The Rotary Harp

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ABSTRACT
This paper outlines the concept of a musical machine which is an automated version of a harp fitted to a circular device. This includes the background, preliminary and final designs, and a reflection of the state of the instrument and creation process. The rotary harp takes the concept of a harp and transforms it to a circular device where notes can be selected through the rotating of a base and set of arms. Sound is then produced through plucking devices which strike the chosen string. Driven by dual stepper motors to rotate both main sections of the harp, it utilizes precise algorithmic note selection to be controlled by a variety of means such as through the use of digital audio workstation softwares. The primarily 3D printed machine uses nickel electric guitar strings of various sizes to produce twenty-four separate pitches. The device can be used as a standalone instrument, or as part of an ensemble to create unique visual and musical artwork.

1. Background

1.1 Concept
The rotary harp is an automation of the regular harp instrument where strings are arranged in a circle around a rotational turret style mechanism. Two plucking mechanisms are located on the base of this harp to excite the strings. To play different notes, a different string will have to be plucked. Each string will have varied lengths and densities so each string corresponds to one note on the harp, much like a traditional harp but reorganized spatially

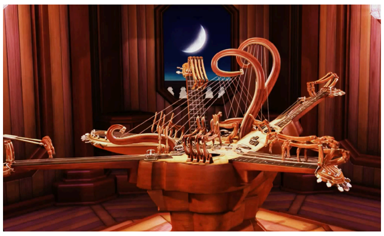
The playing of each string will be done by rotating both the outer turret with the strings attached, and the bottom ring with the actuators attached. They will rotate towards each other until the correct string is lined up with the pick. The plucking arm will then spin to excite the string and can be spun at different velocities to give different volume of notes. This piece will be built upon a sturdy stand so it can be placed as a standalone instrument, or be played as part of a larger orchestral piece

1.2 Motivation
The idea for this instrument stems from attempting to emulate the playing of a harp, but moving the actuator along long linear distances could cause problems and delays between notes, so building around the core mechanic of the rotational turrets can ideally solve this issue. This makes the playing motion almost completely novel and is unlike any way humans play. This harp can provide multiple functions and be used by different types of users. The best use case for the rotary harp that makes it stand out from a normal harp is the ability to function as a standalone instrument with no musician required to play it. The sound of a harp is well suited for background or ambient music, so the rotary harp can function as a good stand alone art installation. It can also be used in combination with other instruments. It can be controlled by a skilled musician in real time through connection to a computer, and it can even be played by hand by anyone, musician or otherwise.

2. Prior Art
There are three projects that relate to and inspire the rotary harp, these being the Phonoliszt-Violina created by Ludwig Hupfeld, Andy Cavatorta's Gravity Harps installation at the Museum of Modern Art NYC, and Animusic's Virtual Resonant Chamber. These three projects all include novel ways of working with the sounds produced by string instruments and each have their own twist on the concept.

2.1 Phonoliszt-Violina
The oldest of these projects is the Phonoliszt-Violina, which was created in 1910, is a machine that plays three violins simultaneously through use of a rotating circular bow. (MAMI, 2025). It used stationary strings and pushed violins against the moving bow. It allowed for fast and accurate playing of complex pieces, but was limited by the constant bow movement speed and pre-set music that had to be prepared on special music rolls.

2.2 Virtual Resonant Chamber
A more modern take on the idea is the Virtual Resonant Chamber. This animation consists of a large musical machine made up from an amalgamation of many different string instruments. It is visually intriguing with the strings of different instruments intertwined and mechanical, claw-like, plucking mechanisms playing in rhythm. It provides an imaginative use of strings where the machine moves around the strings as it plays the notes.



2.3 Gravity Harps

The project that provides the strongest influence on the rotary harp is Andy Cavatorta's Gravity Harps. These large rotating harps inspired the base idea of the rotary harp, that being a set of strings that rotates to select notes. However, the Gravity Harps have many differences from the rotary harp. They are very large and include multiple sets of strings. While this allows for multiple notes to be played at once, it introduces plenty of complexity and the size makes them rather lethargic. Also, and most notable, the Gravity Harps are, as the name suggests, largely powered by gravity to move them along, which puts a heavy restriction on rhythm and tempo as the force of gravity is constant so the harps will always play a note at the same time without mechanical intervention. (Enrico, 2015) The rotary harp will not have this limitation as it is fully controlled by motors, allowing for much more control over tempo and rhythm.

