***Aqua Strings*: Interactive Waterfall Display**

Initial Divide and Conquer Document

EEL4914 – Senior Design I

Group 13

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Chapter 1: Executive Summary

The Aqua Strings Interactive display project is an interactive, immersive system for generating an enticing, immersive water effect that responds to the user's interaction. At its core, the project merges both the visual aesthetic of water in motion with the audio aesthetic of music to provide a multidimensional experience that is enticing and active. The system is powered by water streams that are triggered in synchronicity with music. Once a user's hand interrupts the laser beams, these personalized triggers change the water streams whenever a user's hand interrupts the laser beams. Having this ability allows for a different form of interaction to take place since the water streams and music reaction responds to the individual user's movements in real-time. Thus, when the user's hand interrupts the triggering laser beams, the sensor performs the final and most specific iteration of a user-controlled interface. Laser detection sensors are a precise, reliable way to detect interruptions to trigger water flows and audio elements in harmony, which creates a visually and audibly stunning atmosphere.

The overall system combines a variety of different technologies to operate and provide the intended user experience. Precision water pumps and sensors are used to help control the water level and flow so that the display is constantly in operation and remains visually appealing. The water flow is electronically and finely controlled to ensure the fullness of each water string without unwanted gaps. Further, a variety of sensors monitor and control the water height within each reservoir to ensure continual operation within an acceptable and optimal water height range to prevent any overflow or underflow from occurring. This allows the display to be visually and functionally efficient.

Aqua Strings combines a person's physical touch with the digital world to create an enjoyable user experience. By detecting an interruption in a water string, the system will be able to respond accordingly to the specific user input at the specific water string. This project is more than an entertainment system, it demonstrates how technology can seamlessly blend with one another to create a more indepth project than any one component alone.

Chapter 2: Project Description

Aqua Strings encompasses the combination of real time audio system and sensor integration to develop an engaging musical machine. By utilizing some novel approaches and embedded systems, digital signal processing and sensor technology, this unique musical machine can prompt users to interact in a more modern way by replacing traditional strings with laminar flows of water. The system has pairs of laser photodiodes to recognize brakes in the laminar flow of water caused by hand interactions, which a microcontroller processes and outputs a sound. The project incorporates principles of fluid dynamics, optoelectronic sensing, and digital audio synthesis to create a new platform for multimodal systems that are dependent on user input/ experience. Design with accessibility and innovation goals for inclusive interaction in mind allows Aqua Strings to be experienced by all. Directions within engineering have been steered toward issues of sustainability, immersive user experiences, as well as designing devices for human interaction and this project only supports that.

2.1 Motivation & Background

Over the years, the availability and concept of modern technology is constantly evolving, which allows individuals, such as engineers, to improve existing ways of life. One of these areas of life that is constantly evolving is the entertainment and music industry through how content is created, distributed, and experienced. These advancements allow for vast audiences to immerse themselves within a given culture and/or gain a sense of enjoyment in their day-to-day lives. More specifically, these technical advancements consist of new sensors, Digital Audio Workstations (DAWs), software instruments, and even AI in music composition. Through these advancements we can do a multitude of projects, one of them involves creating a water harp/ interactive waterfall display. The concept of a “water harp” combines the practical use of a traditional harp with the new visual water element which elevates the user and audience's experience.

Water harps, also referred to as water-based instruments, allow for a multisensory experience employing different modes and tones since the sounds are now electronically generated compared to the vibrations from a traditional harp. Whether people like to acknowledge it or not our society revolves around music whether it's listening to music in the car, while doing work or eating in a restaurant. Music is an experience that we all subject ourselves to daily, so why wouldn’t we look to evolve and immerse ourselves further in the experience? Since a water harp would consist of electronically generated sounds, it makes the machine more accessible to younger children of any person that doesn’t have the musical knowledge needed to tune and play a traditional string harp.

Besides the artistic value of the project, it also stands for an innovation of technological integration and a sense of sustainability. While water is used both as the working medium and as an aesthetic component, the integration of natural elements in a technologically heavy project such as this joins two groups together.

The water harp combines modern engineering with creativity while focusing on a user-friendly experience.

2.2 Goals and Objectives

Our Interactive Waterfall Display project aims to integrate interactive technology into an artistic experience to further develop an existing instrument into a multisensory machine by integrating sound, visuals, and user interaction. By achieving our primary goals, we hope to create a more enjoyable musical experience.

The primary (basic) goals of our project are as follows:

- Design and construct a technologically advanced interactive instrument using a multitude of different sensors that will read user input and translate this information into a musical sound/note.
- Create 3 fully functioning strings of water that deal with only three notes and demonstrate how the other component of the project works.
- Implement an efficient real-time signal processing system to achieve responsive reactions with minimal latency, ensuring the expected result from the user's inputs (such as breaking a water string) in correspondence with the desired audio output.
- Maintain a constant, continuous water flow so there is no undesired break in the water (water pump calibration). This will also require additional water level sensors to be installed in each reservoir to make sure there is a constant flow of water through each string.
- Provide a multisensory user-experience involving the necessary audio tones/ notes, visuals (the colors of the laser sensors projected through the water string), and the actual tactile water element creating a laminar flow.

The advanced goals of our project are as follows:

- Complete 8 (5 additional) fully functioning strings of water, so that each note in a musical scale can be accounted for.
- Create different modes consisting of OFF, FOUNTAIN, and HARP. OFF halts all components of the project, FOUNTAIN allows the water to flow without an interactive component, and HARP adds the interactive component to the flowing water.
- Using either solenoid values or a sliding component to cut off the streams off water when needed/ desired.

The stretch goals for our project are as follows:

- Create different modes (possibly three) for different electronic sounds to be played when a string is broken. Modes could include musical, synthesized, etc. If not, we could instead have three different octaves of notes, low, middle, and high.

- Integrate small water turbines at the bottom of the water strings involving a DC motor and a 3D printed curved cup rotating component (Pelton Turbine).
- Using the values mentioned in the advanced goals, we could have motorized sequences that would create breaks in the water at specific times to have a water display without human interaction.
- Install a laser horizontally across the strings of water that would detect hand movement and play different notes for the same string of water depending on if the stream is broken higher or lower.

The overall objectives consist of fulfilling the listed goals from above and then some. The process and techniques we plan to use are subject to change as we research, and new information is discovered.

Our listed objectives are as follows:

- Correct implementation of our hardware design:
    - Incorporate accurate sensors such as laser diodes with photodetectors for interruption detection in water streams to provide steady and accurate input signals.
    - Design a water-pump system capable of generating a uniform, laminar flow for the water strings whose flow rate will vary for dynamic interaction.
- Development of firmware and microcontroller interface:
    - Program microcontroller (MSP430 or ESP 32, not decided yet) to process the inputs from the different sensors and map the user interactions to the necessary MIDI or audio files.
    - Utilize precising timing components, interrupt-driven processing, and other efficient aspects offered by the microcontroller.
- Audio sequence development and implementation:
    - Implement a module of sound generation that is capable to produce customizable tones as desired.
    - Employ DSP techniques to control the audio output to manipulate pitch, amplitude, and waveform shaping depending on the specific audio device chosen (utilizing a speaker).
- Closed loop, recycling water system:
    - Design a water management system that recirculates the water through the machine efficiently, reducing waste and the need for added resources.
    - Use flow sensors/ water level sensors so the system knows whether a specific reservoir is low or filled with water.
- Rigorous testing of the prototype and final project:
    - Ensure all components are acting as intended with little to no errors or mishaps.
        - Ex: sensor accuracy, response time, signal mapping, audio quality, overall latency between different systems
- Hardware safety/ waterproofing:

- Waterproof will include, but not limited to, silicone casing for specific components to ensure separation of electrical systems from the water recirculation system.
- Housing all possible electrical components of the machine above the upper water reservoir to ensure the crucial electrical components do not interact with the flowing water.

From this breakdown of our goals and objects we now have a check list of checkpoints we want/ need to complete for a functioning interactive waterfall display. The expected outcome of this project is to provide our team with actual design experience while also being able to produce a product that is innovative and efficient with a friendly user interface.

2.3 Project Features and Functionalities

The Aqua Strings: Interactive Waterfall Display project brings together the best of modern technology with sensitive designs for an interactive and captivating experience. The machine serves as a water harp and can read user inputs in the form of movement, as the user's fingers or hand pass through the flowing strings of water, causing a note or sound to play out of a speaker embedded in the machine. There is also a dial that switches the modes of OFF, FOUNTAIN and HARP that the user can use at their discretion. Our team will be utilizing both previously existing elements, as well as our own physical design and technical features to create a project that is versatile and unique.

Our project houses a custom engineered water pump with the ability to generate laminar water flow for our harp strings. These strings will keep a uniform look and have a sense of stability so the precise 'pluck,' interruption, of the water string can be detected. The pump system will be designed such that there is a constant and continuous stream of water flowing as our water harp strings since any break in the water can be interpreted as an interruption. This water management system also operates with low power consumption to conserve its energy pull while also maintaining its reliable performance.

Aqua Strings relies on laser-based sensing for the detection of any interactions done by the user. It has laser sensors positioned downward shooting through the water stream to a photodetector, when the laser is detected then the string is unbroken and when it isn't detected then there is an interaction that needs to be noted. This noted occurrence will then translate the input into a musical, audio tone to be played through the speaker. This setup allows for an elevated level of accuracy and real-time sensing, since the robust calibration of these sensors will reduce the possibility of false triggers that could occur for numerous reasons, including the displacement of water done by the user's hand or changes of the lighting conditions in the room the device is in. This ensures there are little to no undesired outcomes, facilitating a flawless experience for the user.

The project also involves a sophisticated audio generation system that maps sensor inputs to digital notes that are saved on file. Users will be able to modify and adjust the different modes of the audio output, whether that entail different sounding notes or different octaves (not determined yet). In addition to this audio display, the laser sensors will also have a color being refracted through the beam, color dependent on the specific sensor we acquire and the wavelength of the laser, to add to the visual component of the project.

A closed loop, recirculating water management system is also embedded into the design of the machine allowing for sustainable operation by collecting and redistributing the water. Flow monitors, consisting of water level sensors, are used to track water levels in the upper and lower reservoirs ensuring consistent operation of the machine free of unnecessary interruptions. The system design is intuitive since it takes constant inputs which turns the water pump on or off in relation to water levels preventing overflows.

Safety and waterproofing of all systems are imperative as electricity and water aren’t a desired mix in our project, especially if users are touching the water strings. All electronic parts are either isolated or encased to prevent users from encountering hazards. It would be a good idea to include sensors to either measure current being passed through the water and/or other overload protection systems to avoid mechanical and/or electrical failures.

Aqua Strings delivers real-time functionality with virtually immediate responses to the inputs detected in the machine. These inputs include water streams breaking causing tones to play, the switching between modes that change the sound of the notes played, and the monitoring of the water levels within the reservoirs. Little to no latency is a major component for this project because without it the project would be inconsistent and not act as expected.

Our project takes our designs of efficiency and user-friendly experience into one product. It operates in a simplistic way for the user and is a bit more complex on the backend but allows for an innovative redesign of a traditional musical instrument. Through concepts of sustainability to progressing technology, our project delivers an in-depth experience unique to this interactive machine.

is a machine that will simply serve as a water harp. Our machine will be able to read user inputs in the form of movement, as the user’s fingers or hand pass through the flowing strings of water, causing a note or sound to play out of a speaker embedded in the machine. Our team will be utilizing both previously existing elements, as well as our own physical design and technical features to create a project that is versatile and unique.

2.4 Existing Products

Thread fountains are a type of water display that is available in today's market and are typically seen through modern and artistic sculptures. Being the focal points in many public spaces such as hotels, offices, or art galleries, the idea for a thread fountain is to have strings of water flow straight down in a linear cascade-like effect. There are a series of strings fixed from the top to the bottom of the fountain, which serve as a guide for each string of water to follow. The strands of thread in the fountains are one of the most important components of achieving the highly smooth illusion of the water flow. Thread fountains also vary in size, shape, and complexity. Some designs have up pre-programed patterns and effects to add another layer of visual entertainment to the viewer. Through the utilization of motors, magnets, and LED lights, thread fountains can achieve many types of visually artistic and entertaining effects and patterns.

