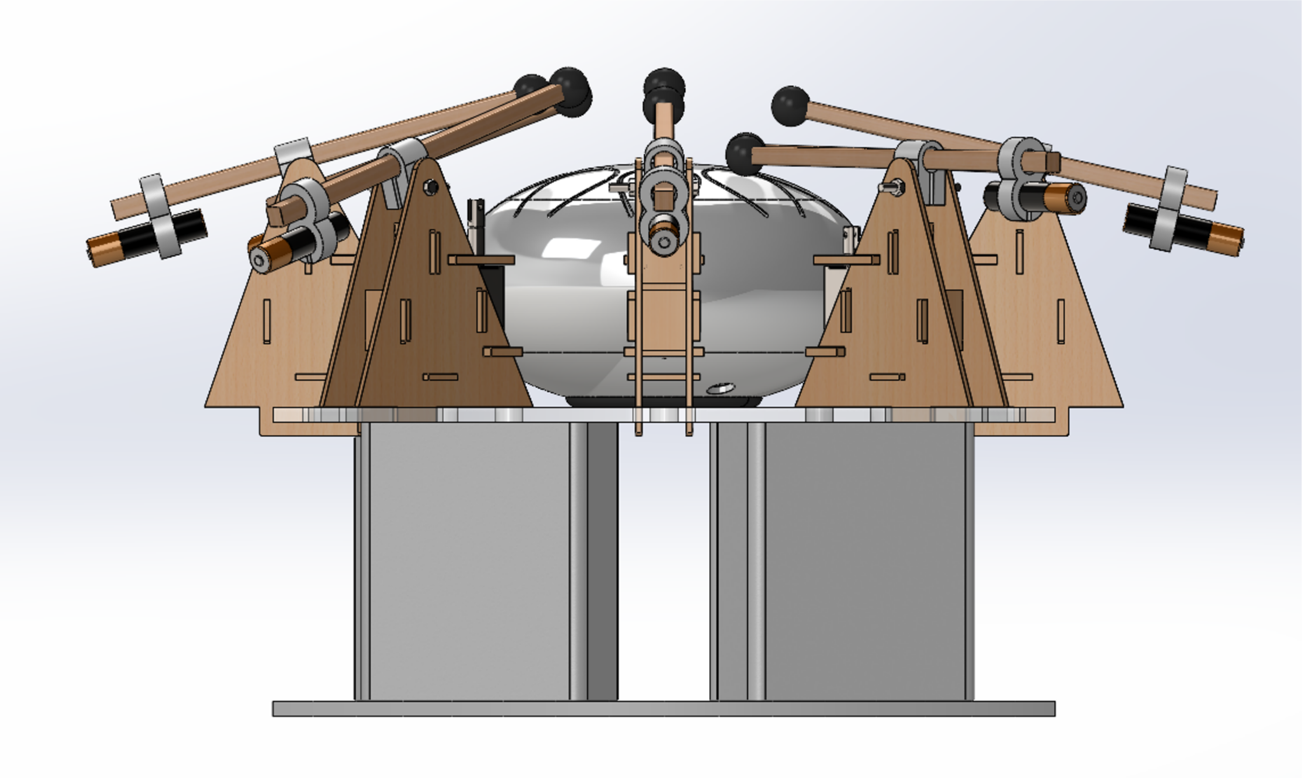


Figure S.4. Side View

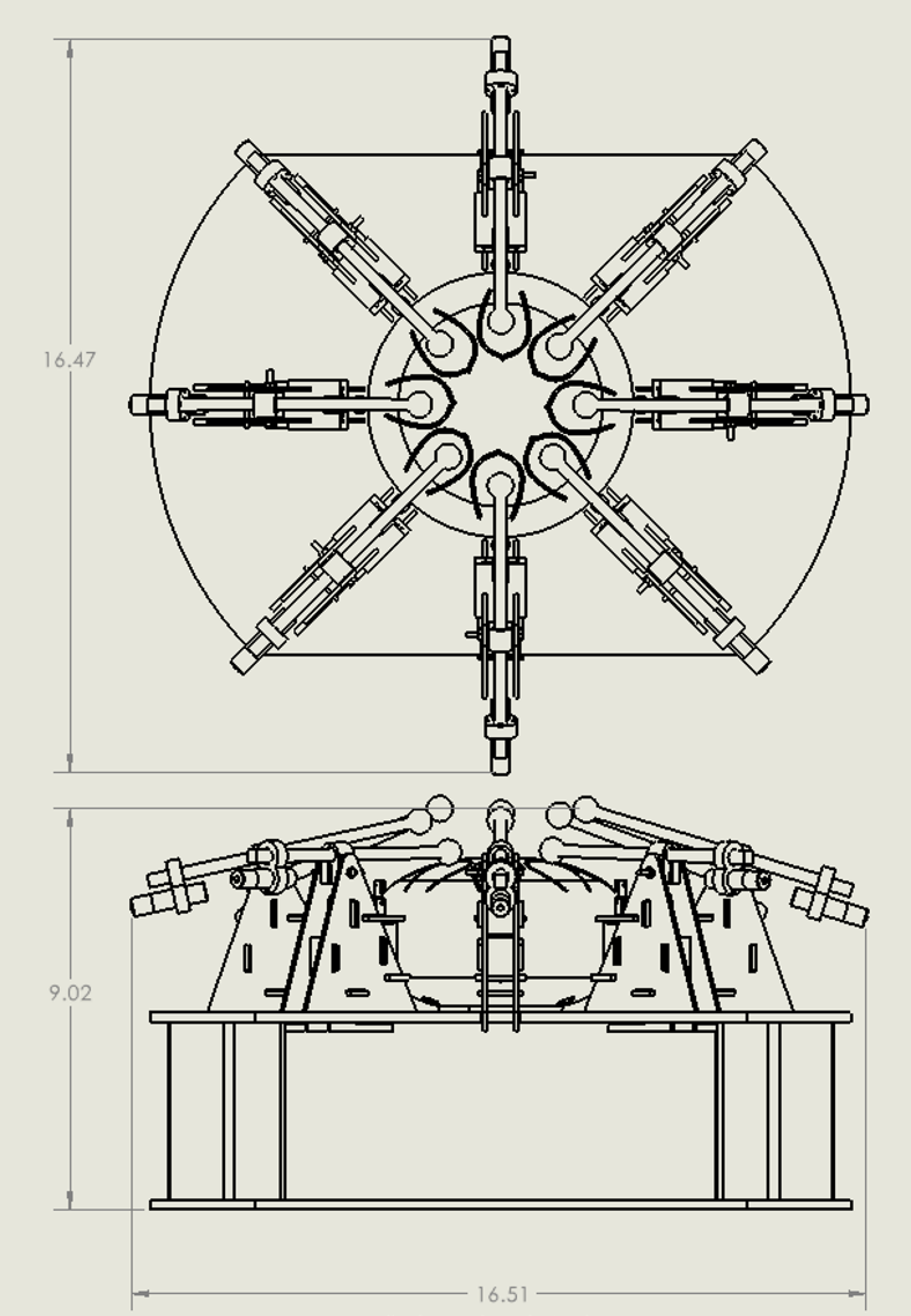


Figure S.5. Drawing of Final Design

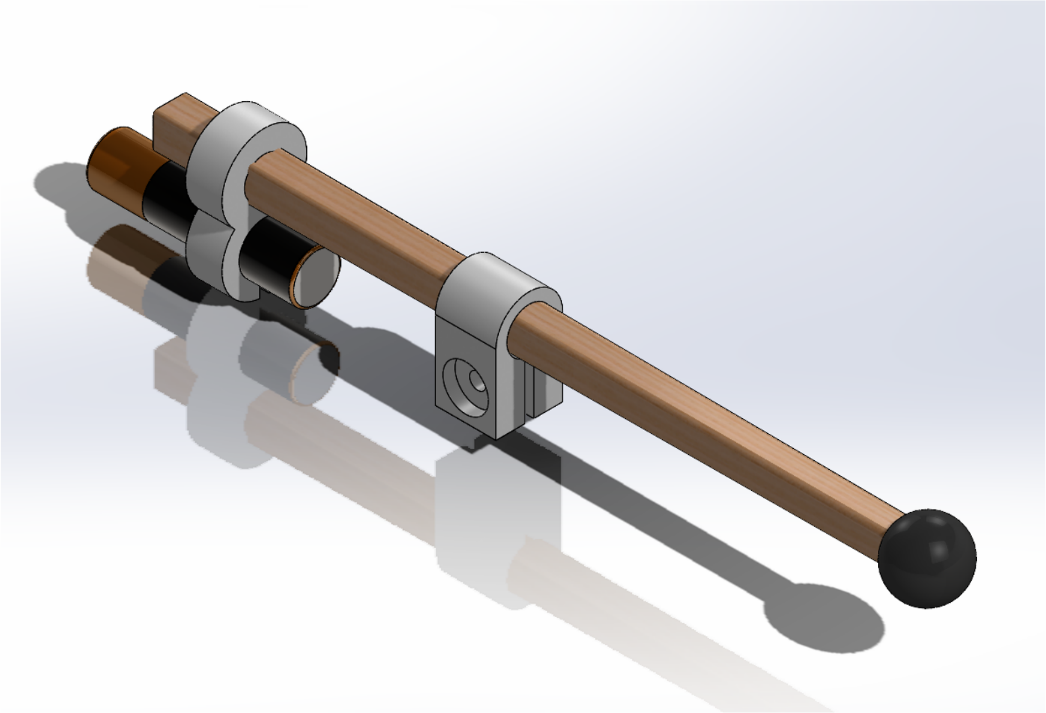


Figure S.6. Mallet & Counterweight Assembly

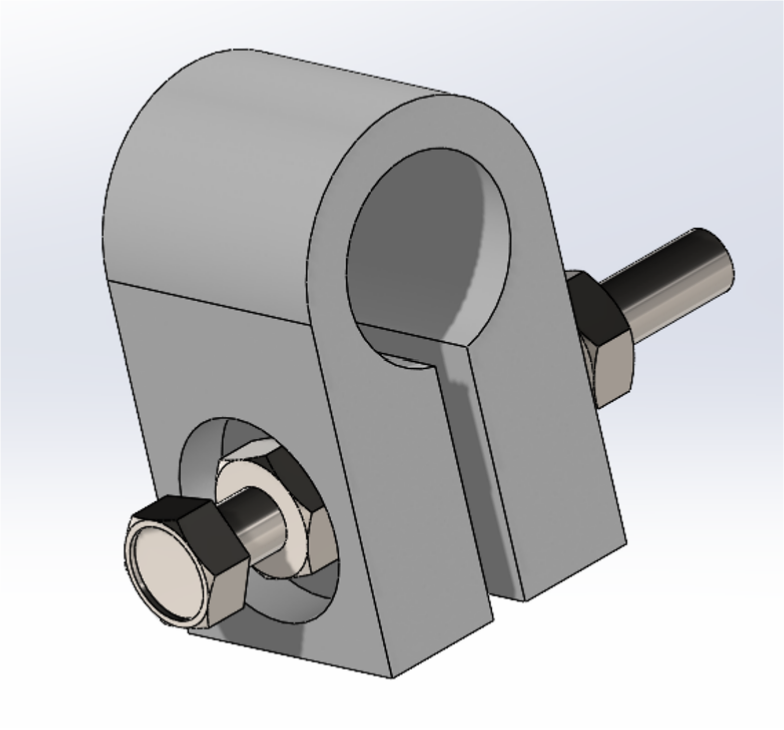


Figure S.7. Mallet Holder with Mounting Hardware

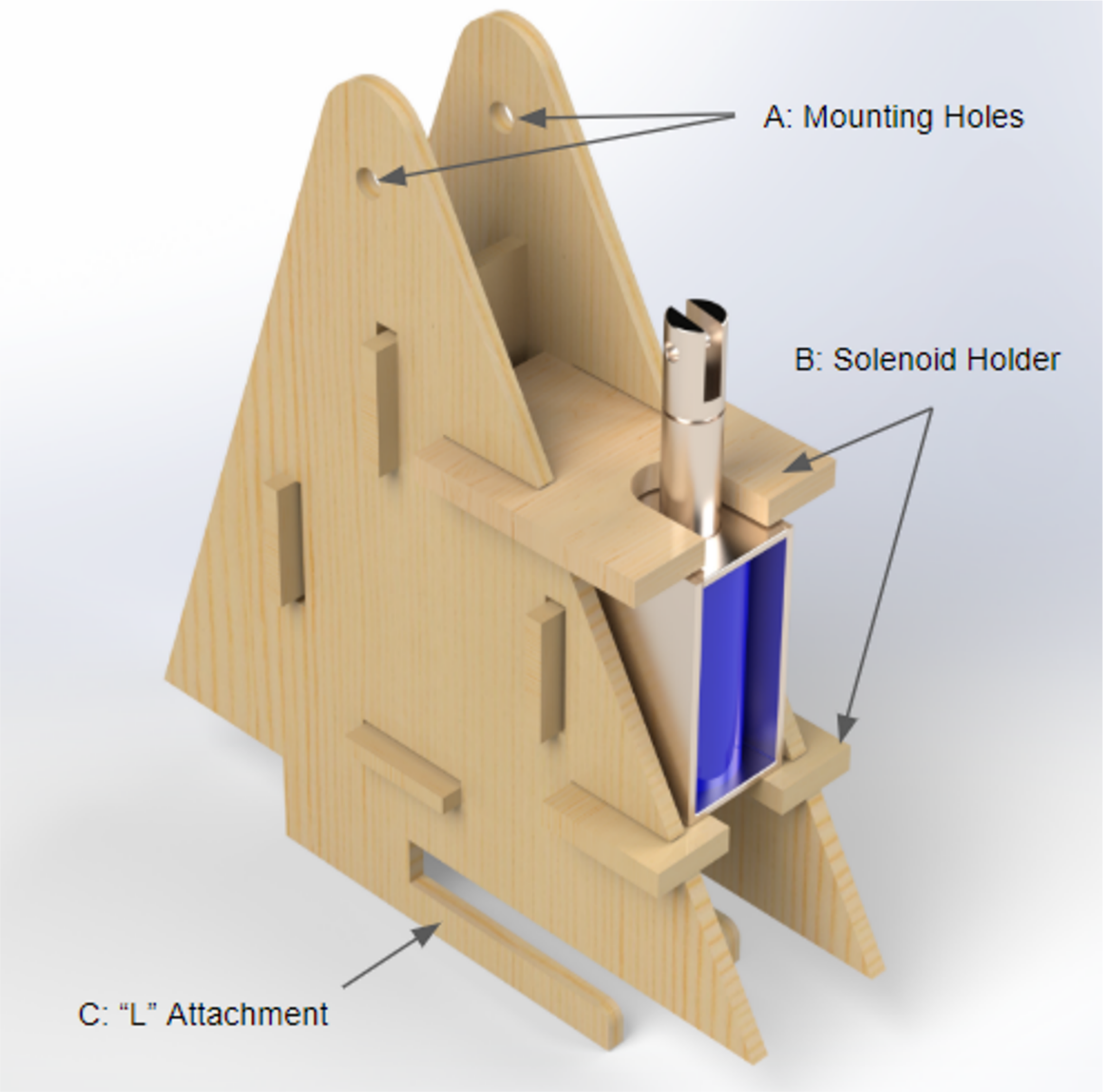


Figure S.8. Mallet/Solenoid Stand

7.21 Appendix T: Bill of Materials

Item	Amount	Price per Item	Total Cost ($)
Solenoid (12V, 1A, LUOYIMAO)	1	9.60	9.60
Solenoid (12V, 1A, Baomain)	7	6.83	47.81
Mallets (Pack of 4)	2	11.30	22.61
1KΩ Resistor Pack	1	5.97	5.97
IN4001 Diode Pack	1	5.89	5.89
TIP102 Transistor Pack	1	7.99	7.99
Power Supply (12V, 3A)	1	15.98	15.98
1/4" Acrylic	1	10.00	10.00
2"x4" Wood	4	0.50	2.00
1/4" Plywood	1	2.00	2.00
