Whirly Tunes - WPI Musical Robotics

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1. CONCEPT, MOTIVATION, AND PURPOSE

It seems like our shared passion for fast moving rotational tubes brought us here. The core concept behind our musical robot is spinning corrugated tubes around one end to produce sound. Whirly Tubes are a brand of sound producing corrugated tubes marketed as a kids toy (Figure 1) which produce uniquely eerie and ethereal sounds. Along with their unique musical capabilities, the juxtaposition of a complex electromechanical system making primary use of a colorful childrens toy should be visually entertaining. Our goal is to produce a whimsical eclectic mix of color, music, and mechanical devices rarely found in either instruments or robotics.

Figure 1: Plastic Whirly Tube toys

Despite being a simple way to make sound, there are very few traditional instruments that utilize this method to create music. This is likely because producing a range of notes requires many instances of slightly different tubes, not dissimilar to how a piano has many strings for different pitches. Unlike a piano, an instrument that utilizes corrugated tubes will have many moving parts that are difficult to hide, and thus a large moving machine will have to be embraced visually. The relatively simple method for producing sound gives us flexibility to go further in other areas, such as prototyping, enhancing visuals, and composition. Perhaps our project can inspire musicians and roboticists to see the excitement in mixing their skills.

Mainly, our project will provide a concise and repeatable way of "playing" multiple whirly tubes at once. Combining the eerie sound with robotic precision could result in both an auditory and visual art installation and/or an additional instrument for the musical robotics lab.

Usually restricted to niche science demos or kids toys, a Whirly Tube utilizes the difference in pressure between each mouth of the tube to produce an air flow inside. When the air flowing over the corrugations reaches particular velocities, it produces standing waves at particular harmonics of the tube, resulting in an audible pitch. The main factors that affect the note produced are the length of the tube, the distance between corrugations, and the difference in air pressure at each end of the tube. Thus, with tuning we can create a full octave of whirly tubes, each attached to motors to be spun separately.

2. PRIOR ART

Upon researching works that utilize whirly tubes, we came across some videos of human whirly performances. They

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demonstrate that a corrugated tube does indeed produce a pitch when spun, and can be used in a musical setting. For example, *Marine A 2* [1] exhibits three performers combining their vocals with whirly tubes in an abandoned grain factory for reverb. The angelic nature of the sound laid groundwork for what we wanted our machine to produce.

In our machine-oriented background research, we discovered several robotic whirly tube robots. Most similar to our idea was *The Dervishes* [2], a massive imposing metallic machine built by Andy Cavatorta. It consists of a set of corrugated tubes mounted to motors enclosed within a huge metal frame (Figure 2). An important design decision worth noting is that The Dervishes attaches the tube to the motor by anchoring it to a rigid rib, which in turn is mounted to the motor.

At points, it sounds like a vocalized opera ensemble, while at other times it creates an eerie harmonic whir. The eerie sound, while useful for horror movie music compositions, is not what we set out to replicate. We would like our timbre to be closer to human vocals, or a mechanical vocal synthesizer.

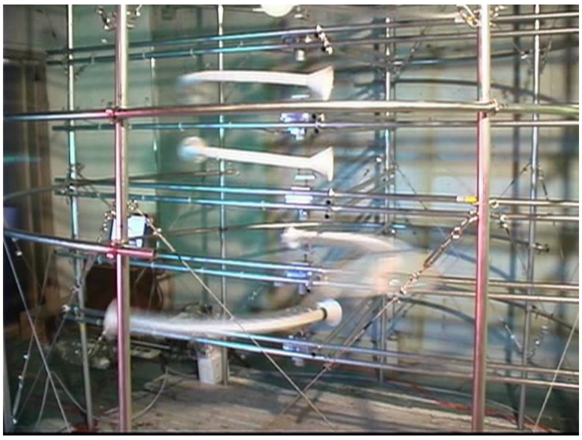

Figure 2: The Dervishes [2]

Tess Oldfield demonstrates another approach to robotic whirly tubes with her *Whirly Chorus* [3]. Her installation is focused more on the composition rather than on the pure technical aspect. *Whirly Chorus* is made up of five different modules which act independently. Unlike *The Dervishes*, *Whirly Chorus* attaches the tube to the motor using only a simple 3D printed adapter. Whirly Chorus seems to be built using brand-name "Whirly Tubes" as opposed to general purpose corrugated tubing used in *The Dervishes*.