An electric harp is a modern extension of the musical instrument, where instead of a musician having to physically pluck harp strings to generate a sound, the strings are replaced with sensor technology to detect finger movements along the empty space. Through various motion sensors along the harp frame, hand movement detected from a set sensor can be translated into a specific note played through a built-in sound system. Numerous adaptations of electric harps have been created and are in current use, primarily for art and entertainment purposes. Electric harps can range from having lasers serve as strings or having invisible string as a whole. Electric harps are not as widely seen or utilized in the professional music world, though they are seen to become more widespread for musicians who may have mobility limitations and are looking for a more accessible instrument to play.

Our team gathered inspiration through both thread fountains and the electric harps. We wanted to design a project that has an element of art and entertainment as well as incorporating music and sound. Motion sensor-based harps can be seen to exist, however adding the element of water adds a unique sensory experience that has rarely been done before. In addition, the thread fountains that are in use today rely on the placement of the string for the water to flow. Aqua strings will have free flowing water drop from the top to the bottom of the structure without the utilization of a thread. This way, the generation of the sound will be solely reliant on the motion sensors rather than the physical pulling of a string. Our project will also utilize elements of both a harp and fountain through having different modes to switch to. Having this versatility adds another layer of uniqueness and creativity to our project, which has not been seen with previously existing products.

2.5 Engineering Specifications Table

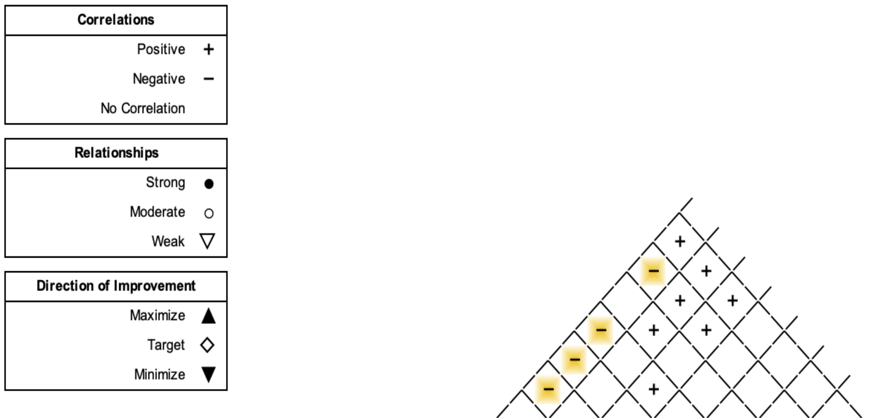
The Engineering Specifications Table shows the key parameters and performance features of the system devices. The detection time and response time of the photoresistor must be high for efficient detection of light. The MCU and speaker and photoresistor have to respond instantaneously to inputs from the system. For the level sensors and water pump, the system must be capable of providing a specified water level within a certain range for efficient water display control. The laser in the system must be low power and distinct wavelength for safety and functionality. The pump must be capable of providing a stable flow rate and sufficient lift height to attain the water display without overloading the system.

Besides, the reservoirs are built in a way that they have enough water volume to allow the operation of the system.

Table 2.5.1: Engineering Specifications Table

Component(s)	**Parameter**	**Specifications**
Photoresistor	Detection Time	< 10 ms
Photoresistor, MCU, Speaker	Response Time	< 100 ms
Water Pump, Level Sensors	Water Level Maintenance	< 2 in of water
Laser	Wavelength	650 nm (Red)
Laser	Power	< 5mW
Pump	Flow Rate	< 1 gallon / minute
Pump	Lift Height	< 1.5 m
Reservoirs (Upper/Lower)	Capacity	2 gallons each

2.6 House of Quality



Column #	1	2	3	4	5	6	7	
Direction of Improvement	▼	▼	▼	▼	◇	▲	▲	
Customer Requirements / Engineering Requirements	Cost	Weight	Detection Time	Response Time	Sustained Water Height	Sensor Accuracy	Safety	Row #
Cost	●	▽	●	●	▽	●	○	1
Portability	●	●	▽	▽	●	▽	○	2
Ease of Use	●	○	●	●	▽	●	●	3
Reliability	●	○	●	●	○	●	●	4
Safety	○	▽	▽	▽	○	▽	●	5
Sound Accuracy	●	▽	●	●	▽	●	▽	6
Low Maintenance	●	○	○	○	▽	○	●	7

Figure 2.6.1: House of Quality

2.7 Hardware Block Diagram

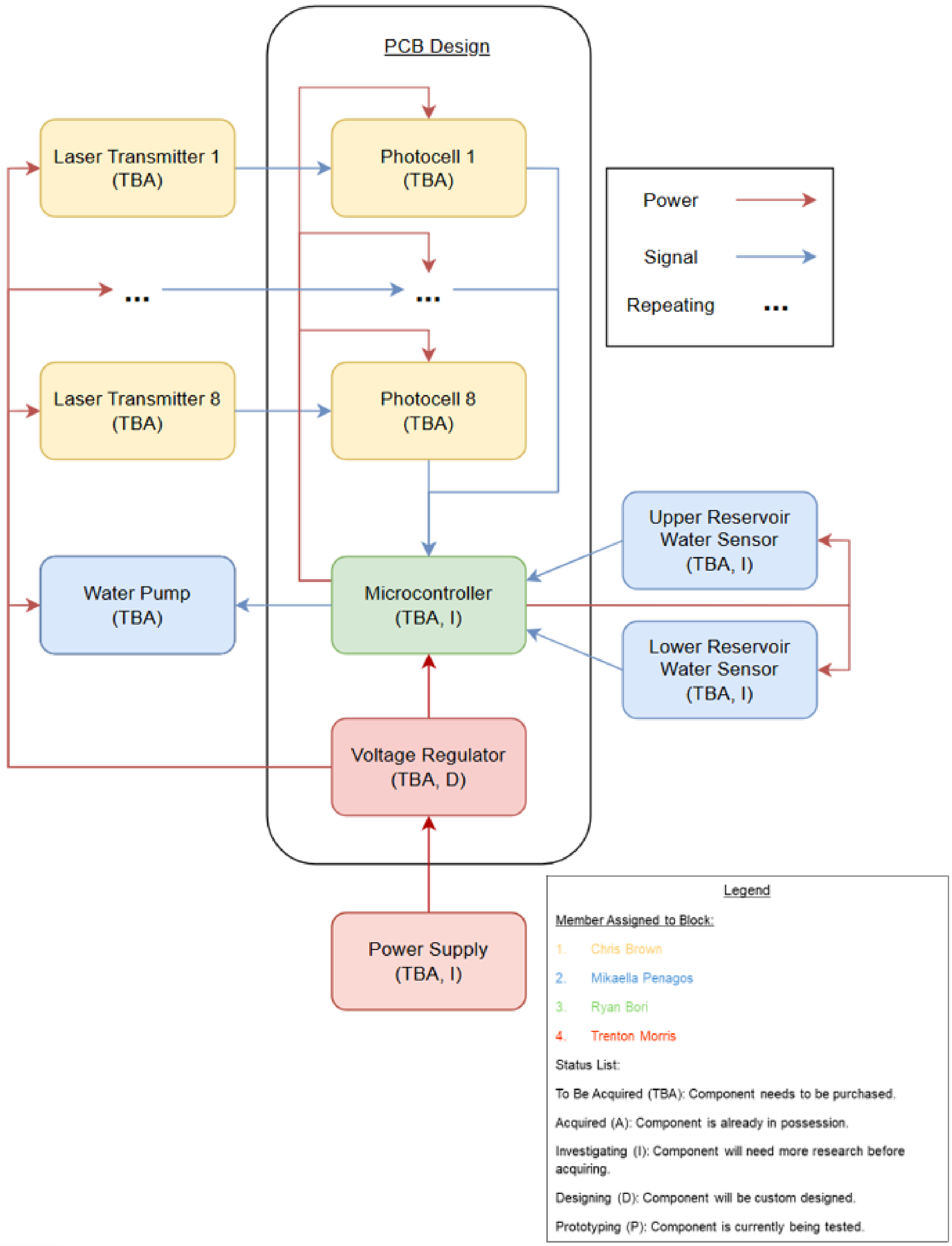


Figure 2.7.1: Hardware Diagram

Components’ Inputs and Outputs

- Power Supply:
  - Input: External power (adapter/outlet) or battery.
  - Output: Power to all components through regulator or microprocessor.
- Microprocessor:
  - Input: Signals from photocells, water level readings, and switch knob.
  - Output: Control signals for MIDI sounds, playback, and pump system.
- Speaker:
  - Input:
  - Output: Sound waves corresponding to
- Photocell(s):
  - Input: Infrared laser beam (unless interrupted by hand).
  - Output: Signal to the microprocessor indicating an interruption.
- Laser:
  - Input: Power from power supply unit/voltage regulator.
  - Output: Continuous infrared beam.
- Pump System:
  - Input: Power from power supply unit/voltage regulator.
  - Output: Water flows to the upper reservoir.
- Reservoirs (Upper and Lower)
  - Input: Water from the pump (upper reservoir) and falling water (lower reservoir).
  - Output: Water columns (upper reservoir) and collected water for recirculation via pump (lower reservoir).
- Water Level Sensors:
  - Input: Power from microcontroller and stimulus of water.
  - Output: Signal for when the water level reaches a certain threshold.

