WAT-R Robot

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Figure 1. Previous WAT-R Design

Motivation

Everyone has tried to blow on a glass bottle with a drink inside to produce a note. Either that, or they have accidentally hit their glass and realized that it produced a rather clear pitch. It is both common and uncommon to have an everyday object like a glass bottle produce a pitch so clear and concise like a musical instrument, and some people have been innovating instruments using multiple bottles pitched at different levels for a long time. Through experimentation, it becomes obvious the pitch produced is changed by varying the volume in the vessel; in fact it is directly related to the volume of the liquid inside: when there is more liquid in a container, the pitch is lower; when there is less liquid, the pitch is higher. Some musicians have started to create a vibraphone-like instrument out of bottles, where each bottle is separated by a half-step and therefore fit within the means of western music styles.*

Many musical installations use a water feature as a complementary element to music. With this instrument we intend to use the flow of water to control the pitch of the glass containers making it an integral part of playing the instrument. With this design we are also looking to use the water to build anticipation and add another visual element to the instrument creating a "natural" art piece/instrument.

Concept

In previous years, students at Worcester Polytechnic Institute have attempted to expand making music with water by creating the musical robot called WAT-R, seen in Figure 1. The basic idea of this instrument is to have a variety of hanging glass funnels that can be filled up with water at various heights throughout time to create different notes. Currently, there are some design and functionality flaws with the piece: it is not programmed to release water into the funnels or to strike them, the basin is not visually appealing, and the piece

* "The Flight of the Bumblebee" was played on glass bottles by three people at the same time. This will be discussed in a later section.

itself is resting on a hat rack. Some other mechanical issues include the strikers not actually hitting the funnels with enough force and the stopcocks not being attached well to their respective servos.

Prior Art

Colm O'Regan was able to play a famous orchestral interlude titled, "Flight of the Bumblebee," on 101 different glass bottles[3]. He and two others ran around a kitchen and hit a series of bottles with sticks. The bottles were filled with water with different volumes in order to produce different pitches, all tuned to the western chromatic scale. The bottles were lined up to the pitches of the notes in each fuge. This process makes for a stellar performance; it's not every day you see three men running around a kitchen hitting 101 bottles with sticks; nevertheless, it is flawed due to human error (timing between notes will inevitably be off). While having the bottles spaced throughout the kitchen creates an interesting visual element when the songs are being played, it is not ideal or efficient. Instead, the thought process for this robot is, "What if each bottle could change the note it was playing so you only needed approximately eight bottles, and what if each bottle had one player?" Not only would this increase efficiency, but it would also make for a far more relaxed visual appeal, which might suit the sound generated from it.

Chandeliers are also an intriguing model to base new designs from. For example, the dangling glass funnels can be styled like lightbulbs in a chandelier creating movement throughout the instrument. Figure 2 showcases a chandelier design similar to our vision for the updated WAT-R robot. This would be a fascinating and appealing way of arranging the funnels in a display.

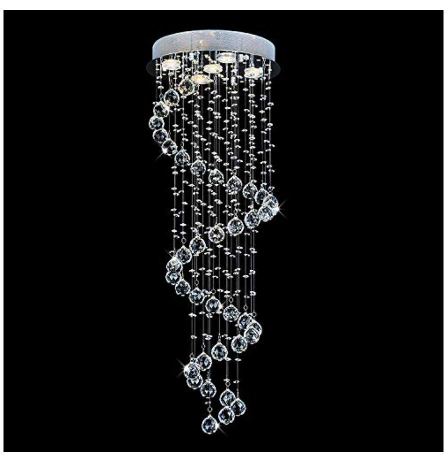

Figure 2. Cascade Chandelier[4]

Figure 3: Dog fountain[2]

Other inspirations come from water fountains. One of the biggest selling points of the water fountains is their ability to recycle their water in a visually compatible way, whether this means hiding the process or making it part of the fountain design. They also illustrate different ways water can be manipulated to be visually appealing. Figure 3 shows a fountain in Canada that has water streaming from the mouths of dog statues[2]. The humor and symmetry of the water recycling back into the fountain makes the piece visually striking and is a unique touch on a classic sculpture. The goal for the WAT-R robot is to also touch on a unique twist on an old classic water fountain - using the fountain's fundamental property of recycling water in an artistic way, but making it different from any other water fountain that exists to this day.