1/8" Plywood	8	0.70	5.60
Fishing Line	1	0.50	0.50
Fastener Assembly(M3 Bolt, Nuts & Nyloc Nut)	8	1.73	13.80
Dead AAA Battery	8	0.00	0.00
Electrical Tape	1	2.00	2.00
Breadboard	1	38.60	38.60
Arduino Uno	1	30.85	30.85
Jumper Cables	1	8.65	8.65
Paint	1	2.00	2.00
Wood Glue	1	2.48	2.48
Epoxy	1	1.00	1.00
Wood Screws	6	0.37	2.21
			244.86

7.22 Appendix U: DIY Instructions and Repairs

7.22.1 U.1. Construction and Assembly

Step 1: To begin constructing the automated steel drum, you first need to collect the materials listed on the materials list given in Table T.1. You will also need additional tools. You should have electrical tape, wire strippers, a file, sandpaper, jumper wires, a mallet, a USB cord for Arduino, pliers, a soldering iron, and wood glue on hand.

Step 2: Now that you have collected the required materials, you should start by 3-D printing the counterweight holders using the appropriate .STL file. It won't take long to print one, but you will need a total of eight counterweight holders to fully manufacture the prototype. Additionally, you will need to print eight mallet holders using the correct .STL file.

Step 3: While you wait for the 3-D printing to finish, you can begin laser cutting the acrylic layer of the multi-platform base. You will also need to laser-cut the $\frac{1}{4}$" plywood for the solenoid stands using the appropriate .PNG file. Similarly, to 3-D printing, cutting all eight solenoid stands may take some time, so plan accordingly.

Step 4: You will now need to cut the wooden piece for the lower level of the multi-platform base and the four 2x4 wooden legs that separate the two levels. The