2.8 Software Block Diagram

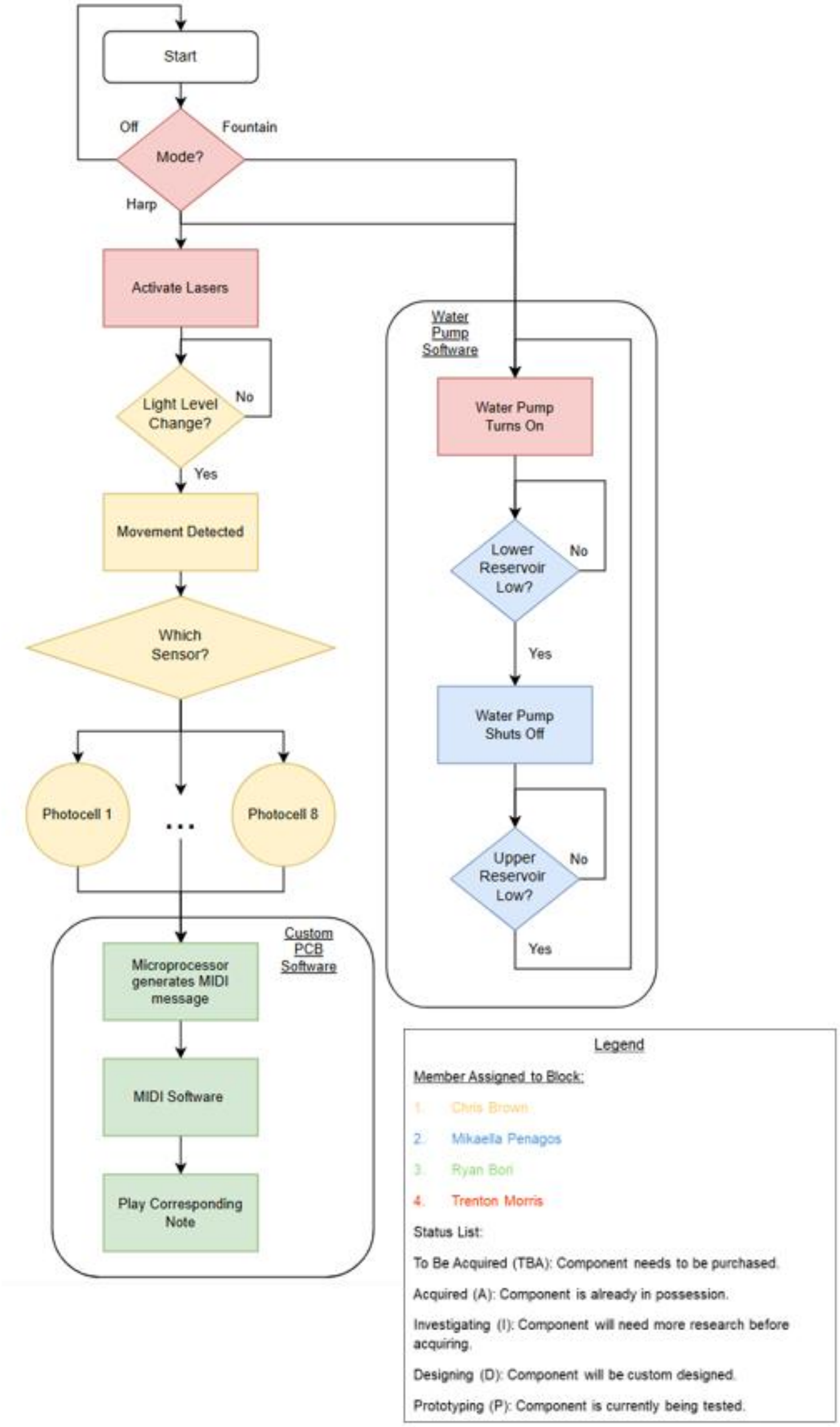


Figure 2.8.1: Software Block Diagram

2.9 Prototype Illustration

2.9.1 Previous Prototype Illustration

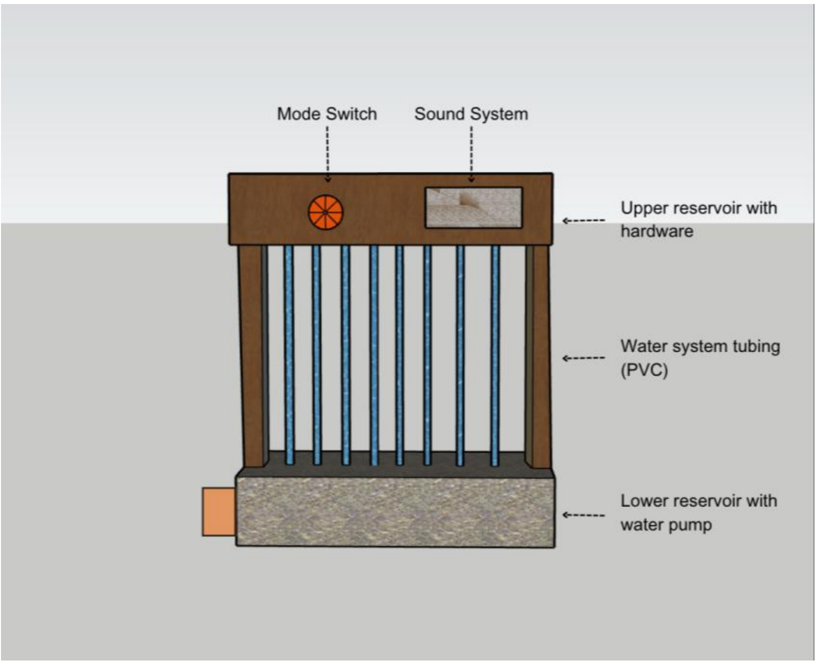


Figure 2.9.1.1: Prototype Illustration 1

The prototype illustration in the figure above displays our initial proposed design of project Aqua Strings, highlighting some of the key components of the construction and organizational structure. Firstly, the frame of the water harp can be seen to be made from a sealed wood finish or a waterproof material. The primary purpose of this framing material is to create durable and protective housing for the sensitive components of the project, including the water systems and electronic hardware. By ensuring a sealed and structured enclosure, the design focuses on preventing potential water damage and maintaining a safe environment for the electronic systems while preserving the aesthetic appeal of the instrument.

The frame is also designed to support the considerable weight of multiple water reservoirs, facilitate vertical water movement through the waterfall and pump system, and accommodate the battery, pipes, sensors, electronics, and sound system. The choice of materials and compartmentalization of the frame not only provides structural integrity but also contributes to the ease of maintenance and safety of the project and users.

The harp features an upper reservoir which houses the bulk of our mechanical elements. This section houses critical hardware, including the motion sensors responsible for detecting interactions with the water strings, a mode switch that offers user control over the instrument's settings, and the sound system that produces audio feedback in response to the water being 'played.' The interior of the upper reservoir is divided into two distinct compartments: the bottom section contains the mechanical tubing and water pipes, while the top section securely holds water-sensitive electronics and hardware. This compartmentalization will be crucial to preventing water from meeting delicate components, thereby enhancing the safety and longevity of the system.

The separation of wet and dry zones within the upper reservoir creates a smooth and safe water flow while also maintaining the visual and functional integrity of a traditional harp instrument. This design decision also allows for a smoother visual, helping the water harp maintain its resemblance to the real string instrument.

The lower reservoir primarily functions to collect the falling water and recycles it back to the upper reservoir using the water pump at the bottom left portion of the frame. The lower section of the frame is designed to be as large as the top section to achieve a balanced distribution of weight and stability. Given the significant weight of the water pump and the volume of water required for the Aqua String's operation, maintaining this balance is important for both safety and performance. The bottom compartment's size also accommodates potential water splashes from the waterfall and provides additional space to manage excess water.

Lastly, the water system uses PVC tubing to channel the water from the pump to the upper reservoir efficiently. The piping is enclosed along the left column of the frame, facilitating a consistent and controlled flow of water while preventing overflow in the lower reservoir. The estimated height of the harp is approximately two feet, in order to have a balance between stability and portability. This design choice makes the harp ideal for offering ease of transport while retaining its full functionality as an interactive musical instrument.

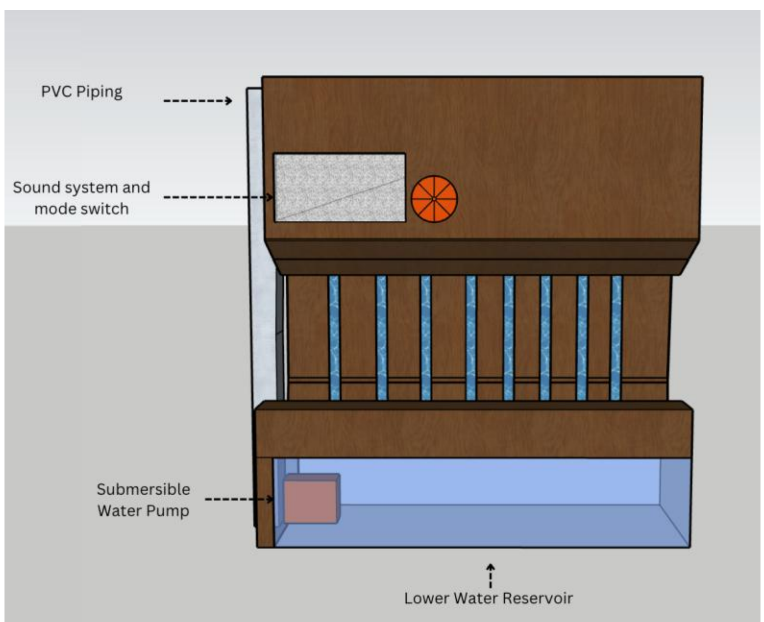


Figure 2.9.1.2: Prototype Illustration 2

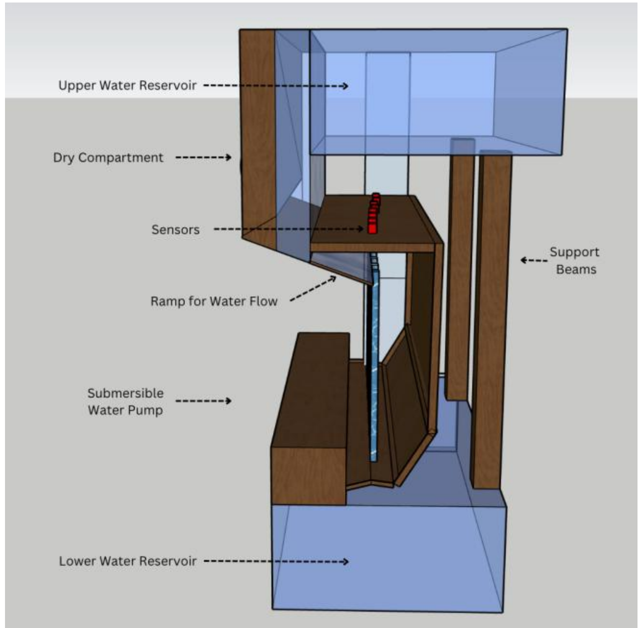


Figure 2.9.1.3: Prototype Illustration 2 Side View

The diagrams above highlight the second prototype of our project, with a slightly different approach. The most prominent change with this is water flow and a structured implementation of the lasers at the top of the structure. A dry compartment on the left side houses the electronic hardware, such as our microcontroller, speaker, mode switch, and all added wiring for the musical component of Aqua Strings. This try component is sealed and a separate space from the water, to ensure a fully safe and distant area for wet and dry spaces. Unlike the original idea of having the funnels of water directly stemming from the upper reservoir, this prototype includes a slight downward ramp at the top, directing water downward to then funnel into eight distinct water strings. Most importantly, this structure allows the lasers to be at the perfect angle to point down directly through each water stream. The ramp implementation is also put in place to assist in achieving laminar flow, which is just as critical for having the lasers work accurately. All together, these controlled streams allow for a structured and playable interface, where interaction occurs when a user disrupts the water flow.

As the sensor detects an interruption in the laser, this action triggers a corresponding note to be played for each string, with the end goal of achieving a scale with each note. On the back end of our structure, there are support beams to provide stability to the structure. As there is a large area of water at the top along with a ramp on the front end of the project, having added support beams on the back is important in maintaining the proper alignment of the water flow and sensors, as well as structural integrity of the frame. The closed-loop water circulation system is achieved through the PVC pipes, where the submersible water pump will transport the water from the lower reservoir to the top reservoir. Overall, these few additions and specifications from the original prototype are beneficial in achieving our fully functioning project.