Currently, when music is tied to fountains, the water in the fountain is programmed to move in time with whatever song is playing at the time. While this is an interesting concept and can be fun to watch, we want to expand on this idea further by making the water a more integral part of the instrument.

Water-based instruments already exist, we mainly focused on the hydraulophone[1]. The inventor, Steve Mann, found that by drilling holes into a pipe and having water pump through the holes, a specific pressure will be produced that will be changed when a finger lays on top of a hole. This specific pressure will produce a pitch that is audible to the human ear. The hydraulophone plays like a blend between a piano and a recorder, and its visual characteristics are limited to the water streaming through each of the individual holes.

Figure 4: Steve Mann's Hydraulophone[1]

The instrument also uses a water recycling system, where water is collected in a trough and is pumped back up to the main pipe. This structural idea will be implemented directly into the WAT-R bot, but instead of a more hidden, less vertical approach, pumps will be sending the water straight back up in the air, like a water fountain.

By combining the ideas of dangling the glass vessels like chandeliers, circulating the water as seen in fountains and in the hydraulophone, and striking the vessels like the three men did to play "The Flight of The Bumblebee," we hope to create a visually-intriguing nuanced instrument.

Design Concept

The goal for the next stage in creating this musical robot is to turn the previous proof of concept into a visually appealing instrument that plays music. To achieve this goal, we plan to take away the hat rack, modify the basin that holds water, redesign the striking and valve mechanisms, and program the servos, valves, and sensors properly.

An idea that can potentially be put into place is to have a metal plate hold the brain (microcontroller and PCB (printed control board) and the basin. This metal plate will potentially be hanging from the ceiling to create a hanging instrument that looks like a chandelier. Hanging from the metal plate and water basin will be a series of clear tubes which will carry water from the basin to each glass container. These tubes will have solenoids near the basin to control the flow of water as well as present the visual appeal of seeing the water fall from a large height to get to the glass funnels. There will also be a flow sensor so the amount of water entering the glass will be known for creating the correct pitches.

To play the individual notes a metal or glass rod will be used to strike the side of the glass container; this rod is currently controlled by a servo motor; however, this is subject to change if better design opportunities arise. At the very bottom of each glass funnel another servo will be used to control how much water can leave the container and when it should drain.

Resting on the floor below the hanging instrument will be a water catch pan with a pump connected to it to recycle the used water back up to the basin. This pump will be contained in a soundproof box so that no noise from it will be heard while the instrument is playing.

Requirements

Sonic Requirements

Due to the design concept, timbre of the instrument is limited to the *clink* of a stick hitting the glass funnels. In order to maximize the variety of sounds possible in the instrument, the pitches of the eight funnels must differ from one another; where the instrument lacks in timbral contrast it will gain in its ability to play any pitch possible within its set range by changing the water level within each funnel. The set pitch range that the robot can play based on the sizes of the funnels; the lowest pitch is possible when the largest funnel is full (an A#5), and the highest pitch is possible when the smallest funnel is empty (a C#7 and beyond). The instrument itself can be tuned to any scale - western or other - by knowing the volume needed in order to produce an in-tune pitch in each of the eight funnels.

An interesting constraint of this instrument is gravity: water can only move so fast in and out of the funnels. In turn, if a song was imported that was far too fast for the robot to play; meaning that water would have to move in and out of it faster than possible, the pitches wouldn't be accurate, so the song wouldn't play back properly. The time that it will take between notes in the same funnel will depend on how far apart the notes are in terms of volume. In the large funnel, a jump from the lowest note to the highest note would take 50 seconds to get to. All other funnels should be able to reach their desired notes in less than that time. Striking the funnels can be done much faster than changing the notes; at the same note, a single solenoid hitting a funnel should be able to hit every 100 milliseconds.

Visual Requirements

To complement the unique musical impact of the robot - it will be playing quieter music with a timbre not well-considered by most people - the instrument must be eye-catching. It should be possible to watch the water rush down the pipes and leave the funnels according to the code loaded in the microcontroller. Therefore, there has to be continuous movement of water through the pipes throughout the song.

In addition, LED lights will be used to highlight which of the glass funnels are being struck to further enhance the presentation. Simply, when a funnel is hit, a light located on the solenoid platform will flash.

Preliminary Design

This robot will be designed to hang from the ceiling like a chandelier, a design similar to the one pictured in Figure 2. Figure 5 shows an initial simplified sketch of the design of the robot. There will be a basin on top that supplies water through pipes to eight glass funnels, all hanging from a plate below the basin. The plate will be hung up by wires to the ceiling of the performing space. There will be another basin below the glass funnels to collect the water being dispensed and a water pump inside the lower basin to shoot water back up to the upper basin through piping.