dimensions of the pieces can be found in Appendix S. After cutting, make sure to sand the edges to prevent splinters. As an optional step, you can now paint or varnish the wood to your liking.

Step 5: The multi-platform base can be assembled by screwing the wooden leven to the bottom of the cut 2x4 legs via wood screws. The acrylic layer is then fixed to the 2x4s with epoxy, making sure to not cover or interfere with any of the cut-outs in the acrylic.

Step 6: Assemble the solenoid stands by jigsawing all of the wooden pieces together as shown in Figure S.8. The fastener assembly must be tightened onto the mallet holder and inserted into the holes of the solenoid stand prior to wood-gluing the stands. Once the mallet holder and fastener assembly are properly mounted in the solenoid stands, the pieces of the stand may be glued together with wood glue.

Step 7: Strip one end of the jumper wires. Solder the end of one jumper wire to the wire of the solenoid. Repeat for all solenoid wires. Once all the wires have been soldered, cover with electrical tape for safety.

Step 8: Place the solenoid inside the solenoid holder as shown in Figure S.8. You may need to use a file or sandpaper to reduce the tolerance of the holder. You may also need to use a rubber mallet to gently force the solenoid inside of the solenoid holder. When using the mallet, be careful not to hit the coil inside the solenoid. You must hit the frame of the solenoid lightly. The legs of the solenoid holder should slide easily into the slots of the acrylic platform and the solenoid wires may be routed through the available holes in the acrylic.