2.9.2 Final Prototype Illustration

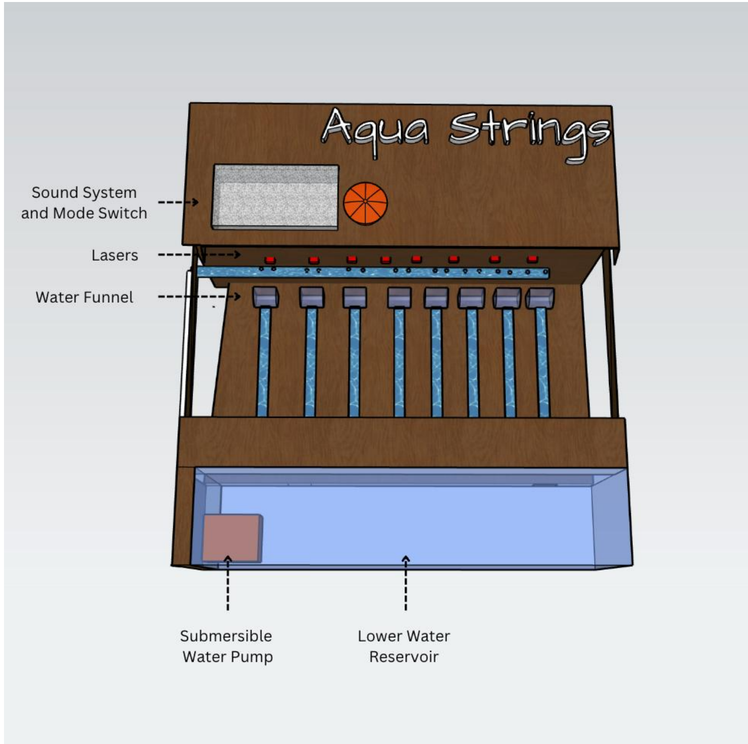


Figure 2.9.2.1: Prototype Illustration 3 Front View

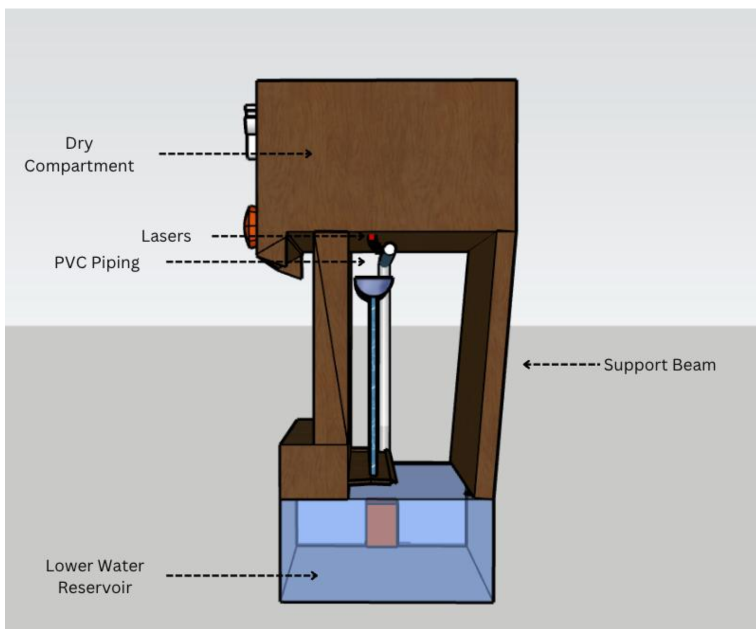


Figure 2.9.2.2: Prototype Illustration 3 Side View

In our groups third and final prototype, there are numerous changes that have been made to the structure of our project. This model also incorporates a design involving sensors to detect hand movement, however a few areas were reorganized to make the fountain more optimal. Firstly, this prototype compares with the other two ideas, as each system has a lower reservoir with a submersible pump that continuously recirculates the water, and this serves the purpose of constantly providing water flow through the structure. Additionally, this structure incorporates an upper section that distributes the water into individual waterfalls, and this follows the same idea from the past two designs.

However, the water distribution of this third design differs. In the first prototype illustration, water is pumped directly into an upper reservoir, from which it falls freely into the eight water strings. This method relies on gravity for even distribution and a natural cascading effect. On the other hand, the finalized model does not have an upper water reservoir. Instead, it utilizes a PVC pipe with pre-drilled holes that direct water into a cylindrical funnel before it flows down the strings. This alternative method provides a more controlled distribution of water compared to the free-fall design we had originally planned.

Another key difference is the location and space of the hardware integration. The first two illustrations keep all the electronic components within a dry compartment by the upper reservoir, while the final design integrates a mode switch and sound system within the entire top wooden structure. There is no upper reservoir, so this allows for much more space and flexibility with the hardware in the project. The use of a cylindrical funnel as seen in the figures is put in place to manage the water by ensuring even flow and creating a laminar water stream to its highest extent. Consequently, the lasers located on the top of the funnel will be able to detect hand movement accurately.

Chapter 3: Research and Investigation

Aqua Strings is a project that will incorporate numerous connected systems that will leverage a variety of different technologies and physical properties. These systems, while independently serving their own function, need to work seamlessly in tandem. As such, an extensive level of research is required to properly solve the number of complexities regarding the project's design. If these systems were isolated or if the project were downsized, this might not require as much preparation. However, Aqua Strings reflects several different layers of systems coming together. What this means is combining sensing technology, electronics, and audio, all potentially submerged in water, requires a delicate level of planning. Questions such as "how to protect the electronics from water damage", "how to control the flow of water" and "what methods of sensing are most optimal" are essential to ask in this section. The following research will cover considerations carried in regards to the selection of relevant technologies and components deemed appropriate for use in Aqua Strings.

3.1 Technology Comparison and Selection

3.1.1 Laser Harp Design

Fundamentally, Aqua Strings' core design is that of a laser harp with the additional element of flowing water. While this element adds significant complexity to the electrical design, the priority of design is how to construct the harp first and add water later. There are several ways to design a multiple stringed laser harp. The first we had considered was using a single high wattage laser that was refracted into multiple beams. The beam would be aimed at a small mirror sheet attached to a galvanometer. This galvanometer would be vibrating the sheet at high speeds of approximately 20,000 positions per second. As the beam shoots out the laser, it continuously hits the mirror at precise angles every few milliseconds. This refracts the single beam in multiple directions so quickly that it appears continuous. This design would allow us to allocate more of our budget towards a single, higher wattage laser instead of multiple cheaper lasers. However, a significant drawback is that all the beams shoot from the same point (where the mirror is held by galvanometer). This method would be impossible to implement with the water element as the beams would be angled but the water columns would need to be vertical. Thus, we considered another design where a laser would be positioned above each column of water. Using this design, the laser beam would be parallel with the flow of water and imposed inside of it. The downside of this implication would be an increased budget, as every musical note, or "string," would need its own laser, photocell, and any additional components to moderate the water column.

3.1.2 Waterproofing Options

Once we had a general idea of the electrical system without considering the water element, we then needed to brainstorm how to protect the electronics while still delivering on the Aqua portion of the project. We knew we needed to introduce several water-sensitive peripherals inside of water reservoirs. For these inputs and sensors to function, they needed to properly isolated from their environment. However, if this protection inhibited their ability to function (i.e., interrupted the laser beam before it could reach its corresponding photocell) then that level of protection cannot be used.

3.1.2.1 Mineral Oil

At first, we considered that the laser and the photocell would be isolated in corresponding enclosures that would be submerged in the upper and lower reservoirs, respectively. This would mean that the enclosure would need to be transparent enough for the laser beam to pass through twice (once at the top after the laser and once at the bottom before the photocell). It would also need to be removable to access each component and perform maintenance if necessary.

However, this method assumes we use water as our liquid for interaction. Water is a natural default, but its properties conflict with the electronic system. We turned our attention to alternatives for the liquid element. One we had considered was mineral oil. Unlike water, mineral oil is non-conductive and will not cause short-circuits if these components are submerged. This would also allow these optical components to avoid being distorted or refracted by containers. Initially, this idea seemed strong. Some PCs even use food-grade mineral oil for use in cooling as an alternative to water-cooling. While mineral oil would be great in an application such as thermal cooling, its optical clarity presents a significant con. The oil possesses a different refractive index than water, altering the laser differently than water would. This will require recalibration if we switch liquids throughout the project. Additionally, mineral oil tends to grow cloudy over time due to contamination. Unless we sealed each reservoir, which would be difficult during the prototype and testing phases, this cloudiness dust, debris, or bacteria would occur. And if we sealed the reservoir, it would be difficult to clear any bubbles that may form in the oil. Trapped air does not dissolve easily in the material and may negatively impact the optics. This does not consider how the pumps required to move the liquid would interact with this alternative. The pumps we have considered so far are rated for water. Mineral oil is much more viscous than water and may interfere with the functionality of the pumps. On top of this, mineral oil is significantly more expensive than water. Procuring gallons of electronic-safe mineral oil would be magnitudes more costly than something as cheap and accessible as water. Finally, the user would need to interact with oil columns to strum the harp. This would mean that oil would coat the user’s hands and skin. The oily residue would leave users uncomfortable and make it harder to clean the instrument. Due to these many logistical downsides, water will be considered as liquid of choice.

This returns us to waterproofing the electronics. For something versatile, we considered using waterproof spray. Acrylic or silicone-based sprays work for most conformal coating applications. They are recommended to protect against harmful environmental conditions like moisture, static, and vibration, but aren't ideal for full submersion, as the lasers and photocells will be. A rubberized spray would be better suited for long term submersion. However, water will also be moving throughout the system, and continuous use may wear down the layers of sealant. While not a bad consideration, spray should be regarded as an additional means of protection and not the baseline.

If we are looking for full water-sealed protection, we then need to consider enclosing the electronics in waterproof housing. The two main options are:

1. enclosing electronics within watertight acrylic or other transparent boxes for short-term seal between maintenances.
2. potting individual components for permanent seal.

3.1.2.2 Waterproof Enclosure

Our first option would be to use a clear material-based box to enclose the electronics. Acrylic boxes would offer the most versatility while still providing a waterproof environment for the electronics to operate within. One of the biggest constraints is that the optical elements of the project would still need to operate despite being enclosed. Acrylic is a suitable candidate for this. Its transparent properties are ideal for an enclosure and the material could be cut to size. This is especially important as each enclosure might need to be custom made for each electronic. For economic purposes, only one side of the enclosure needs to be acrylic. The rest of the box could be 3D-printed and adhered to the acrylic panel. To run a cable through, we could cut a hole in the side of the box or design the 3D print with an opening. To seal any wiring or penetration points, a cable gland with a rubber compression seal can be used to create a watertight seal around any external cables. Finally, we can seal any additional seams (i.e., between the PLA and acrylic) with silicone or rubber sealant. Alternatively, for a more permanent bond, we could use epoxy to close these gaps. Realistically, the former will be used in the event that the enclosure must be opened. Thus, this first approach will be considered for components that might need maintenance, such as the laser.

3.1.2.3 Potting

Our second option would be potting the electronics. This might work particularly well for the photocell sensor, as it would not need much physical maintenance. One primary concern is how the compound will affect the optical transparency of the enclosure. There is a chance the sealant might alter the way the sensor can read the laser beam within its protection. The epoxy or potting compound must be clear and non-scattering to allow the laser to pass through. Bubbles or other imperfections may reduce the accuracy of the sensor. To help with this, the thickness of its encapsulation should be considered. Ideally, it must be thick enough to provide protection but still thin to best minimize light loss. Another main concern is that sealing the electronics by potting them would make maintenance impossible. We will need to evaluate and ensure that each element works perfectly before potting. This will be complicated when considering how water will affect the optical system. This approach may be used later in the design process once prototyping has been completed. Once we know for sure how elements will affect the system, then we can permanently seal the electronics using something like potting.

A potential third option could be to combine the two. Instead of fully potting the photocell, we could pot everything except the sensor area and place a clear acrylic panel over the sensor. This would maintain optical clarity while still ensuring the electronics stay waterproof. While this approach would not be as ideal for parts that might need maintenance or be difficult to replace, such as the laser, it could work better for components like the sensors. If a complication with the component arose, it would be easier to replace it instead of attempting to reopen the potted electronic. Replacing lasers wouldn't make much economic sense, but lower cost electronics like photocells would. This approach will be considered for such items.

3.1.2.4 Moisture Protection (Conformal Coating/Silica Gel Packets)

When we consider a means to enclose the electronics, we need to consider the possibility of trapped moisture. While this might not be an issue for potted electronics, those that will be protected using the first method may be subject to condensation. This may happen due to several reasons. For instance, if the electronics were sealed in an already humid environment, they would be sealed in air that's already moist. Compounding this, temperature changes within the system may support condensation. The microcontroller or laser may generate heat when running, and when they cool down, moisture can form. This issue may worsen if there are small enough leaks for air to move through. Shifts in temperature and pressure will draw in air and moisture along with it. To protect against unwanted moisture within the enclosure, we could use silica gel packets. Silica gel absorbs moisture from the air inside the enclosure, reducing the odds that condensation will form. These packets will be placed inside the enclosure before sealing it. To guarantee they will not interfere with the electronics, we plan their placement not to be in direct contact. These will also only be placed in electronic enclosures that can be reopened and maintained. Their function would drastically decrease if they became saturated with water, thus they won't be initially considered for use in permanent sealed electronics. If we can guarantee a permanent seal where airflow is not possible (i.e. in a prototype), then silica gel packets within potting compounds will be reconsidered.