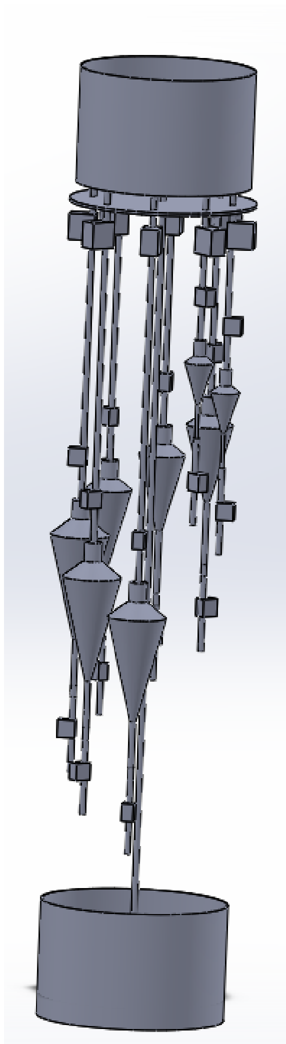

Figure 5. Preliminary Design

Attached to the glass funnels will be a platform where two servos rest, one will be attached to the stopcock to control the amount of water leaving the funnel, and the other will control when the metal rod will hit the glass funnel. At this time, we are planning to keep the same platform as used on the previous iteration of this robot. The flow of water into the funnels will be controlled using a valve and flow sensor placed along the piping. We will be using flow sensors on either side of the funnels to simplify the calculations for how much water is entering and exiting the funnels. The water flowing through the funnels will be colored and the tubes will be transparent to create a more visually appealing instrument. To magnify the movement of water, the solenoid valves will release water from the top of the tubes.

The program will read and play MIDI files by queueing funnels. As the program reads a midi file the program will "interview" each funnel in the waiting room (not queued) by asking how close each funnel's current pitch is to the MIDI value and will add the closest one to a queue. The program will decide which funnel is the closest by comparing the known volume of each funnel to the desired volume of the note from the MIDI file. While in the queue the instrument will fill or drain the funnel to its target pitch. The queue will start playing once there are no candidates left in the waiting room and the first queued funnel is at the correct pitch. Once a funnel plays a note it is returned to the waiting room to be queued again. One flaw of this design is that a funnel may not be at the correct pitch by the time it reaches the front of the queue depending on the flow and drain rate. As a result a fast tempo song with a large pitch range may need to occasionally stop to allow the funnel to reach the correct pitch or be played at a slower tempo.

Final Design

The final design of the WAT-R robot can be seen in Figure 6. The CAD model does not include the fishing line that the funnels will be hung with, the wires that will connect all the electrical components, or the power supply and brain, but our plan for these components will be discussed later in this section.