Step 9: Connect the wiring to the breadboard as shown in Figure I.1. When the wires from the solenoid are facing you, connect the right wire to the cathode of the diode and the left wire to the anode. As an optional step, you can cut the legs of the resistors and diodes to reduce the space they take and make working on the breadboard easier. *Important: Figure I.1 shows the necessary circuitry for one solenoid. This circuit will need to be repeated eight times for all eight solenoids, and the solenoids must be connected in parallel.*

Step 10: Slide the mallet into the mallet holder. You need to make sure the mallet is pushed all the way back on the holder, so it is friction tightened. Next, slide the counterweight holder onto the mallet until it is friction tightened. The counterweight (a AAA battery) may be placed into the counterweight holder and adjusted to the proper location. You may need to use electrical tape to thicken the diameter of the mallet to ensure a friction fit of both the mallet and counterweight holders.

Step 11: Attach the mallet to the solenoid using fishing line and hand-tied knots. Use electrical tape to fix the location of the attachment point on the mallet.

Step 12: Lastly, connect the Arduino to the PC with the USB cord. Upload the code onto the Arduino. Disconnect the USB cord and connect the 12V power source to the Arduino. Click the play button to start the song and test that all mallets are hitting the steel drum and they are bouncing back into their initial positions.

7.22.2 U.2. Repairs

Mallet not bouncing back – Slide the mallet all the way in. The mallet is conical and is thinner on the side of the mallet head. Push towards the thicker side until it's tight and it doesn't move.

Mallet not moving – Move the battery closer to the pivot location and place electrical tape around either side of the battery once it's working properly, so it doesn't keep moving.

Mallet not aligned with steel drum - Rotate steel drum to align mallet heads with steel drum. If the mallet head does not sit directly above the steel drum, adjust the position of the mallet head by sliding the mallet/solenoid stand assembly along the slots on the acrylic platform.

Sound quality is insufficient – Move the solenoid stand along the acrylic slotting such that the mallet head hits the upper area of the steel drum's note.

Mallet not hitting the steel drum – Shorten the length of the fishing line to reduce the distance the mallet must travel to hit the steel drum. Once the mallet is working properly, tape the string onto the mallet so it doesn't move.

Arduino not recognized by computer - If the Arduino is not recognized by the arduino software, make sure the correct port and COM are selected. Ensure the USB cable is plugged in correctly and is functional.

Solenoids do not actuate - Electrical issue: If the solenoids do not actuate, ensure there are no loose jumper cable connections on the breadboard or Arduino. The wiring can also be checked by referring to Figure I.1. Mechanical issue: Refer to other U.2. repairs. If necessary, the solenoid can be replaced by sliding the solenoid stand out of its slot in the acrylic base, removing the solenoid from the stand, and severing the solenoid wires from the jumper wires. A new solenoid can be placed into the stand and the new solenoid wires can be directly soldered back onto the open jumper wires without any necessary rewiring of the breadboard.

7.22.3 U.3. Operating Instructions

If the requirements for the following steps are not meant, refer to Appendix U.2.

1. Ensure the mallet head sits directly above the steel drum.
2. Ensure the mallet rotates freely. This can be done by manually pressing on the solenoid while the device is off and ensuring the mallet smoothly strikes the steel drum.
3. Plug the USB cable from the Arduino into a computer. Verify and upload our code utilizing Arduino software to upload songs/tunes onto the Arduino. After uploading, unplug the USB cable.
4. Plug power supply barrel head into Arduino and plug power supply to wall outlet.
5. Press the reset switch on the Arduino.
6. Utilize buttons on the breadboard to play/pause and skip between songs.
   a. One button starts the song, while pressing the button a second time will pause the song
   b. The second button skips between songs