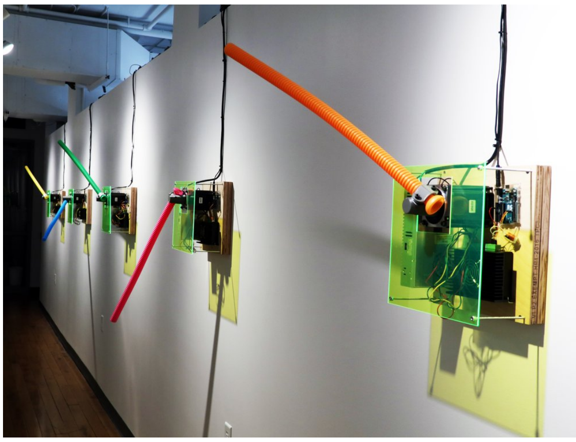

Figure 3: Whirly Chorus [3]

3. REQUIREMENTS

In deciding on our requirements, we wanted to clearly lay out what we expect our machine to do. In addition to taking inspiration from the precious projects, as an additional goal in our project, we've identified that if we are able to cover one end of the whirly tube, we can start/stop the noise instantaneously without adjusting motor speed. This would allow us to have more complexity in composition. This differs from all the examples we could find online by using a servo/solenoid to cap off the end and thus stop the airflow. The other examples slow down the tubes below the first harmonic to cut off any sound. This takes energy and time to perform.

3.1 Timbre

The timbre of our tubes is one of the aspects that make them unique. They are light and eerie while also having a somewhat more imposing character, a bit like an organ. The clarity yet depth of a whirly tube's sound can be understood by looking at a spectrogram of their sound. They produce a very clean sinusoidal wave with a spread of some lower pitches (Figure 4).

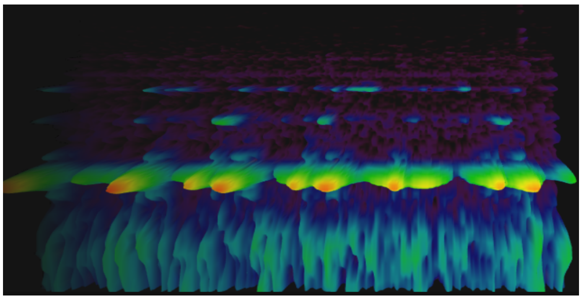

Figure 4: Spectrogram reading of a Whirly Tube

3.2 Timing

By allowing tubes to ambiently spin at an intermediate (non-resonating) frequency we expect to be able to turn notes on and off reasonably quickly by adjusting motor speed up and down. While it's hard to determine exactly how fast this might be, we hope to reach speeds of 2-4 notes per second. If we are able to implement our stretch goal of adding a mechanism to turn the tubes on/off by capping the ends, we may be able to reach much faster speeds!

3.3 Pitch

With respect to pitch, we would like to have at least one octave from the chromatic scale. However, it would be very useful to have at least two octaves as that would give us much more creative freedom in composition. Because each motor controls a separate tube, the machine is polyphonic, able to play up to 12 notes at the same time. Should someone want to play a piece with a scale other than the chromatic one, it should be easy to swap out tubes to play a different set of pitches.

3.4 Dynamic Range

In testing, we noticed that the volume is related to rotational speed (in RPM) with higher speeds producing louder notes. Thus, harmonics requiring a lower RPM are quieter. Sometimes much quieter! We hope we might be able to have some control over note dynamics by adjusting the acceleration/deceleration curves we use to control our motors. Additionally, if we are able to partially cap the tubes, we might be able to reduce airflow and thus control volume.