3. Purpose

The rotary harp combines ideas from all three of the projects mentioned above to include interesting ideas, and address drawbacks that some prior projects may have faced. It includes the ideas of strings that move against a device to play them and strings that stay stationary as the machine moves around them. Both the strings and the means at which they are played can be controlled, allowing for precise, quick, and complex movements.

4. Preliminary Design

4.1 Interaction and Visuals

The rotary harp should have two forms of interaction: live playing from a musician, and automated playing of a preloaded song. The former, musician control, will consist of a musician generating a live stream of midi data which the harp will be able to play in real time as the data gets generated. This data will be generated by a DAW, either in the interface or with a connected instrument like a keyboard. For communications, an additional requirement is that it will be capable of being transmitted to the harp via wifi, allowing for simplicity and ease of use. The other way the harp shall be able to be played is by loading a song (or multiple) into storage that it can play autonomously. Functionally this works exactly like a live stream of midi data, except it does not need an external source for the data. This allows it to function as a standalone art piece, as well as a playable instrument.

The rotary harp is, first and foremost, an art piece. Though functionality is what gives the work musical accreditation, the form of the instrument is vital to the project. Visually, the harp should not just be an instrument, but also a sculpture piece. It will be built upon a sturdy base so it can be moveable and, since it is wifi capable, will only need to plug into wall power and connect to wifi and it will work as intended. This gives the instrument a simple and clean form and function that fit together to create a unique, functional, musical art piece.

4.2 Sound Dynamics and Time

The rotary harp should have metallic strings; it provides a clean sound and the possibility of amplification. The rotary harp will have twenty-four strings each tuned to a different pitch. These notes will be chromatic from C3 to C5. The harp must also be able to control the strength or velocity of a note being played. The rotary harp relies on temporal accuracy as the desired functionality of both an instrument that can be played live by a musician, and one that can play full songs autonomously. It must be capable of playing notes quickly and reliably, and have the ability to perform fast arpeggios and chromatic runs.

5. Preliminary Decisions

5.1 Sound Dynamics Choices

The rotary harp will use nickel electric guitar strings and thus its timbre will reflect this, making it sound similar to an unamplified electric guitar. Due to the hollow rod running through the middle of the instrument it will resonate slightly, amplifying the sound. Though the core design still resembles a harp, the number of strings has been reduced. This not only reduces the size of the instrument but allows the central section holding the strings to rotate faster. As well this reduces the distance between the strings leading to less delay between notes. In addition the plucking mechanism was designed to mimic hand movement using a pick. Each string's tension will be controlled by tuning pegs mounted on the top of the rotary harp.

The rotary shape of the harp allows for interesting dynamics and composition that a normal harp or guitar would not be able to achieve. The main example of this is the possibility of fast chromatic runs or arpeggios, which can be played easily by spinning one or both moving parts rapidly and playing each note (or alternating notes) as they spin. These runs or arpeggios will take significant coordination with the software to be able to play smoothly without breaks between notes, but if done correctly, allows for unique capabilities for dynamics.

The main aspect of dynamics the harp lacks, however, is the capability to dampen or mute strings. There is currently no plan to include a dampening device, neither for one string nor all, so once a string is played, the sound will resonate fully. This can be mitigated by the harp's ability to control velocity of notes, which gives the capability for making notes louder and brighter or softer and more muted.

5.2 Time Choices

Though temporal accuracy and speed are requirements, the harp has some very strict limitations on tempo, specifically in the speed at which it can play the average note. Due to the distance between each note and the speed at which the arm and harp can move, the time between any given note is variable on which note was played and which note is next. This means there is no guarantee that a note can be played instantly after another, thus limiting the maximum tempo at which the instrument can play. To mitigate this as much as possible, the harp uses two rotating parts in order to raise the maximum possible tempo which it can play. To move to a note, each rotating part(the turret and the pick) will move half the distance between notes, joining in the center to play a specific note. This cuts transition time in half from one rotating piece. This is important especially as certain note transitions between the opposite sides of the harp will take longer than ones on neighboring strings. Currently the longest latency between notes would be ~0.8 seconds. This is when the harp needs to play a note on the opposite side of the harp that the pick currently is on. The addition of another plucking arm has been considered, as it could theoretically cut the time to play the furthest interval in half. This would, however, involve significant changes in the design to the current iteration.