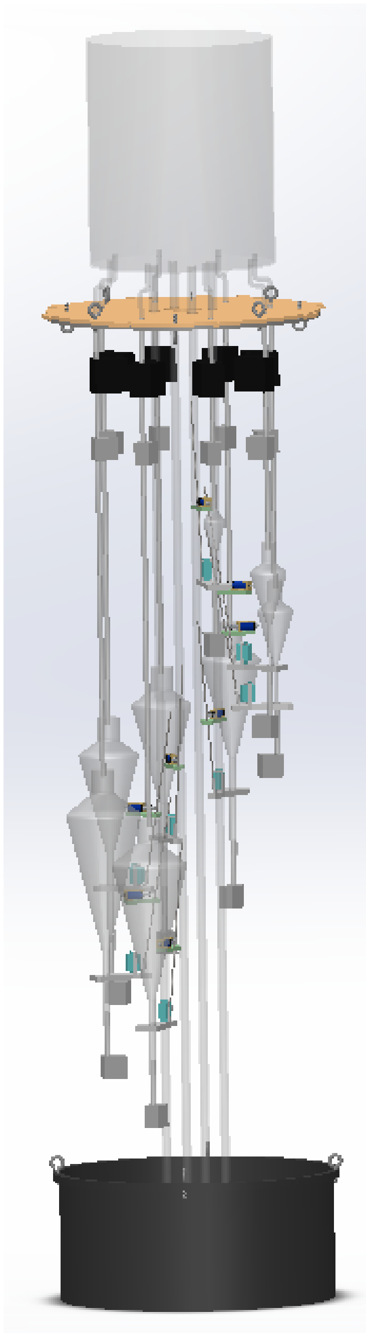

Figure 6. Final Design

Upper & Lower Basins

Initially, there was a basin that would hold water at the top of the sculpture with tubes sticking out of the bottom of it to distribute water to each funnel individually. The previous design team did not decide on how to collect the water leaving the funnels, though, and did not decide on how to produce a steady amount of water to the funnels so that the robot could replenish its own water. The design has been updated to include a lower basin that will collect the water, and a water pump that will be sitting inside of the basin with a tube attached to it; this pump configuration will pump water continuously to the upper basin at a constant flow rate to ensure steady supply of water in the upper basin and in the funnels. There will also be an ultrasonic sensor in the lower basin to ensure the water level never drops below two inches as this would burn out the pump.

Overall Structure

In order to suspend the sculpture in air, a steel plate will rest under the upper basin and will have four steel cables connected from it to the ceiling where it will be displayed. There will be a wooden disc that's notched resting in between the basin and the plate where the glass funnels will be hanging using fishing line. The steel plate will also hold up the lower basin with cables.

Framework

A wooden frame will be built so that the robot can be its full height and be designed completely before it is finally displayed. It will be about eight feet tall and wide enough to create enough room for the robot to be created and hung freely.

The Brain & Wiring

The brain will be contained in a water resistant container with waterproof electrical connectors connecting the wires so that the brain can be disconnected for easy disassembly. Within the brain box there will be the Arduino Mega, the 16-servo controller, and the H-bridges for the solenoids. The Arduino Mega has 16 analog pins and 54 digital pins; for our design we are using all of the analog ports and some of the digital ports for the LEDs, for the solenoids and flow sensors we are using digital ports, and for the servos the servo controller will be connected to the SDA and SCL ports on the Arduino Mega. The brain will be mounted on one side of the top water basin and the power supply will be mounted on the opposite side to balance the visual appeal of the robot. Wiring schematics for the major part of the electrical system can be seen in Figures 7 through 10 below.