4. PRELIMINARY DESIGN

Similar to spinning a single whirly tube by hand, our machine will have multiple tubes attached to a motor and a controller to spin it at a specific velocity to achieve a 1st, 2nd, and possibly 3rd harmonic pitch. Having two or more corrugated tubes per motor will make the module symmetric about the axis of rotation dramatically decreasing vibrations.

Tubes will be attached to motors using a custom 3D printed mount and tube clamp structure. We initially considered adding a thin structural rib (Figure 6), made from wood or plastic to provide the flimsy tubes with more support. However, after thinking about our capabilities, we concluded that having such a large rib would require a more powerful motor then we were able to afford. Additionally, we were worried about the potential for injury when spinning 3ft plywood arms. To keep our design within scope, this idea was abandoned in favor of a simple clamp design (Figure 5).

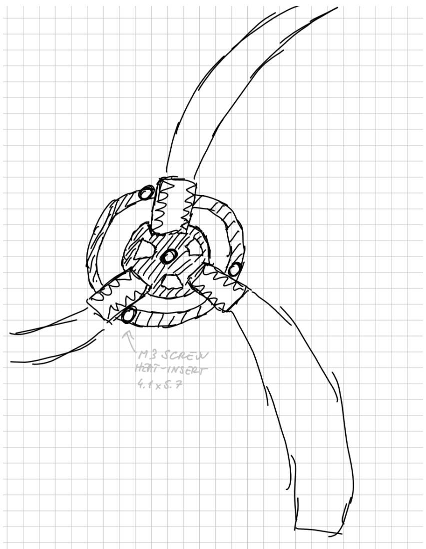

Figure 5: Clamping system and mount

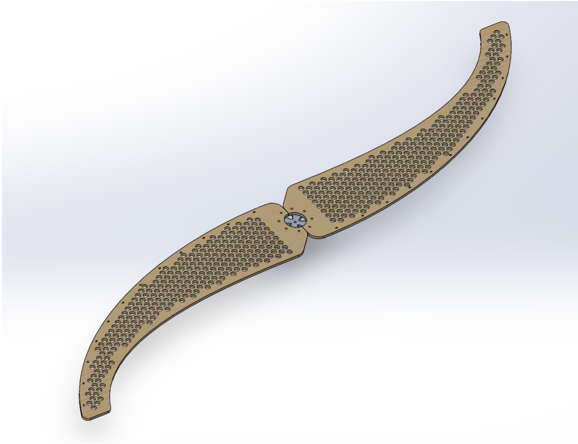

Figure 6: Scrapped prototype for holding two tubes on a motor shaft

Our initial idea was to build separate modules for each motor. However, this idea seemed inefficient as each motor would need to have a processor capable of interfacing with our DAW of choice. Therefore, we combined 4 motors into one larger module. These motors would be connected via wires to a central control hub which would house motor drivers, our central processor, and a power input (Figure 7). Each module can then be separately mounted to various surfaces (tables, chars, a wall, or even a ceiling).

An additional feature we wanted to implement was a linear actuator built around a micro-servo to cap off the tubes while they spin. This in turn should give us more control over fast note production as well as potentially more volume control by having a direct control over the amount of air flowing in the tubes.

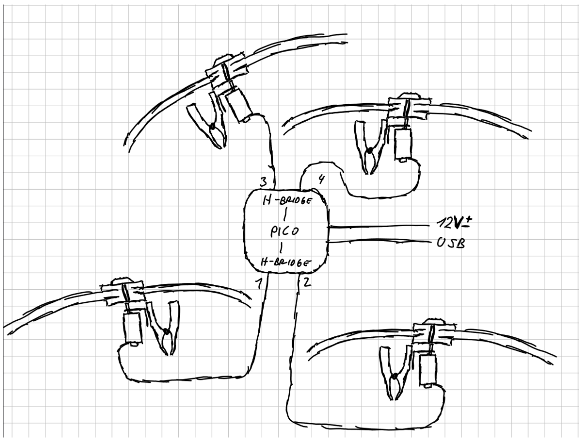

Figure 7: Larger module capable of independently interfacing with DAW

5. PROTOTYPING AND TESTS

5.1 Tubing Types

We tested several types of tubes, [large diameter (1.2”) pop tubes](), [small ½” diameter pop tubes](), [½” corrugated tubing](), and [1” corrugated tubing]() (pictured left to right, top to bottom).