Revisiting a previous idea, an additional layer of protection would be conformal coating. While we had considered this unsuitable as a baseline level of protection, a spray would work best once the electronic has been placed inside its enclosure. A thin, waterproof coating applied to circuit boards or other electronics would protect against condensation and moisture. This extra process would be done before sealing the electronics and again at specific maintenance instances. This will add even more redundancy against moisture in case of leaks or failure of the silica gel.

3.1.6.4.1 Waterproof Technology Comparison Table

Feature	Mineral Oil	Waterproof Enclosure	Potting Electronics	Moisture Protection
Functionality	Submerge electronics in a non-conductive liquid to circumvent water damage	Seal electronics inside of an enclosure that allows them to function while submerged	Fully encapsulate electronics in resin for permanent waterproofing	Additional measure utilizing silica gel or coating to prevent moisture inside options 2 and 3
Advantages	No need for airtight sealing	Reusable and maintenance accessible, potentially compatible with laser	Offers most extreme waterproofing and durability	Good for additional layer of protection and synergizes with enclosure and potting
Disadvantages	Messy, difficult to clean, not suitable for user interaction	Requires proper sealing and cable gaskets	Inaccessible to maintenance, may block laser	Not enough on its own, needs to paired

3.1.3 Applicable Sensor Options for Water String Detection

To have a fully functioning prototype and final project we need affordable, reliable, and precise sensors that work properly when used in conjunction with water. These sensors need to be able to travel roughly 1 to 2 feet between the transmitter to receiver with minimal refraction in the water string.

3.1.3.1 Capacitive Sensors

Capacitive sensors work by detecting changes in the dielectric properties of a given environment. This system consists of two plates that form a capacitor and when a conductive material, such as the water strings, enters the field the capacitance between the plates will change, causing the sensor to detect when a break in the water occurs. One advantage of this type of sensor is that it is highly sensitive and is capable of sensing both solid and liquid conductive materials making. Another advantage is how these sensors are able to detect changes in the water through a material making it a good choice when trying to waterproof the electrical components of the project.

However, even though there are some advantages the disadvantages make it not a good fit. For example, since a water component is involved and this project is taking place in a state where humidity is typically high, this could lead to false triggers of the capacitive sensor due to high humidity or temperatures. Another disadvantage is the sensors' limited range, especially when detecting liquids, making it difficult to accurately detect when a string of water is broken.

Capacitive sensors offer a variety of benefits including high sensitivity options to detect liquids along with their non-contact detection approach but due to environmental factors this type of sensor would not be suitable for our project’s needs.

3.1.3.2 Ultrasonic Sensors

Ultrasonic sensors work by detecting and measuring the distance from the sensor itself to an object, the object being the string of water. These sensors could be mounted in the lower part of the system to detect any changes of where the water lands at the bottom of each water string. These sensors would send high frequency sound waves and wait for these waves to bounce back (called an echo). When there is a displacement of where the water is landing there would be a change in the normal pattern of echoes, causing the sensor to detect when a water string is broken. One advantage of this type of sensor is its non-contact form of detection since it doesn’t need to be submerged in the water.

The disadvantages of these sensors include their high sensitivity to environmental factors such as temperature and humidity, causing inaccuracies when detecting water breaks. These sensors also aren’t quite precise as other sensor options meaning they wouldn’t be able to detect small changes, such as if a water string is broken for a very short amount of time. A third disadvantage is how it would handle the water movement of the lower reservoir. Since we would have up to 8 water strings flowing into the same reservoir this will cause movement within the water as it falls, possibly triggering a false detection.

Even though ultrasonic sensors pose a creative and innovative solution, there are numerous issues that would arise if these sensors were implemented to detect the breaks in the water strings.

3.1.3.3 Piezoelectric Sensors

Piezoelectric sensors work by generating an electrical charge due to mechanical stress. In relation to applications such as this Aqua Strings project, the sensor would detect unusual disturbances such as vibrations that could be caused due to a break in a string. Without a break, the flow of each water string would be at a constant rate, so where there is a break there would be a change in the tension of the string causing the sensor to trigger. This would convert mechanical energy into electrical energy through the sensor. These sensors non-contact type of sensor would be an advantage since it would help with waterproofing the system. These types of sensors are also very compact and low power since they convert mechanical energy into electrical current.

Even with these advantages, the disadvantages make it a poor choice for our project’s needs. One disadvantage is the output signal complexity which typically requires amplification and/or filtering of the voltage signal, which would overcomplicate the system as a whole. Another disadvantage is how sensitive it is to small vibrations which could cause false triggers such as if string 1 breaks but string 2's sensor detects the movement and throws a false trigger. A third disadvantage or challenge would be determining where to mount the sensor so that only the intent string would affect each sensor, which would be an intensive task.

Due to these three main issues that concern the reliability and accuracy of this type of sensor, it would not be a wise choice to implement them in our project.

3.1.3.4 Inferred (IR) Beam Sensors & IR Receiver

Inferred sensors work by using both a transmitter and receiver to detect any break between the two points. Depending on the type of transmitter used the inferred beam could either be a continuous beam or a pulsating beam but regardless the beam would need to be calibrated and aimed directly at the receiver opposite the transmitter. This beam would have to be pointed downward to go through the water string into the waterproof receiver since the water string would be falling on top of the component. One advantage is that multiple manufacturers have epoxy or silicone encased parts already so that solves the water proofing concern. Also, these sensors have a fast response time which is a main requirement for our project since it is supposed to trigger a note to play when a string is broken.

One disadvantage to using IR sensors would be having to embed the receiver component in the water but since waterproof encased components are already manufactured that solves that concern. Another disadvantage would have to be the difficulty with aligning the laser beam to hit the receiver. Since infrared beams are typically greater than 900nm in wavelength that makes the beam inviable to the naked human eye so it will be hard to make sure the beam is hitting the receiver properly.

Infrared beam sensors wouldn't be a bad choice since they have a vast number of advantages along with disadvantages that could be mitigated but the next choice is able to meet all the necessary requirements.

3.1.3.5 Laser Sensors & Photodiode (Selected Option)

Laser sensors work similarly to infrared beam sensors since they both require a receiver component to detect a change in the system. With these laser sensors high focused beams of visible light are used to detect an interruption, this means the wavelength of these beams must fall between 380nm to 700nm (the visible light spectrum). When applied to this project, these laser beams will be mounted above each water string for the light beam to be sent through the water where it would meet the photodiode (receiver) on the opposing end. An advantage to using laser beams over IR beams is how the human eye can see the direction of the beam which aids in aligning the transmitter and the receiver. Another advantage is its instantons response time, reducing latency and meeting the previously outlined project objectives and requirements. A third advantage is its extended maximum distance between transmitter and receiver of 6 feet compared to the 1.5 feet for IR sensors. These sensors are also manufactured to be epoxy or silicone encased essentially waterproofing the component.

One disadvantage to these sensors is their need to precise alignments but since their laser beams have wavelengths that fall between those on the visible light spectrum, the alignment process won't be as difficult. Another disadvantage is how the water element typically absorbs the light beam, reducing the distance the laser beam can accurately travel. The absorption is least occurring when wavelengths fall between roughly 400nm to 530nm, which are the colors green and blue.

According to the research done on the different applicable sensors, the transmitter beam and photodiode combination has proven to be more efficient and effective. However, the LED laser sensor is the better option compared to the IR sensor due to its larger range, visible beam (for needs involving alignment) and its ability to be waterproof.

Table 3.1.3.5.1: Sensor Comparison

Specification	**Capacitive Sensor**	**Ultra-sonic Sensor**	**Piezo-electric Sensor**	**IR Beam Sensor**	**Laser Beam Sensor**
Detection Method	Changes in conductivity (capacitance)	Echo detection, pattern recognition	Mechanical stress conversion, pattern recognition	Transmitter-receiver beam interruption	
Possible False Triggers	High (humidity & temp interference)		High (vibration inter-ference)	Moderate (water absorption)	
Alignment Difficulty	Low (mounting two metal plates)	High (multiple sensors pointing at strings next to one another)	High (mounting issues, water strings are too close together)	High (beam is not visible to human eye)	Moderate (beam is visible)

Effective Range	Limited (effective within centimeters)	Mid-range (~1 to 2 feet)	Less than a few centimeters	~1.5 feet MAX	~6 feet MAX
Cost & Availability	\$5 - \$20	\$10 - \$20	\$2 - \$25	\$3 - \$25	\$3 - \$25

3.1.4 Laminar Flow of Water Strings Options

For the Aqua Strings project to work as designed, each usable water string needs to have a laminar flow. A laminar flow is defined as a flow of liquid that follows a linear and parallel pattern which ensures a smooth flow. The need for this type of water flow is because the laser beam requires minimum refraction within the string so that the beam can reach the photodiode (receiver) on the opposing end without alignment issues. To ensure laminar flow can be reached at a consistent flow rate there are multiple techniques or devices that could be used.

3.1.4.1 Perforated Material

Perforated plastic sheets are a fast and effective means of achieving laminar flow by diffusion of the incoming flow and relief of turbulence. Perforated sheets usually have an array of small, evenly spaced holes or slits that allow air or liquid flow at a predetermined rate. The fundamental principle with the application of perforated sheets is that they diffuse or filter, distributing the flow and allowing it to stabilize before it moves into a more sensitive system. The size and pattern of the perforations will have a bearing on laminarization efficiency.

The perforations reduce the velocity of flow at various points in the sheet. If fluid is supplied through the holes, the velocity distribution is made more uniform, promoting smoother downstream flow. The flow becomes less turbulent, a state necessary for laminar flow. In gas or air usage, the sheets are used to prevent high-velocity air from striking or mingling in such a way that it would result in random flow. Perforated sheets have the same role in liquid systems by reducing areas of high-speed that would produce turbulent flow.

Perforated plastic sheets possess various advantages that can be utilized across various applications. They are cost-effective and therefore do not put pressure on the budget for a system that demands a simple method of flow control. They are easy to use and implement since they can easily be cut or molded to suit the specific application needs of the system without requiring major modifications. Apart from this, they are also not fixed; the size and the shape of the holes can be customized to better suit the needs of the airflow or fluid system. However, there are limitations in perforated sheets. They cannot provide the perfect laminar flow in high-velocity systems since their diffusion and reduction of turbulence capability is limited to a certain extent. With time, they also become clogged, when there are particles in the fluid, and thus become useless. The success of perforated sheets largely depends on the precise alignment of the holes; error or improper spacing of the perforations could result in poor laminarization and therefore needs precise pattern design.

3.1.4.2 Honeycomb Flow Straighteners

Honeycomb flow straightening devices are a series of hexagonal open flow channels that are uniformly spaced for flow conditioning, very similar to perforated materials. This setup forces the fluid through small uniform channels along a set-controlled pathway that reduces the random motion caused by turbulence and promotes motion in smooth, parallel lines. The structure does resemble a honeycomb, in which each cell is a channel for fluid passage. They find widespread applications such as scientific experiments, aerospace engineering, and HVAC systems, where flow has to be controlled and measured accurately.

The honeycomb design works by inducing multiple parallel, small-flow pathways so that the flow is biased toward uniform direction. Bigger-sized and lesser-numbered honeycomb cells can enhance performance; smaller cells will, however, cause high flow resistance; more channeling results in better interference. The fluid enters with random turbulence and gradually loses this through multiple cells, resulting in a significant reduction in turbulence with the increase in distance traveled within the honeycomb material due to flow streamlining. The cells in the honeycomb structure act as a series of simple flow conditioners, each slightly redirecting the flow until the entire fluid stream is aligned into parallel paths. This straightening effect assumes great relevance for applications wherein the fluid must enter sensitive systems or components with minimum disturbance since turbulence could cause measurement errors or operational inefficiency-even damage in precision environments.