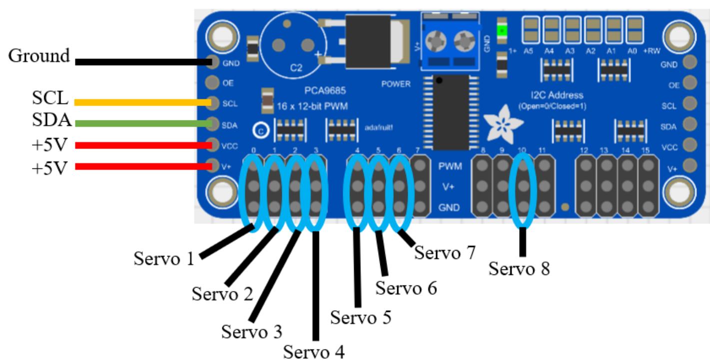

Figure 7. PCA9685 Servo Board Schematic

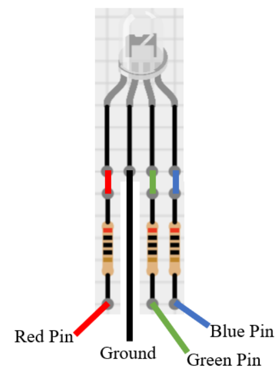

Figure 8. LED Schematic

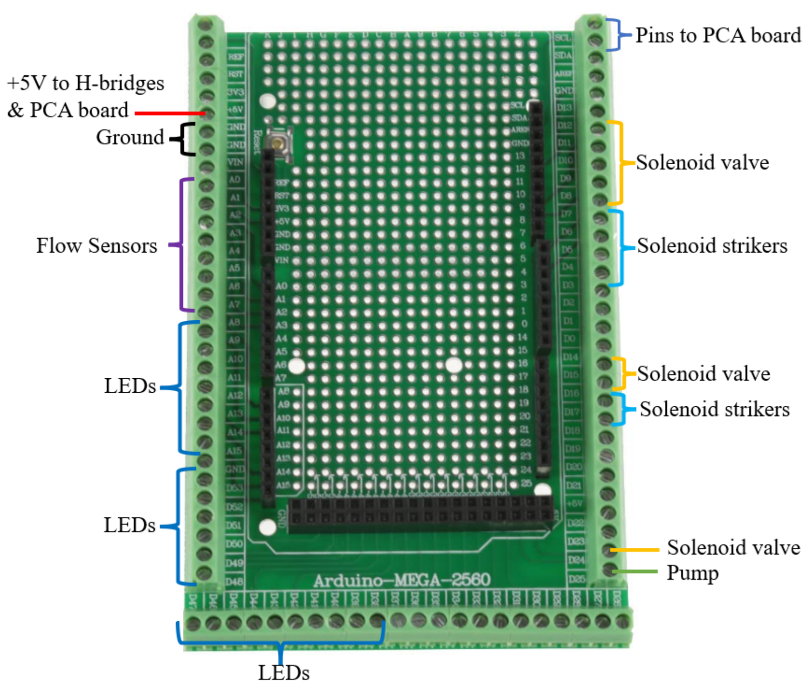

Figure 9. Arduino Mega Schematic

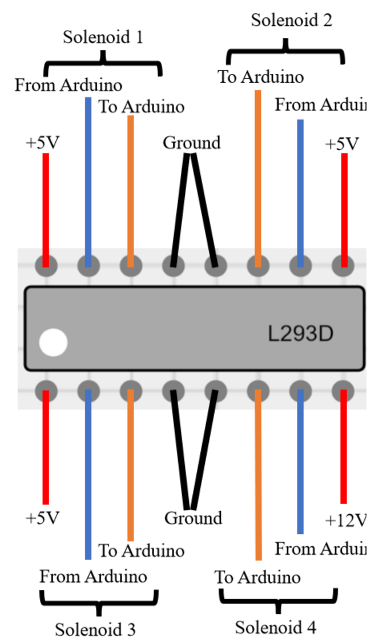

Figure 10. L293D Solenoid Schematic

All of the wires leaving the brain will be contained within a wire harness and stay hidden in the wire harness until they reach the component they need to be connected to. The wires are all waterproof which adds another layer of safety when working with water. They are also color coded which makes it easier to tell which wires need to go where and what components they need to be plugged into. Finally, the wires have connectors that allow them to easily be detached from their components. This will make it significantly easier to move the robot as it makes the funnels modular and allows for them to be easily and safely removed for travel.

Servo Mounts

The prior team designed platforms that were placed at the bottom of the glass funnels where two servos were lodged: one controlled the outflow of the water in the funnel by being attached to the stopcock, and the other was attached to a glass rod in order to hit the funnels. This setup has been redesigned in order to maximize resonance in the glass funnels: the servo/rod combination has been replaced by a solenoid suspended on the platform by a pole, as can be seen in Figure 11. The pole will be angled to be parallel to the angle of the funnels and will be held in place by an O-ring. The servo attached to the stopcock remains the same as before. In order to maximize visual appeal, the solenoids and servos will be positioned toward the inside of the sculpture so they are harder to see; on the outside, a counterweight will be placed that adds character to the sculpture consisting of led lights so that when a solenoid strikes a glass funnel it lights up.

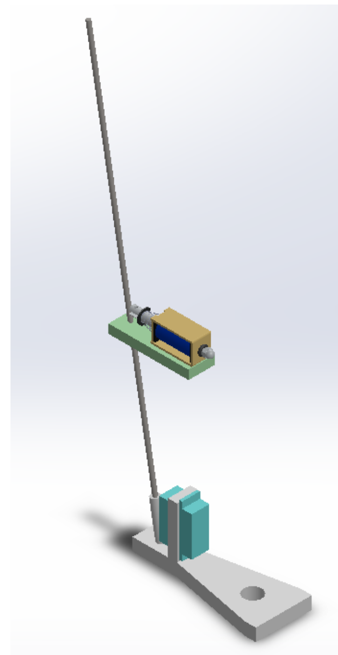

Figure 11. Actuator Mounts

Tubing

In order to carry the water to the tubing, pipes would drape from inside the upper basin to inside each funnel. Along the tubing would exist a valve and a flow sensor respectively in order to control the flow velocity coming into the funnels from the upper basin, as can be seen in Figure 12. After the water passes through the flow sensor it will fall into a funnel. The water will flow into its respective funnel until the flow sensor tells the solenoid valve to close. The water will stay in its funnel until the servo attached to the stopcock turns, opening the valve on the bottom of the funnel. From there, the water is free to fall into the lower basin where it will be recycled back to the upper basin through a pump.