Figure 8: examples of various options for corrugated tubes

The large pop tubes worked poorly (they were flimsy and did not make much sound). The small pop tubes worked very well. The half inch corrugated tubing did not resonate as well as the small pop tubes (despite having the same inner diameter). It was not able to resonate at the fundamental frequency at all and struggled to stay resonating clearly at other harmonics. The one inch corrugated tubing did not produce sound at all. After this testing we concluded the small pop tubes would be a good choice moving forward.

5.2 Tube Frequency Tests

With a little bit of testing, we found that tube frequency seems to be well approximated by the formula $f = C/L$. Here, L is the length of the tube in inches, f is the frequency in Hz, and C is an empirical constant. For our set of small pop tubes C seems to be about 5800 inch*Hz. Below is a table with some rough data measuring the expected RPM needed to spin various small pop tubes.

Table 1. Frequency vs Length, RPM

Tube Frequency	Tube Length	RPM for natural harmonic resonance
C4 tube (~262 Hz)	22.75 in	96
E4 tube (~330 Hz)	17.75 in	110
E4 tube at second harmonic (~659 Hz)	17.75 in	225
B4 tube (~294 Hz)	11.25 in	235

5.2 Motor Tests

After spending some time evaluating the best mechanism to drive our tubes, we began by testing using a Nema 17 stepper motor. This was able to rotate the tubes at high speeds successfully (Figure 10) however it produced more noise than would be desirable.

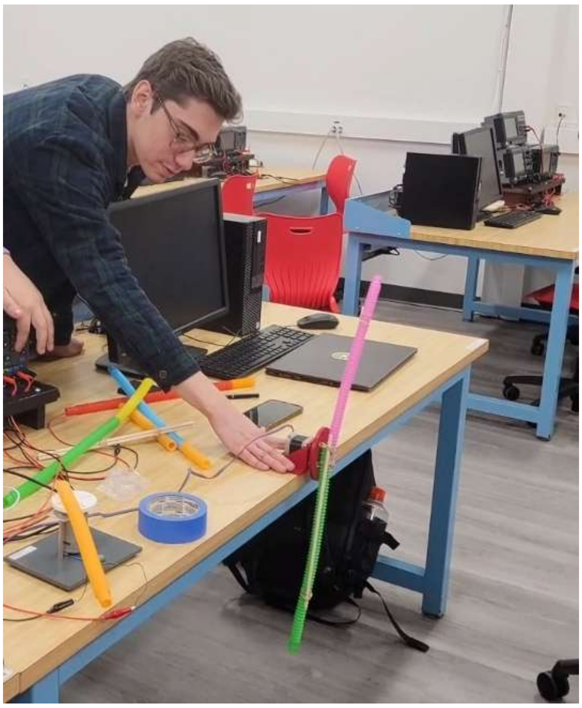

Figure 9: Initial tests using a stepper motor

Stepper motors can perform at speed, but they lose most of their torque in doing so. As a result, we knew that DC motors would likely be the way to go. We think brushless motors would have been even better for our use case, since they are usually much quieter than brushed motors, but due to cost restrictions we stuck with basic brushed DC motors. However, DC motors presented another small issue for us to deal with: how do we control the speed with precision? These motors require encoders as well, which, with a little signal processing, gives an accurate reading of position which we can use to calculate speed. Therefore, we ordered several DC motors that we hoped to test before coming to a final decision about what mechanism to use.