Honeycomb flow straighteners are the most efficient means of generating laminar flow. The designs streamline the flow into paths almost parallel to each other, hence directing the fluid uniformly and minimizing turbulence. They are resistant and strong structures for use in high-pressure environments; therefore, honeycomb straighteners are widely used in various industrial applications. Moreover, they have the additional strength of being customized to specific flow conditions by cell sizes, material, and density, enhancing their versatility. These provide good flow uniformity, beneficial for delicate operations, for instance, scientific experimentation or precision fluid systems. Their downfalls entail larger sizes, and therefore space-consuming, unsuitable for compact systems. Their manufactured costs, concerning simpler alternatives, are relatively high. They are efficient, but an optimized design for a honeycomb structure suitable for a specific application requires meticulous engineering to promise the best performance.

3.1.4.3 Funnels and Nozzles

Some of the basic devices that are used to control and direct the flow of fluids in either states that are liquid or gaseous type include funnels and nozzles. A funnel is as such designed to direct fluid from a wide opening to a narrow outlet so that spillages or mess is minimum, such as in laboratories or industrial sites. Unlike a nozzle, a funnel is not designed to direct the shape and direction of fluid then leaving the system. Though both devices shape and direct fluid flow, a nozzle typically gives much more precise shaping of the three flow parameters - pressure, velocity, and the pattern of the fluid stream. Together, these two are basically required wherever efficient management of fluid dynamics is needed. Through the control over speed and direction of flow, they prevent problems, like uncontrolled separation of flow or turbulence, having the potential to arise without any restriction on fluid behavior.

Funnels and nozzles control the flow of fluids by controlling the cross-section of the area through which they pass. The velocity and pressure of flow are regulated in the same manner. A funnel is a hollowed-out cylindrical item, which when placed in an upright position has a funnel-shaped mouth opening at the top and a smaller outlet at the bottom. The flow of the fluid accelerates as the fluid enters a funnel. The broad opening is then progressively narrowed down to a smaller opening. A narrow stream is produced, which can then be controlled to direct the flow of the liquid or disperse it, as required. It is designed in such a way that the liquid is practically undisturbed, meaning that it tapers gradually rather than having acute bends and sudden velocity changing conditions that could give rise to turbulence. Nozzles do similar things, although they are generally more than just a faster fluid flow in restriction; they are also designed to shape the manner of the discharge through different forms like a finely nebulized jet, a straight jet stream, or a diffused spray. Here fluid will be accelerated on the moving fluid in a converging nozzle, where it moves through the way of narrowed pipes and pressure will be acted upon resulting in kinetic energy. Therefore, this gradual acceleration maintains orderliness in the liquid flow throughout without inducing chaotic movement hence suitable for laminar flow. When nozzles and funnels are paired with diffusers later on to reduce the flow speed, they become effective individuals to minimize turbulence and instigate more even flow patterns with controlled fluid movement. Ideal as they are fast and dependent on each other, appropriate conditions must be ensured so that no hazard occurs when velocity alters because variations will cause flow separations and with that, additional turbulence will occur finally, nullifying benefits of laminar flows.

Funnels and nozzles are rather simplistic yet practical devices when it comes to controlling and directing fluid movement. The implementation is relatively straightforward and finds multiple applications in industrial fluid handling systems. The simplicity of construction and low cost make them a viable option for tasks that do not require sophisticated flow conditioning. Funnels and nozzles are equally applicable to treat the flow of either air or liquid, and the design can be suitably modified to achieve the desired flow rate. Even with these positives such systems come with disadvantages. An abrupt transition from a large to narrow configuration may induce flow separation resulting in turbulence, so a slow gradual shape change is needed. Similarly, if laminar flow has higher velocities, funnels and nozzles may not play an efficient role: they generally serve purposes inclusive of flow control, not turbulence elimination. The functionality of such an aid depends on the flow rate; at higher speeds, turbulence will develop, even with the use of such.

Table 3.1.4.3.1 Laminar Flow Specification Comparison

Specification	**Perforated Material**	**Honeycomb Flow Straighteners**	**Funnels and Nozzles**
Efficiency in Achieving Laminar Flow	Moderate (Reduces turbulence for low-velocity flow over high-velocity flow)	High (Structures are more uniform with parallel pathways)	Moderate (Best for directing flow but doesn’t ensure laminar flow)
Design Complexity	Simple (can easily be constructed with a drill and spare plastic)	High (requires a uniform pattern, possible 3D print)	Simple (can obtain from store)
Cost	~$1 - $5	~$5 - $10	~$5 - $10

After researching different techniques, the three mentioned approaches stand out the most. To achieve as close to a laminar flow as an affordable price point a combination of all three mentioned methods should be used. See section 6.1 for figure(s) that demonstrate possible configurations. For this reason, the table shows all three methods being highlighted and selected.

3.1.5 Applicable Sensors for Water Level Detection

For the project to run smoothly with playable water strings, the water in both the upper and lower reservoir needs to be monitored and maintained. This can be done by having a water level sensor in the upper reservoir that tracks the level of the water in the tank and adjusts the state of the water pump whether it is on or off. This would be an essential part of the functionality of the project because without it the upper reservoir could run out of water, which would ruin the flow of water falling leaving the user without water to run their hands through. On the other hand, the lower reservoir could also run low on water if the speed of the water pump exceeds the rate at which the water falls from the upper to lower reservoir. To avoid any lower water issues, a water level sensing would need to be implemented to ensure proper functionality of the project.

3.1.5.1 Pressure Sensors

Pressure sensors work by being fully submerged in water and measure the hydrostatic pressure exerted by the water mass above the sensor in a tank. The pressure throughout the tank is directly proportional to the height/ depth of the tank as it can be represented by the following pressure equation:

$$P = \rho g h$$

"P" represents the pressure as seen by the sensor, "ρ" represents the density of water which would be about 1000 kg/m^3, "g" represents the acceleration due to gravity (9.81 m/s^2), and lastly "h" represents the height of the tank/ reservoir in meters. By understanding this height could be calculated based on the other variables with an acceptable threshold for the height being set and if the water level falls outside of said threshold the water pump will act accordingly.

Some advantages with this type of sensor include but are not limited to, are its designed capability to be submerged in water meaning there are no other necessary waterproofing measures need for this sensor along with ability to accurately work regardless of environment changes such as humidity or presence of mist/ vapor. By utilizing a sensor that is specifically made for the environment it would be measuring in reduces the occurrence of inaccurate data being measured and/or calculated.

Even with a list of advantages, there still are some significant disadvantages to this type of sensor. The main downside to pressure sensors is the high cost for these sensors compared to other traditional methods or sensors. When the same outcome could be reached with a different component then the project will tend to veer in that direction. Another disadvantage is how these sensors typically are made for deep, large tanks and in this project, we wouldn't be utilizing reservoirs anywhere near the size at which these sensors are rated for. This would be an insufficient use of funds based on the project needs.

3.1.5.2 Optical Sensors (Infrared)

Optical sensors provide accurate and contactless measurement of water levels based on infrared or laser-based reflection principles (see section 3.1.3.4 for additional information). The mounting configuration is relative to the environment and application, with three primary methods: sidewall, top-mounted, and submersible installations. The sidewall mounting consists of mounting the sensor at a stationary location within or outside the tank and detecting water by the sensor at a predetermined level. This is the simplest form of level sensing and is commonly utilized for on/off type control applications, e.g., the pump start-up once the water reaches a critical level. Fitted externally, there may be a requirement for a transparent window for the sensor to be able to read effectively. This can be applied to high- or low-level water sensing but does not provide continuous level measurement.

To measure level continuously, a top-mounted optical sensor would be the typical selection. They are positioned at the top of the tank, sloping downwards, and measure readings for the water level based on infrared or laser beam reflection. It is appropriate for large or enclosed tanks where water contact is to be avoided. The alignment and detection path should, however, be clear to provide reliable readings since surface disturbance or obstructions can bend the readings. Alternatively, submersible optical sensors are mounted inside the tank at different levels to facilitate multi-level measurement. These sensors are particularly handy for small tanks where there is a need for continuous level measurement at multiple points.

There are numerous advantages to optical sensors in the field of non-contact water level detection. In contrast to pressure or float sensors, they do not contact the water, which prevents mechanical wear and grime. They are often touted for their accuracy, whereby even slight movements in water levels can be recorded, which may make all the difference in applications that need accurate measurement. In contrast, these sensors are highly suited to sealed and pressurized tanks, where traditional levels of measurement may not work well. Optical sensors are also fast instruments and, hence, used in most real-time monitoring and automation control systems.

At the same time, some shortcomings are associated with optical sensors. For example, turbidity, foam, or strong ambient light can create conditions under which optical sensors may fail to operate effectively. In dirty or contaminated water environments, sensor surfaces may become dirty from easily adhered particulates causing the eventual misreading of the actual parameter. Proper alignment and installation are a must, especially for sensors mounted above since they can undergo reflection distortion when the shapes of tanks are not regular. Furthermore, optical sensors are much more expensive than float switches-probes, for instance, which is another drawback. Optical sensors will require maintenance periodically and calibration based on the operating environment to ensure that they perform as good as new.

3.1.5.3 Float Switch Sensors

The float switch sensors are among the most affordable and reliable options for water level detection, which is why they find the most common application in both residential and industrial functions. The basic operation involves simple mechanical design: the buoyant float travels linked to the height level in the tank and, when it reaches a certain height above the tank floor, activates a switch. Such low-cost, simple operation actuators are best used in applications where basic on/off control is required, protection against overflow, or starting the pump when the water level becomes low. The most common installation is side wall mounting, where the float is set at the desired height inside the tank. If the float sensor is in a vertical position, the set switch will activate and start other devices, like a pump or an alarm. This kind of installation requires minimal calibration work, and provides consistent performance a long way without heavy, complex electronics.

Another mounting option could involve a top-mounted float switch hanging from the very top of the tank, permitting them to move freely in accordance with the liquid level. Being simple mechanically, float switches are very reliable since they do not depend on electronic components that are prone to damage by the environment. Submersible float switches provide an alternative for applications in which external mounting may prove difficult and allow multi-level detection of the different sensor depths. Unlike the more sophisticated types of sensors, maintenance or specialized calibration are not required by float switches, thus providing a long-term standby service in most cases. Further, since the float switch operates even with very turbid water with a lot of foam and potential contaminants in it, the application is quite practical.

One of the biggest advantages of float switch sensors is that they are inexpensive and mechanically rugged. That their operation is simple, based on buoyancy and a mechanical switch, makes them work reliably with little maintenance. Float switches perform just as well as electronic sensors, which have to be carefully calibrated, for example. They are very versatile and perform well in various water conditions, including turbid, foamy, or dirty water. Their mounting simplicity makes them an ideal choice for small-scale applications other than industrial applications, conserving mounting time and money. Also, because they are devoid of high-technology electronics, they are power-efficient and ideal for low-power or off-grid applications.

While reliable, float switches are not perfect due to their mechanical nature. Over time, mechanical abrasion on moving components, where sediment or mineral buildup might be introducing operation interference, can happen. In addition, in very turbid water, excessive float movement may sometimes introduce spurious triggering or erratic operation. While being extremely capable at simple high/low water level detection, they are not suited for continuous level measurement, which could be a drawback where high accuracy measurements are required in an application. Simple cleaning and inspection can help to maintain function, but under harsh conditions more frequent maintenance will be necessary. Float switch sensors remain an inexpensive and reliable choice for water level control despite these challenges, making them the perfect option for the Aqua Strings project.

3.1.5.4 Resistive Sensors

Resistive sensors are electronic sensors that measure water level through conductive traces that operate based on changes in electrical resistance. These sensors typically have about two to five conductive lines that are separated by some sort of resistive material such as conductive ink or metal traces. When these lines come into contact with liquids such as water, the liquid contact will then adjust the resistance of the material causing the voltage and/ or current to also adjust accordingly throughout the circuit. Either a microcontroller or some sort of measurement circuit would be able to understand these changes read by the sensor to determine whether there was presence of water, at what height the top of the water has reached and/ or the amount of force/ pressure the device experiences. The sensors work by relying on measuring the conductivity of the water to complete the circuit of the traces on the sensor itself. As the sensor becomes for submerged the conductivity will change proportionally so that it can read a numerical value and relatively dictate the level of the water.