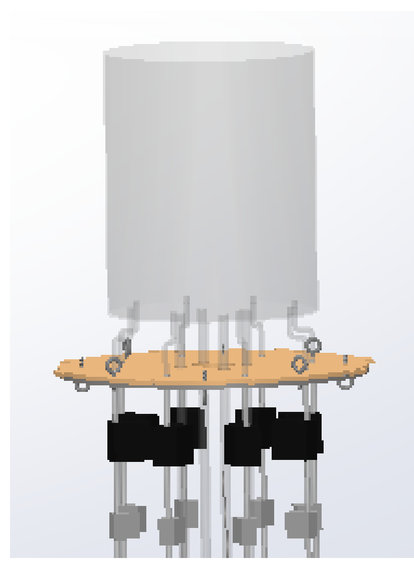

Figure 12. Upper Basin, Valves, & Flow Sensors

Programming

We coded a Max patch that will control the instrument. On the interface of the Max patch users will have the ability to set the volume of water that is in each funnel, see the current level of water in each funnel, tell each individual striking solenoid when to hit, and change the color of the default LED and striking LED. Eventually, this Max patch could be connected to a MIDI file and played that way, but that was outside the scope of our time limit. The interface of the Max patch can be seen in Figure 13 and the code for the Max patch can be seen in the Max Patch section of the Appendix.

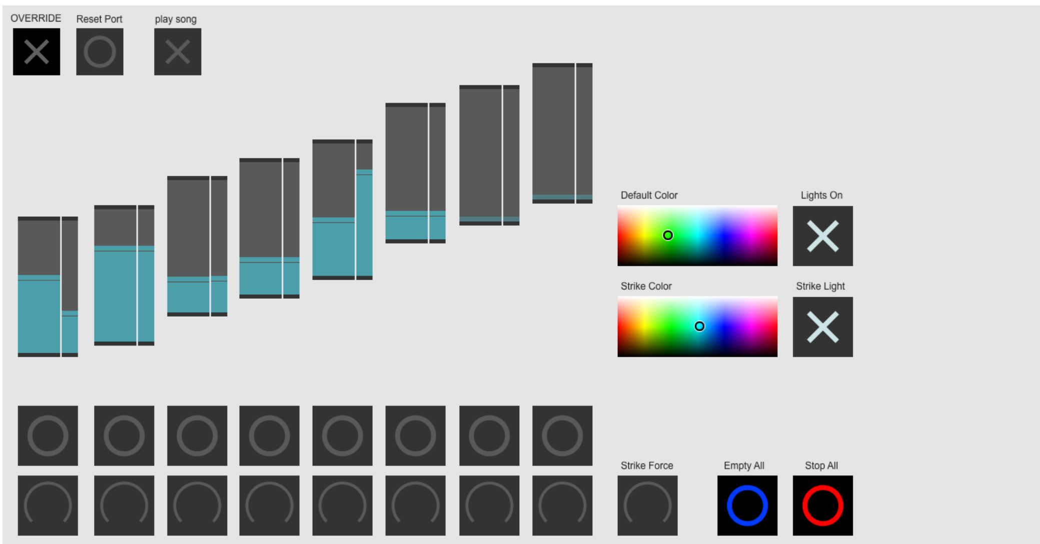

Figure 13. Max Patch Interface

The Arduino Mega has a framework setup to communicate with the Max patch and make changes to the individual components (i.e. solenoid, servos, LEDs, etc.) to reflect the changes made in the Max patch. The Ardunio communicates to the components through different digital ports on the board. The flow sensors will provide the Arduino with information to know when to open and close the solenoid valves. Similarly, there is an assumed constant drain rate for each of the funnels. When it is time for a funnel to drain its servo will open the stopcock and the water will be allowed to drain for a set number of seconds based on the new desired water level in the funnel and its specified drain rate. The code can be seen in the Arduino Code section of the Appendix at the end of this report.

Pitches

Each funnel will be able to play different notes depending on the amount of water that is in the funnel when it is struck by the solenoid. The current range over all eight funnels is A#5 to C#7 meaning the funnels are a very high pitched instrument with little resonance. For this reason the instrument will act more as pitched percussion.

The flow rate sensor above the funnel will keep track of the amount of water flowing into the funnel and the assumed drain rate will keep track of the water flowing out. While this math will not be perfect, the amount of water within each funnel should be relatively known. However, WAT-R will not play specific notes. In the future it could be modified to do so, but that would require adding a built-in tuning device and much more control over the amount of water.