We did a few qualitative tests regarding the maximum motor speeds we needed, but our final motor decision came down to pricing. We tested an excellent 24V 800RPM 33mm long geared motor that would have perfectly fulfilled our needs if it were not more expensive than the alternative and if it had speed encoders. The only motors that matched our RPM requirement as well as our power supply voltage and our budget were the 12V 520RPM motors that are present in our final design.

6. FINAL DESIGN

6.1 Overview

Our final design deviated somewhat from our preliminary design. Instead of having all the motors connect to one central control board, we decided to build three entirely separate modules, each with four motors. Each motor spins three tubes tuned to a single pitch (initial testing in Figure 10).

Figure 10: First triple-tube mount test on a DC motor

Each module is controlled separately via a serial connection over USB. All together, the 3x modules should be able to play each note on an octave of the chromatic scale. By playing the first and second harmonic of each tube, we should be able to play 2x octaves.

6.2 Module Design

Each module will contain a Pi Pico to act as our control board. This is connected to 2x L298N dual H-bridge motor controller boards. Each of these motor controllers is connected to 2x motors (so 4x motors per module). All of this control circuitry is contained within a plastic food storage container. Each module has 6 bundles of wires entering/exiting it. One set of wires goes to each motor/encoder, one set provides power, and a USB cable provides a serial connection. All modules are powered centrally off of a 12V power supply.

Instead of building a custom frame for each module, instead we opted to attach clips to each motor to allow it to be mounted freely to various surfaces. Each module is wired follows a simple schematic (Figure 12, Figure 13).

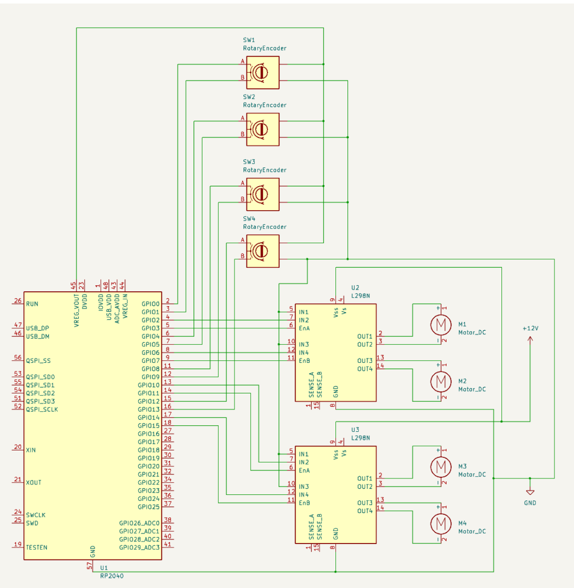

Figure 11: Wiring diagram in KiCAD

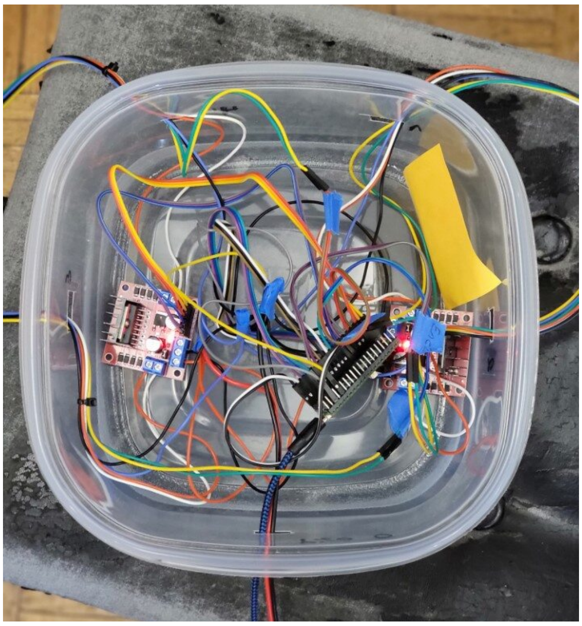

Figure 12: Physical wiring for a module

6.3 Module Assembly

Tubes are attached to motors using a custom 3D printed mount and tube clamp structure (Figure 14). Designed to house a 6mm motor D-shaft, and M3 screws and 5.7mm heat insert nuts embedded into the PLA plastic.