Two of the major advantages of these types of sensors are their simplicity and their affordability. These sensors typically can be purchased ready to use or may need some slight additional parts that also don't cost much. Their components are manufactured at a very low cost due to their mass production for the consumer market along with their industrial applications. In addition, they also are highly sensitive, allowing for quite accurate results and interpretation of data that can be used to modify other portions of our project, such as turning the water pump on and off as needed. Another benefit would be how intuitively the sensor can integrate with microcontrollers such as Arduino, which would be perfect for our needs, since it only requires an analog to digital converter (ADC) to read the changes in resistance. There is no need for over complexity since the sensor fundamentally works based on the basic electrical properties on conductivity and can be easily implemented for applications involving touch screens, water level detection or force measurement of a system.

Even though this option has vast advantages in its application to our project, it is important to note the disadvantages as well in the hope of mitigating them. One of the major downsides is its susceptibility to degrading over time, especially when it is left within a liquid for an extended period of time, causing its functionality to eventually stop working and require the sensor to be replaced. To mitigate this, we would just have to order a batch of these sensors and since they are already so cheap that would not be a major issue. Another disadvantage would be how temperature of the surrounding environment affects the values the sensor reads. Our team would just need to make sure these water level sensors are placed near the laser beam transmitters since those will increase in temperature so there should be no other components that would alter this read data. This would be an excellent option for our Aqua Strings project due to its low cost and simple detection design.

3.1.5.4.1 Water Level Sensor Comparison Table

Specification	Pressure Sensor	Infrared (IR) Sensor	Float Switch Sensor	Resistive Sensor
Functionality	Measures hydrostatic pressure (water depth and pressure	Measures water level based on	Float moves with top of water,	Measures resistance based on changes in

	have a direct relationship)	beam reflection	activates switch	water conductivity
Advantages	Accurate in humid environment, no alignment or calibration needed	Contactless, no mechanical wear	Simple, cheap, reliable	Simple, cheap, easily integrated with microcontrollers
Disadvantages	Costly, best for large tanks, high maintenance cost	Interference from turbidity, lighting	Mechanical wear	Possible corrosion of electrical components
Cost	~$30+	~$20 - $40	$3 - $15	$3 - $15

3.1.6 Applicable Laser Beam Technology for Harp Strings

For the magic of Aqua Strings to work, we need a means for the instrument to properly “strum” whenever the user interacts with a column of water. This relies on the interaction between the sensor, the water column, and the laser beam. All three of these factors need to work together to properly pull off this effect. As such, it’s important that we also consider what laser technology we will use that will pass through the falling columns of water. This beam needs to be safe (since players will interact with the beams), reliable in water environments (such that they won’t scatter too much or be absorbed), and easily detectable by the sensor at the bottom of the water column. An additional factor that we can consider for the laser beam is whether or not we want to make the laser beam visible. Having it visible may help the instrument be more intuitive. If the user can see the beam they are strumming through the water column, it may be easier for the user to play the harp. Additionally, we can coordinate the visible beams of light to be different colors. This would add a layer of interest that would synergize with the water columns. Each note could potentially be represented by a different color. Or, if the project is set to “Fountain Mode”, the harp will function like a water installation and be lit up by the different color lasers. A potential downside of having different color lasers is that their interactions with the sensors may differ. In a project where our main priority is consistency and latency, having an optional feature that would inhibit reaction time would be a poor decision. There’s a chance this wouldn’t be the case, thus it’s worth prototyping the error to see if this additional feature is worth implementing. The alternative is to choose a laser beam that is invisible. This would hide the laser beam’s reflection when the user passes their hand through the column of water. In this case, it appears as if the water column has become a functioning harp string. If the beam were invisible, the only interaction the user could see would be with the water. Both cases are tempting and will be considered at a further stage in development. At minimum, the laser beam’s safety, reliability, and detectability will be considered at the research stage.

3.1.6.1 Diode Lasers (Point Laser)

A diode laser consists of a p-n junction semiconductor that emits coherent light when electrons and holes are stimulated by an electrical current. This light is then amplified by an optical cavity where the light would shoot out from. The wavelength (and corresponding color) of the emitted light will change depending on the semiconductor material used. One key feature of diode lasers is that they are compact. This is important due to the potential waterproofing of these electronics. If the laser beams are stored in an enclave below the upper reservoir, then they would need to be compact to fit with the design. If they are implemented within the reservoir, it would be ideal to be compact to minimize the size of the electronic needed for waterproofing. Another key feature is that they are efficient. They consume a low amount of power during operation. Additionally, there exists a range of wavelengths for diode lasers. Red (650-670nm) is the most common and easy to source. Green (520-532nm) and Blue (405-450nm) are brighter but may be more expensive. There are also infrared (780-1550nm) wavelengths that are invisible to the naked eye. We will touch on this application in a later section. One advantage of this technology for our project is that they are safe for eye exposure under normal conditions. For instance, a class 2 diode laser, like a laser pointer, is safe for eye exposure assuming it was not directly aimed at the eye. Since the output of a diode laser is a single point at the aimed surface, there shouldn’t be any safety concern as long as it is not aimed at a person. For the user of the harp, this certainly will not be a problem. The laser beam will be shining directly down and be enclosed within a water column. A potential safety consideration is for our team during testing and assembly of the project. We will have to ensure that the laser beam is never directly aimed at another person or ourselves while testing these optical systems. Another advantage is that they produce continuous and coherent beams. This will ensure reliable detection at the base of the water column. Additionally, these lasers are affordable and often readily available. Their power levels are offered at a wide range (roughly 10mW-5W), making them accessible for this project depending on the intensity of the beam. This will be important when considering how lower power lasers may scatter in water and require a more intense beam. The biggest downside of a diode laser is that the beam itself is invisible. The initial output of light at the base of the laser might be seen, but the beam as it shoots through the water column won’t be. This isn’t a major fault, as the visibility of the beam is an optional component. However, it is worth noting that a diode laser will only produce visible light when it hits its corresponding sensor at the bottom of the harp. Ultimately, a diode laser is an excellent choice for a laser harp due to their visibility to the sensor and their affordability.

3.1.6.1 Line Lasers

A line laser is a specialize laser module that projects a straight, thin laser beam. It utilizes the same technology as a diode laser to produce light: a semiconductor. The difference lies in how the light is altered before it is emitted. A basic diode laser produces a single dot onto whatever surface the laser is aiming at. This makes it ideal for applications like a laser pointer where the user needs to highlight a specific physical location. The size of this dot is incredibly small but will expand over distance due to beam divergence. A line laser starts with the same source as a diode but uses an optical element, like a lens or diffraction grating, to spread the beam into a linear shape. This converts the single, focused dot produced from a diode laser into a visible and thin, elongated line. Ultimately, a line laser is essentially a diode laser that has been optically manipulated to have a different beam shape, spreading into a line instead of a single point. Thus, it's able to produce different wavelengths just like a diode laser. The most common colors are red, green, and blue. This matters more as the entire line of the laser is visible. If we wanted to add some aesthetic appeal using colors, we would likely pick line lasers as their colors would be more visible. That's one of the technologies' greatest advantages for the context of this project. It would provide a greater level of interaction between the laser beam and the water column. This may provide a greater detection area, making the optical system more reliable. In a similar vein, the broader beam will be easier for users to see. This would lean more into the optional requirement of making the beams visible and more like a harp string. This feature of the visible light scattering through the water could create a more immersive visual experience. A potential concern of this technology is that the beam may unintentionally spread when passing through the water column. Since the technology is already manipulating the beam away from a point and into a line, there's a greater chance that the beam might not stay uniform. This might be caused by the water's refraction (assuming it is not exhibiting laminar flow). Additionally, this technology is generally more expensive than its diode laser counterpart. Aside from this, the line laser exhibits similar qualities to that of the diode laser. Regarding its safety, the same considerations would be applied to ensure no one is hurt. Line lasers could be a great alternative to diode lasers for this project, especially if we're aiming for visibility of the harp's strings and a greater aesthetic.

3.1.6.3 Infrared Lasers

Infrared lasers emit light that is in the infrared spectrum and invisible to the human eye. Despite this, specific sensors can read and detect infrared light. They operate at wavelengths greater than 700nm. Common wavelengths that are available for infrared lasers are at lengths of 808nm, 980nm, and 1550nm. Similar to line laser technology, infrared lasers are produced from the same semiconductor base that diode lasers operate on. The primary difference is in the frequency of the lasers produced. While diode lasers produce a visible colored dot at the end of its beam, infrared will produce the same effect, but the dot will not be visible. The entire effect from an infrared laser would be outside the range of human vision. This offers a key advantage in making Aqua Strings a more immersive project. By having completely concealed laser beams, the effect of strumming water columns would be in full force. The water interaction would become the focal point of the instrument as the electronic portion becomes literally invisible. This could elevate the experience of the project and make the experience of strumming the harp more magical. Unfortunately, concealing the laser beams is a double-edged sword. If implemented properly, it can add to the experience. However, if something went wrong during testing, it could be incredibly difficult to troubleshoot a misalignment because the beam is invisible. We would have no immediate means of determining where something is going wrong (i.e. if the laser is malfunctioning, if the laser is misaligned, if the infrared sensor is malfunctioning, if the laser is not being properly detected by the infrared sensor, etc.). Additionally, infrared lasers might not coincide with the water element as smoothly as its alternatives. Shorter infrared wavelengths, like 808nm) penetrate water better, but as these wavelengths get longer, they tend to get absorbed. Wavelengths at longer values like 1550nm are often heavily absorbed, which would disrupt the detection from the sensors. This could be avoided by working on a shorter wavelength of infrared. If we were to leverage this technology, this is an important consideration that we would keep in mind. Infrared lasers could provide a stealthy means of achieving the optical element of the harp. The water interaction and sensor selection need to be carefully considered for this technology. Specifically, an invisible beam with a wavelength around 808nm paired with an infrared photodiode detector could be a viable option. Utilizing this combination would allow for the water interaction to take full focus and obscure the electronics.

3.1.6.4 Vertical-Cavity Surface-Emitting Lasers (VCSELs)

Vertical-Cavity Surface-Emitting Lasers (VCSELs) are a specialized type of semiconductor diode laser that produces a different beam. They are similar in this vein to the line laser: both generate a beam using a semiconductor but manipulate the beam optically before emitting. VCSELs use a resonant optical cavity formed by layering two mirrors on either side of the semiconductor region. This difference results in emitted light is projected perpendicular to the surface of the semiconductor wafer. This means that the laser beam is emitted vertically as compared to traditional edge-emitting lasers. When using this technology, a highly collimated (parallel), low-divergence beam is produced. This is one key advantage of the VCSEL. The emitted light is a nearly circular beam with minimal spread over distance. This would result in improved detection accuracy, an aspect especially important when transmitting through water. Additionally, they are both energy efficient, in that they consume less power than traditional laser diodes, and both durable and reliable. Like their diode counterpart, they also can produce beams at varying wavelengths. These options span the visible light spectrum and even include infrared. To summarize, VCSELs boast several advantages like improved beam consistency, more accurate laser-sensor interaction, and lower power consumption. The largest drawback of this technology is that their availability is typically lower than a standard diode laser. They are common in industrial applications, but fewer are available on the consumer or hobbyist level. As such, they are often more expensive for an individual laser than all of the previous technologies. Unfortunately, this makes VCSEL a less likely pick as a laser technology, despite all its advantages. Its inaccessible for the scale of the project is too large a drawback to overcome this. However, they are a worthwhile consideration if this project were to be scaled up in the future.