5.3 Accuracy Choices

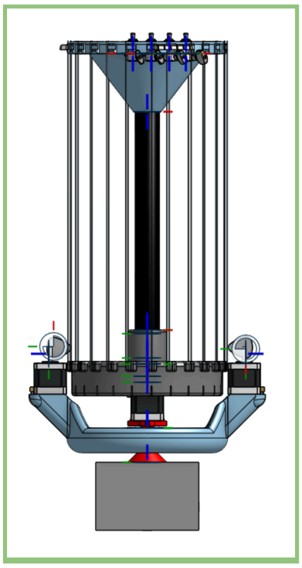
Stepper motors will be used for all motions as steppers offer finer control of angular position, and with microstepping, can provide smoother actuation at varied velocities, which is important for musical nuance They are also capable of precise repeatability without drift, which is critical for an instrument that must align the plucker with specific strings. The turret and pick will have geared-down rotation, to be as accurate as possible and ensure no damage is caused to components from centripetal forces. There will be a function that automatically pathfinds the shortest distance for each part to rotate.

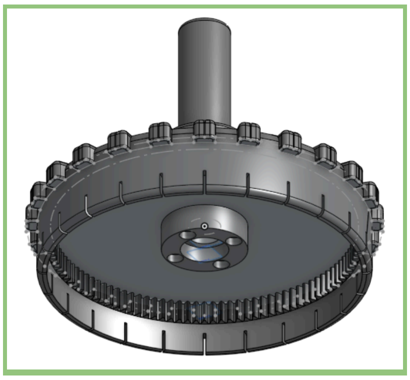
6. Final Design

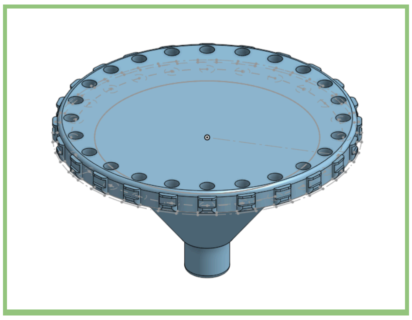
6.1 Aesthetic Goals

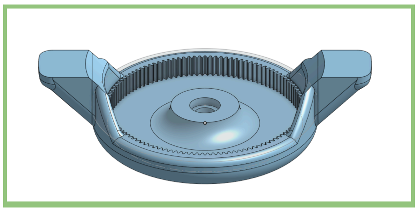
In our final design the main updates were for functionality; but in those updates we added many small aesthetic touches such as rounding off almost all corners on the harp. These minor additions allowed the harp to be more smooth and cohesive when printed, and when used. We used all black materials including filament, the center support pipe, and the base. These were all either already black or were painted during the process of building.

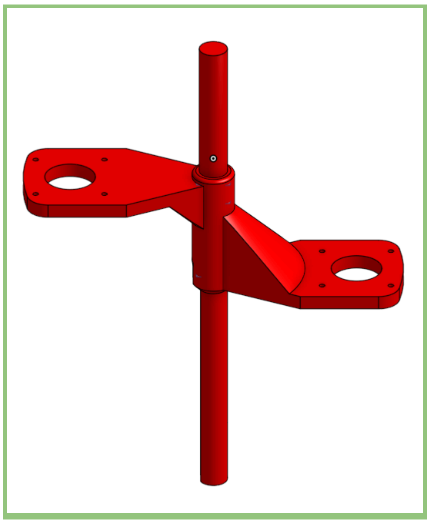
6.2 Actuation and Structure











Harp core: made up of string base and harp hat, with strings. Carbon fiber PETG, core rod is a hollow tube of 1/16 wall steel.

Harp arms: regular PETG

Motor holder stick: carbon fiber nylon

Stand: wood

6.3 Sonic Objects

The rotary harp uses a mix of single strand and coiled nickel strings in order to produce sound. These strings are organized chromatically and take up two octaves from C3 to B4. This range was chosen as it gives a good amount of musical freedom while also being achievable within our design. The strings are acted upon by two stepper motors which use plectrums to strike the strings to produce a tone. On the top ends of the strings, to create a wood bridge, guitar nuts are cut into 6, with one part on each string. This ensures we get a clean bridge of the string, and no extra vibration.