Bill of Materials

The total cost of our project is $635.63, the breakdown of this cost can be seen in our Bill of Materials. Also in the Bill of Materials are links to all the different components and the quantity of each. Our Bill of Materials can be seen in the link here.

Evaluation and Design Modifications

Although our final design was pretty specific in its consideration of all of the moving parts, some of the aspects of the instrument have been modified since the construction of its final prototype. Instead of the instrument having active movement occur throughout a piece, it has been decided that, due to the range constraints of the instrument, it would make sense to have the funnels tuned to the key that the instrument is playing in. WAT-R can only play in two octaves, and two very high octaves at that. It makes more sense to have the instrument act as more of a pitched percussion and not as a melodic instrument, because not many melodic instruments are constrained to the higher registers of pitches perceived by humans.

The physical design itself has remained close to identical to the final design, minus the physical appearance of the different materials used. The only difference is that the upper basin is now hanging, whereas before it was planned to be connected to the steel plate.

In Figure 13, the wiring can be seen in its wire harness in the center hole of the steel and wood plates. Ultimately this wiring will be hidden on top of the plates within a box for the brain, this will also help with protecting it from any possible water that may leak out.

Figure 13. Hanging support plates for the rest of the pieces of the robot.

The funnels are still being hung like depicted in the final design - spiraling upward and decreasing in volume as the height of them from the plates decreases. The lower basin will still be put in place at the bottom.

The steel plate that will support the entire system can be seen in Figure 14. The wiring will go through the large hole in the middle, the pump will lead to four tubes going through the four holes surrounding the large center one. The next circle of holes is for the tubes that connect to the funnels. Finally, the smallest outer holes will be used to connect the lower basin and suspend the

Figure 14. Steel plate that supports the system.

The wooden plate in Figure 15 will rest on top of the steel plate in Figure 14. The main purpose of the wooden plate is to hole the funnels with the small spikes that are extending all around it. The funnels will be suspended with a fishing line that is hooked around these spikes. The rest of the holes are just mirrored off of the steel plate to ensure everything fits together nicely.

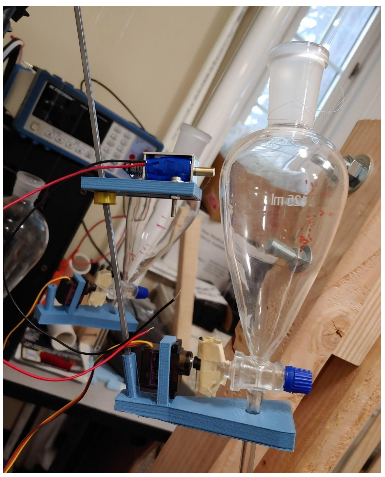

Figure 16. Assembled Actuator

entire robot for the ceiling.

Figure 15. Wooden plate that holds the funnels.

In Figure 16, the assembled actuator is seen. There is an O-ring under the lower plastic piece to ensure it stays on the funnel. Attached to the lower piece is the servo that opens and closes the valve on the funnel and a metal rod that holds the solenoid platform. The solenoid platform is adjustable and can be held in any position by changing the height and moving the yellow piece and its O-ring directly under the platform. The LEDs will be attached to the underside of the platform to light up the funnels from behind. The funnels are suspended with thin fishing line and can be seen in Figure 13 hanging from the wooden plate.

In Figure 17, our final instrument can be seen. It resembles quite closely the CAD design seen in Figure 6. In assembling the instrument, we learned that the bottom basin we have does not have a wide enough opening to catch all the water falling from the ends of the funnels. We also decided that it was better to hang the upper basin to help relieve some stress on the steel plate and because it was more clean and visually appealing than adding a supporting box to hold it up. On the underside of the platforms that hold the striking solenoids we attached LEDs that will change color when the solenoid is activated. Overall, we are very pleased with the design and look of WAT-R.