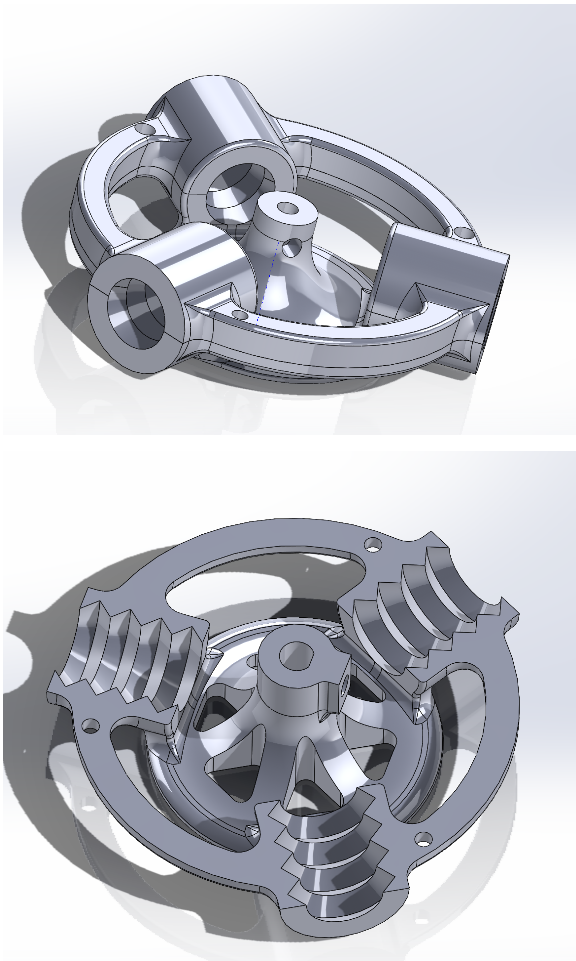

Figure 13: CAD drawing of the tube connecting module

6.4 Communication and Control

We use a patch written in Max/MSP to communicate between a DAW and our Raspberry Pi Picos. Max processes our MIDI output from Ableton, isolates the note and velocity data, and then sends it over to all three serial ports at once. The Picos, programmed in MicroPython, continuously poll the serial port for new info, and upon receiving note and velocity data, set a corresponding target speed for the correct motor. Speed control for the motors are programmed as Proportional-Integral Controllers, updating the motor efforts continuously in the background by software timers that trigger set callback functions every 20ms. Encoder counts for the motors are also handled asynchronously by utilizing the Programmable-IO State Machines present on the RP2040 processors, which are written in assembly and set registers with the current encoder count as the signals come in. This allowed us to keep track and control the speed of up to four motors at a time with minimal CPU overhead.

6.5 Missed Requirements

Unfortunately, we didn't have time to attempt to use a servo to cap off the tubes while they spin. Manual testing proved that capping off the intake does indeed cut the note off nearly instantly.

7. RESULTS

7.1 Musical Usage

As expected, our machine sounds somewhere between a choir, an organ, and an angry ceiling fan. It sounds eerie but subtly different from any instrument we've seen before. It works best when playing slow harmonies with many simultaneous notes rather than quick melodies with single notes.

Additionally, the visual aspect of this project can not be overstated. The bright spinning colors are reminiscent of a carnival while the spider web of wires and background noise from the air being moved makes you feel like hearing an angel's voice in the background while cutting your way out of a hell-ish jungle.

Figure 14: Whirly tube module mid-performance

7.2 Evaluation

We were able to reasonably well realize our design with respect to our initial requirements. We successfully designed a machine to play music by spinning tubes and produced over an octave of usable pitches. However, there were quite a few improvements to our design that we did not have time to develop. We did not have time (or likely the hardware ability) to control note dynamics by adjusting the acceleration/deceleration curves of our motors. We also did not have time to implement our idea of partially or completely capping the tubes to reduce airflow and control note volume more quickly.