6.4 Excitation

All of the motors are run off of BIGTREETECH TMC2209 stepper motor drivers, which get their signals from a Raspberry pi pico. Our reasoning for choosing TMC2209 was its ability to make stepper motors quieter. Normally, stepper motors are quite loud with lots of vibration, so lowering the overall sound was important so that the Harp would be the main focus. There are also simple controls through the step and dir (direction) pins. Another option was UART, as it has advanced controls, however we did not implement UART since many of these advanced features were unnecessary for us, but it does offer nice features to keep in mind for future projects. Stealthchop is a stock feature of the TMC2209, and it takes each microstep of the stepper and interpolates between it and the next step. This causes the motion to be much smoother and provides the silent aspect of the motor.

6.5 Motion

The rotary harp has two main moving parts, the harp core and the harp arms. 2 stepper motors are used to create this motion, one faces up and interfaces with a gear on the inside of the base to drive the harp core, while a second motor faces down and uses a similar system to drive the arms. One of the important changes between the preliminary design and the final design was that another arm was added to the base. This lets the harp pick two notes at once, each exactly across from each other on the harp. This also cuts the distance to each note in half, as the harp can choose either arm for any note.

6.6 Software

The software for the harp was written in Python (MicroPython). Python was chosen for its simplicity and as a challenge for the programmer who wanted a project in Python. The code consisted of two main sections, communication, and hardware control.

The software had various forms of communication; wifi, serial, and no communication (autonomous playing). All was handled by the communication side of the file and made calls to an abstracted hardware control layer. The communications section stayed simple due to Python's capabilities for simple network and serial communication. The same is not true for the hardware control.

The hardware control section of code provided an abstracted layer of control for the communications code to make calls to the hardware. The software could not manually generate pulses to move the motors as Python unpredictably pauses execution for background tasks such as garbage collection. To get around this, Raspberry Pi's P/IO capabilities were used, which offloaded pulse generation to custom low-level functions written in assembly-like language. While providing the ability to reliably rotate motors, these P/IO programs were tricky to use and complicated the code significantly.

7. Final Capabilities

7.1 Sonic

After completion, the rotary harp achieved the required sound capabilities. The correct tuning for each string proved to be difficult to reach, as tightening one string led to differing tension being placed on other strings, but the plucking motion of strings produced the correct sound. Roughly half of the strings were able to be tuned to the correct pitch. We encountered an issue plucking the strings with guitar picks; the plucking motors did not have enough torque to reliably pluck a string without getting caught. We remedied this by using zip ties to pluck notes which gave the motor more flexibility.

7.2 Time

The preliminary goal of speed for the harp was not realized in the final designs due to a few reasons regarding both physical movement, and computation speed loss. One reason for the lack of speed was physical delay. The motors used were capable of rotating the weight of the harp at an acceptable top speed, but needed time to accelerate to reach such speed. However, due to the small distances the harp would spin, for most the harp would not get close to top speed. Another reason for the lethargic nature of the final design was communication latency. When using serial connection to relay data to the harp, it would have a long delay (~0.3 seconds) before playing a note. This was due to a programming flaw stemming from the fact that serial connection was a rushed feature which did not have ample time to be tested (more on this shortly). These two flaws caused the harp to be much slower than anticipated, a disappointing outcome for a design that chose to add complexity to save time.

7.3 Communication

The requirement of wifi was achieved fully and worked well. However, it was not versatile. It required a program to be running on the host device to send information to the harp. This meant downloading and running a program to run externally while using a DAW which was complicated and not portable. Also, the wifi connection was not robust enough to handle connecting to complicated networks, such as protected networks, like that of Eduroam. This meant that for the presentation of the harp, serial communication would be necessary.

Serial communication was set up using a Max for Live patch in Ableton. Because the requirement of serial communication was only realized days before the presentation of the instrument, the development was rather rushed and bare-bones. This caused a severe delay in data communication and slowed down the harp dramatically. With more time to test and implement serial communication, the harp could be much faster.