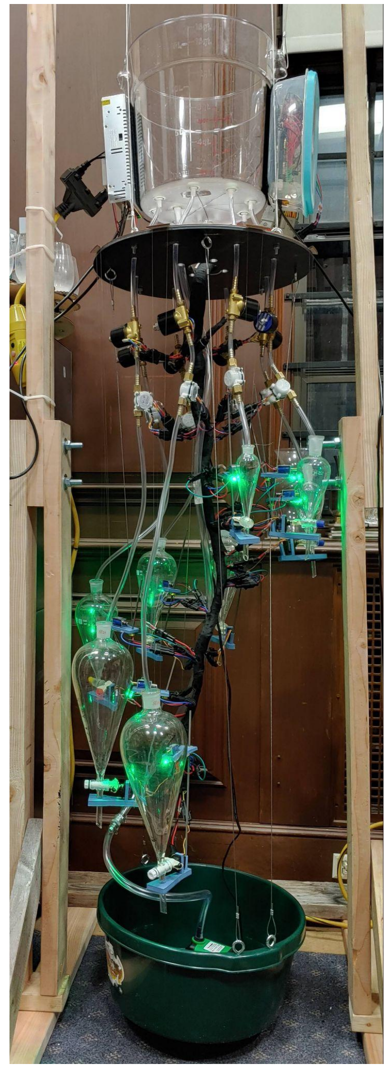
Figure 17. Assembled Instrument

Musical Usage

WAT-R is more of a background instrument. It is not very loud or expressive. WAT-R was designed to be more of an art installation with the addition of music than an addition to an orchestra. The ideal situation for this instrument to play in would be a quiet environment as background music or as a secondary instrument in a song that adds small ad libbed sections every so often. WAT-R is a pitched percussion instrument with a very high register making its melodic and harmonic capabilities very limited.

Reflections

Overall, we were very successful in bringing our ideas to life. Visually WAT-R looks great; it is a huge improvement over the coat rack and nest of wires that existed previously. Also, compared to our original motivation and preliminary design our final instrument looks quite similar. Visually we have completed every idea we have had: making the wiring less noticeable, adding lights to illuminate the funnels, making the funnels spiral like the chandelier in Figure 2. The only things that have changed slightly are that we are no longer having the instrument play specific notes and that at this time the water will not be able to flow through the instrument as much as we originally wanted it to.

The biggest inhibitors to the water flowing often through the instrument were a lack of time and not large enough lower basin. Because the basin is too small we are unable to freely cycle water through the robot, this makes it impossible to have water constantly moving. In the future we would recommend purchasing a basin with a larger diameter opening to catch all the water falling from the funnels.

While designing, assembling, and programming WAT-R we encountered a few different hurdles. First, the original wood that we have found to cut the upper plate out of was too thick which created an issue when trying to laser cut it. This issue was solved by purchasing thinner wood that would be easier to laser cut. The next hurdle we encountered was a short in our perf board that houses three of our L293D H-bridges. Once we found the short in the system - a stray wire connecting power to ground - this issue was easy to fix. Our next two hurdles were in respect to our tubing and upper basin. First, our initial attempt to apply sealant to the tubing holes in the upper basin failed; this ended with us buying new sealant to reseal the holes. Second, the one-way valve we bought to keep water flowing from the upper basin to the lower basin was slightly too small for the pump tubing. To keep the valve connected to the tubing we used hose clamps to tighten the tubing around the connectors on the valve. Other than these four hurdles we did not encounter many major issues. We had to do a lot of debugging and testing with the code and Max patch, but that's normal and we built time for it into our overall plan.

Overall, we are all very proud of the instrument we created and think it nicely satisfies most of the goals we set out for ourselves at the beginning of the term. The goals that we fell short on are addressed in the Future Directions section along with what we would have done to complete them if we had time.

Future Directions

There were three main components that we thought could be improved. First is a better way to attach the servos to the stopcocks on the funnels. We had to use tape due to a lack of time to design a better solution, but a more structured method of connecting the two would make opening and closing the stopcocks a lot easier. Second, as previously mentioned, a larger lower basin is needed to effectively catch all the water that falls from the funnels. Finally, there are two different improvements that could be made to keep track of the volume of water within each funnel. The first change could be adding a secondary flow sensor to the bottom of the funnel that can track how much water is leaving more accurately. The second change could be getting rid of both the top flow sensor and the servo and adding a pressure sensor and second solenoid valve below the funnel. For this to work, the funnel would need to remain open the entire time and the amount of pressure sensed by the pressure sensor would determine if the upper solenoid valve needs to open to add more water or the lower solenoid valve needs to open to drain out some of the water.

References

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Appendix

Max Patch Code

The code from the Max patch can be accessed by the following link.

- Max Patch Code

Arduino Code

The Arduino code can be accessed by the following links.

- WAT-R_Program.ino
- Funnel.h
- Funnel.cpp