Something we were able to do was use very low notes (D0, C0) outside our instrument range to control start/stop all the motors at once. The low-pitch long tubes had a tendency to tangle, therefore a slow startup sequence could be initiated. The stop command was used at the end of a piece to make all the tubes "flop" simultaneously and introduce sudden quietness into the room.

7.3 Problems and Potential Improvement

The largest problems we faced were those of volume (too much or too little) and range. We had too much background noise and not enough sound production from the tubes. Our largest unanticipated source of sound was that of the wind produced by a dozen spinning tubes. Additionally, the dozen motors and their gearboxes produced an expected amount of background noise. Some of our tubes on the other hand were much quieter then we had anticipated. The lower the tube the quieter the note. In particular, our first four tubes (C4 to D#4) were almost inaudible when playing the thair first harmonic (though plenty loud playing their second (C5 to D#5). In future iterations of this project, spending more time to find tubes with a large range of loud first harmonics would be a great idea. We also were unable to reach the second harmonics on our three highest-pitched tubes. This was mostly a limitation of our motors lacking the torque to spin them fast enough, or the back electromotive force being too large at high speeds limiting the maximum RPM. To lower current draw and lessen the impact of voltage drops over long cables, a 24V system could have been used. Another great next step that occurred to us when presenting the final project would be to use brushless motors as they are quieter, have more speed and torque, and can also be precisely controlled. The only issue that poses is their high purchase cost.

One of our early ideas was to use ribs to support the tubes and prevent them from drooping. While the tubes are able to stay mostly straight while spinning, using some form of ribs, perhaps only half-length, would be tremendously useful to keep the tubes from getting tangled when spinning up and keep long low notes from making an arc which hurts air pressure difference, and thus overall sound.

7.4 Summary

Overall we would describe our machine as a prototype that shows excellent promise and begs for future iterations that improve on its design. Whirly Tunes combines music, robotics, and colorful tubes in an eclectic blend that is both visually stunning and sonically entracing.

Figure 15: Whirly Tunes in all of its glory

8. REFERENCES

[1] N. Hall, S. Bozzuto, and M. Fromm. Marine A2. *Elevator Music*, (2017), https://nathan-hall.net/elevator-music.

[2] A. Cavatorta and K. Biewald. The Dervishes. https://andycavatorta.com/dervishes.html

[3] T. Oldfield. Whirly Chorus. *New Bedford Art Museum*, (2021), https://www.tessodesign.com/whirly-chorus.

9. APPENDICES

9.1 Appendix A: Bill Of Materials (BOM)

* signifies zero cost for us as we had that part on hand

Part	Part #	Specs	Link	Qty	cost/part	Total Cost
32 Pack of Pop Tubes	-	-	here	3	$9	$27
Tube motor mount (custom 3D print)	-	-	N/A	12	$1	$12
DC motor with encoder	JGB37-520	Datasheet	here	12	$10	$120
4x Dual H-bridge	L298N	Datasheet	here	2	$12	$24
Pi Pico W	-	Datasheet	here	3	$6	$18
6x Spools of 33ft 22AWG Solid Core Wire	-	-	here	2	$13	$26
40ft 18AWG Wire	-	-	here	1	$11	$11
Desktop Power Supply	-	12V 30A	here	1	$24*	$24*
3x 10' USB-A to Micro USB	-	-	here	1	$10	$10
3x food storage containers	-	-	here	1	$10	$10
6x 6 inch spring clamps	-	-	here	2	$13	$26

9.2 Appendix B: Github Repository

All of the code used on the WhirlyTune can be found here: https://github.com/Kreeevin/WhirlyBoi

9.2 Appendix C: More Information

More information about this project can be found here: https://wp.wpi.edu/musicalmachines/2023/12/17/whirly-tunes/