7.4 Alignment

Stepper motors were chosen to drive the harp's motion due to their precise motion. However, the motors can skip steps when rotating, usually due to the motor starting and stopping abruptly when moving too much mass. This causes the code to think the motor is at a different place than it actually is. These misalignments can build up, causing the harp to miss notes. The final design of the harp featured a ramping effect for the central harp motor which addressed much of this misalignment, but not all of it. While still an issue, because the harp often switched directions, the misalignments tended to cancel out each other which helped to minimize the problem.

That, however, is not the only issue the final harp had with alignment. The software for figuring out how many steps to move to play a note operates under the assumption that each string is one half-step up in pitch from the last. However, the harp was not strung up this way. Instead, it was strung up such that notes would ascend chromatically until reaching the halfway mark, then jump up and begin descending. The difference in the software and physical implementation stemmed from a miscommunication. This ended up in the harp playing incorrect notes half of the time, farthing the misalignment problems.

8. Musical Usage

With the previous capabilities in mind, the harp was used for final musical composition in a piece that focused on slow ambience. This gave the harp plenty of time to communicate over serial and move to each note. Accompanying the harp in this piece included a percussion drum, and Cyther (another musical machine capable of playing notes similar to an electric guitar). The drums played a simple beat, allowing the harp and Cyther to take center stage in the piece. The piece uses dissonant chord progressions while the harp plays accompanying notes to form a melody overlaid on top of the ambient drum track. The two string instruments take turns dominating the piece and both fade out at the end.

The harp performed well in an ambient piece. The slow tempo allowed the harp time to position, and a faster or louder track would tend to drown out the harp as it was not amplified. The Cyther helped mitigate the harp's monochromatic capabilities by dictating the chord progressions of the piece. The drums relied mostly on hi-hat and snare, as to not overtake the focus of the piece, but included toms and cymbals for flair and emphasis throughout the piece.

9. Reflection

9.1 Communication and Multithreading

As mentioned above, serial communication was a rushed feature and caused a severe slowdown in the harp's speed capabilities. With more testing and optimization, serial could be much faster. Additionally, the wifi capabilities were limited and only served as a proof of concept, rather than a robust feature. This too could be improved to allow easier wifi connection and support connections on protected networks.

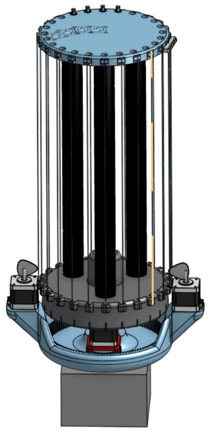
Both serial and wifi could be optimized to reduce latency in playing by offloading communication to a separate thread. The Raspberry Pi Pico W used does support multithreaded programming, and this was an original software idea that never was implemented. Dedicating one thread to communication and another to hardware control would speed up the harp and allow for more complex information processing.

9.2 Physical Stability

One of our biggest issues in the overall final design was the struggle to tune the harp correctly. This was mostly mitigated by a new print of the base piece that had a more sturdy and supportive mount for the tube. However any tilt of the harp hat causes drastic effects on the ability to tune. We designed a prototype to fix this issue but didn't have the time to implement it. This prototype replaces the current center pipe with 3 separate pipes in a triangular shape. This should eliminate wobble on the top section, and make the harp easier to tune.

The base itself could have been improved due to the slight angle it created in the harp's balance point. The mounting point for the motor holder stick was a hand drilled hole, which caused the slight angle, making the entire harp off center. In the future I would use a specifically custom machined piece done in a drill press, or another machining tool such as a mill or CNC.

The harp overall had a bit too much flex in the motor holder stick, causing any abrupt motion to make the harp wobble. This could be improved by updating the design or making the motor holder stick out of a much stronger material, such as aluminium or steel. The motor holder stick itself doesn't spin, so weight and balance is not an issue here. We thought carbon fiber nylon would be strong enough, and it is, but even though it is an inflexible and brittle material, the sheer amount of weight and side to side forces placed on it caused some flex.



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[5] Alex Wilkinson

[6] Keith Palmer-Poirier

11. Appendix

BOM: Rotary Harp BOM.xlsx

GITHUB: https://github.com/RobertBranchaud/rhx0

CAD: Onshape