3.1.6.4.1 Laser Technology Comparison Table

Feature	Diode Laser	Line Laser	Infrared Laser	VCSEL
Cost	\$5 - \$20	\$10 - \$50	\$10 - \$20	~\$20
Wavelength Range	400 – 980 nm (generally)	400 – 980 nm (generally)	780 – 1550 nm	400 – 940 nm
Power Output	1 – 5mW	1 – 5mW	1 – 100mW	0.1 – 10mW
Beam Shape	Circular Dot (on surface)	Thin line	Circular Dot	Circular Dot
Functionality	Emits a focused beam on the aimed surface	Projects a thin, visible line to emulate a string	Invisible laser detection for more subtle applications	Similar to Diode, utilizes a more efficient technology
Advantages	Cheapest, easy to integrate, has many colors	Visible laser allows for aesthetic applications	No visible beam allows for seamless applications	High-speed and very efficient, lowest power output
Disadvantages	More susceptible to divergence	Reflections from water can refract the beam itself	Needs appropriate IR-sensors	Higher cost than diode, less accessible

3.2 Part Comparison and Selection

3.2.1 Microcontroller Selection

The microcontroller will be at the heart of this project; thus, it's important that the most optimal one is chosen. Microcontrollers contain many essential components housed all in one chip, each with their own specs. One must consider the central processing unit (CPU), memory, RAM, I/O pins, serial communication interfaces, and more. For our case, we also need to consider the Digital-to-Analog Converter (DAC) and Pulse Width Modulation (PWM) capabilities of the chips due to the audio generation aspect. Microcontrollers are designed to execute specifics tasks using all these aspects; and as they are used, community support for these specific tasks grows. Another primary consideration is how available the libraries and community support are for each microcontroller. Additionally, the programming language to operate the system is important. Ideally, support for a higher-level language such as C or C++ would be preferable. While there is an abundance of microcontroller families to choose from, we decided to limit our selection to a few. For the scope of this project, we are considering options amongst ATmega328, ATmega2560, MSP430FR, ESP32, and Teensy4.0.

3.2.1.1 ATmega (Arduino)

The ATmega family of microcontrollers is a series of low power, CMOS 8-bit processors developed by Atmel, which was later acquired by Microchip Technologies in 2016. They run on AVR enhanced RISC (Reduced Instruction Set Computer) architecture. These chips are generally used most often in embedded systems due to pros like simplicity, low power consumption, and extensive library support. Specifically, we will consider both the ATmega328 and ATmega2560 microcontrollers. The ATmega328 is a simpler microcontroller with a fraction of the latter's flash memory, SRAM, GPIO pins, and PWM channels. However, it also operates on a much lower power consumption rate, even beating the most efficient ultra-low power consumption settings of its competitor. ATmega2560 boasts a larger capacity of memory and pins, allowing it to handle a greater level of scalability with the project (i.e. adding more strings to the harp). For our application, we will consider both microcontrollers' presence on Arduino boards. ATmega328 is featured on select models of the Arduino Uno and Arduino Nano. ATmega2560 is featured exclusively Arduino Mega 2560. Both of these boards offer the potential to meet the demands and constraints of our microcontroller.

3.2.1.2 MSP430

The MSP430 family of microcontrollers is a series of ultra-low power, 16-bit RISC processors developed by Texas Instruments (TI). These chips are generally used for similar applications to the ATmega, such as low-power embedded system applications, but especially ideal for battery-operated devices due to low power consumption. And unlike the 8-bit microcontrollers from the ATmega series, the MSP430's 16-bit architecture allows for a greater degree of processing whilst also reducing power consumption. One defining feature of the MSP430 is the ultra-low power consumption with operating currents ranging at 100uA in active mode. When in standby mode, currents can go as low as 0.4uA typically. This is a significant advantage if our power source is from a battery. When the system will have to power multiple lasers, sensors, and a water pump, having a low power cost to the microcontroller is a plus. Additionally, the MSP430 features a built-in DAC which can generate simple waveforms or synthesize audio directly. This produces a sound that's much higher quality than sound generated from PWM, as the ATmega microprocessor will have to do. For this project, we will consider the MSP430FR6869 specifically due to experience with the hardware.

3.2.1.3 ESP32

The ESP32 microcontroller is a powerful and versatile option for embedded applications, especially those involving Wi-Fi and Bluetooth connectivity. Developed by Espressif systems, it is the successor to the ESP8266, improving upon its predecessor with dual-core processing, added RAM, and integrated Bluetooth capabilities. These chips are generally used in Internet of Things (IoT) applications, but its versatility applies to a wide range of robotics and automation. The ESP32's wireless connectivity offers an interesting opportunity for this project. Using its built-in Wi-Fi and Bluetooth, the ESP32 could be used to transmit MIDI signals wirelessly. This would allow for a cable-free system when interfacing with potential MIDI modules, a wireless speaker, or a computer. Considering our need to isolate any electronics from the risk of water, having a wireless connection would be beneficial. However, there is a risk of latency when sending audio signals over wireless connections. If selected, this feature is something that we will consider. Another key feature is the ESP32's much higher clock speed. With its 240 MHz processor, multiple laser interruptions could be processed much faster and sound outputs could be triggered with minimal latency. This offers a significant advantage over both ATmega models and the MSP430, especially considering our demonstrable specifications. We are aiming for a detection and a response time that is within tens of milliseconds. The microcontroller that we have chosen for this project may have a significant influence on this factor. If the difference between the ESP32 and its competitors were smaller, maybe this would not be worth highlighting. However, it is operating at a clock speed that is at least twelve times faster than its fastest competitor so far. Because of this, the ESP32 has a noticeable edge over the other options, alongside its higher flash memory and SRAM. One downside to note is that it has a much smaller pool of general purpose I/O pins to operate with. This shouldn't be a problem with the scale of the project and the number of strings we want the harp to have. However, it is worth noting if we decide to scale up the size of the project. Considering all of ESP32's features, it will be regarded as a solid pick for the microcontroller.

3.2.1.4 Teensy 4.0

Teensy4.0 is a high-performance microcontroller board designed by PJRC. Using a NXP i.MX RT1062 processor, it is one of the fastest microcontrollers available for hobbyist and embedded projects. It boasts powerful processing specifications, a wide range of I/O applications, and native USB support. If the advantage that the ESP32 has over the ATmega models and MSP430 is impressive, then the Teensy4.0 is leaps and bounds over the competition. It operates at a clock speed almost forty times faster than ATmega and MSP430 and almost three times faster than the ESP32. Another great feature is the native USB support that allows for a seamless connection to a computer for audio tweaking. Unlike the ESP32, it has native USB MIDI support, allowing it to be recognized as a MIDI device by a computer without extra components (i.e. external modules) or software workarounds. Perhaps its biggest proponent is the Teensy4.0's community and software support. It has a custom audio library that would be particularly useful for building a sound font for the harp. Additionally, the extension, Teensyduino, for Arduino IDE software provides support for MIDI, audio synthesis, and sensor interfacing. This would greatly reduce development time in this sector of the project. Overall, Teensy4.0 rivals ESP32's processing power while also providing an interesting advantage in the MIDI application. This makes it a solid option amongst the other microcontrollers.

3.2.1.5 Microcontroller Sound Generation Methods

Before selecting a microcontroller, it is important to consider how that system will synthesize the sound. Based on each of their own limitations, they will generate sound differently. Some of these microcontroller-specific differences lie in their processing power, complexity of digital-to-analog converters, and ease of audio implementation. There are several common approaches to producing audio, each with different hardware requirements and varying levels of complexity. The three primary methods are Digital-to-Analog Converters (DACs), Pulse-Width Modulation (PWM) audio, and MIDI (Musical Instrument Digital Interface) output. Each approach holds its own strengths and weaknesses, impacting what specific microcontroller is most optimal for the project.

3.2.1.5.1 Digital-to-Analog Converter (DAC)

Digital-to-Analog Converter (DACs) is the most direct method for sound generation. This method allows the microcontroller to output smooth, continuous waveform by converting digital values into corresponding voltage levels. The result is high-quality audio without requiring any additional external components for processing analog signals. Microcontrollers like the ESP32 and Teensy4.0 include native DACs, meaning they can generate sound signal directly. These signals can then be immediately fed into an amplifier or a speaker. Having a built-in DAC is a huge benefit because it allows these systems to use a method of sound generation that is almost universally applied. Internal DACs have reached a point technologically where they are the best they have ever been. Only small differences lie between DAC to DAC, but generally every modern DAC is entirely transparent and doesn't introduce noise when converting signals. DACs are particularly useful for playing pre-recorded audio samples, synthesizing waveforms (such as sine or square waves), and implementing real-time sound effects. These are all incredibly applicable for producing sound from an instrument. This gives us the freedom to choose between pre-recording notes or synthesizing the waveforms and playing in real-time. One downside, however, is DAC-based audio is often demanding on processing power and memory. Especially if it involves generating complex waveforms or handling multiple audio channels (such as having multiple different strings on a harp). For our application, DACs provide high-quality sound output with minimal external circuitry, making the ESP32 and Teensy4.0 stronger options as a microcontroller.

3.2.1.5.2 Pulse-Width Modulation (PWM)

Pulse-Width Modulation (PWM) is a widely used technique to generate sound when a native DAC isn't available. This method approximates an analog waveform by pulsing an output signal. Specifically, the microcontroller rapidly switches an output pin between a high and low voltage state at a specific frequency. By switching between the two states, the microcontroller creates a duty cycle, or a ratio when the output is "on" compared to when it is "off". And to create an analog waveform, the microcontroller rapidly alters this duty cycle. The result is a waveform that, once passed through a low-pass filter, can produce sound. Microcontrollers like the ATmega328, ATmega2560, and some models of the MSP430 (MSP430FR6869 includes a native DAC however) rely on PWM for sound generation. This allows them to produce basic tones and simple waveforms. However, this means that the audio typically is of lower sound quality compared to DAC output. This is a result of unwanted high-frequency noise and requires additional filtering and external circuitry to resolve the issue. Despite these downsides, PWM is still an effective method where audio fidelity isn't critical. For Aqua Strings purpose, producing the highest quality sound is not a priority as long as the intended notes are played at the right frequencies. Thus, it is a potential consideration for those microcontrollers that rely on PWM to generate sound, like the ATmega328 and ATmega2560.

3.2.1.5.3 Musical Instrument Digital Interface (MIDI)

Musical Instrument Digital Interface (MIDI) is a method that, rather than directly generating sound, the microcontroller sends digital control signal to an external synthesizer or similar software-based sound engine. Using this digital signal, the MIDI will generate any necessary data regarding the noise, such as the pitch, velocity, and instrument data. It is important to note that MIDI software does not produce the audio directly. MIDI will then transmit this data to an external system, such as an amplifier or a speaker, to generate that sound accordingly. A microcontroller like Teensy4.0 is particularly suited for MIDI for this method. Since utilizing MIDI requires connecting to an external synthesizer, Teensy4.0's native USB-MIDI support provides it a significant edge. This allows it to function as a plug-and-play MIDI controller for external audio synthesis. The ESP32 also benefits from the MIDI approach. Using its Bluetooth capabilities, the microcontroller could connect to a computer and synthesize audio from a software-based sound engine. MIDI-based sound generation has several advantages. Since the sound generation occurs externally to the microcontroller, it allows for high-quality instrument playback without any additional processing power. It essentially offloads the audio synthesis and relieves the microcontroller of generating the soundwaves itself. Additionally, synthesizers boast greater versatility and can produce a wider range of instrument-specific sounds. If accurate, instrument-like audio is what we are aiming for, then MIDI-based audio generation is the method we should aim for. Consequently, ESP32 and Teensy4.0 are both microcontrollers we should consider.

3.2.1.5.4 Comparison of Microcontroller Sound Generation

Table 3.2.1.5.4.1: Comparing Microcontroller Audio Systems

Feature	ATmega (Both models)	MSP430	ESP32	Teensy 4.0
DAC (native)	No	Some models (FR6869)	Yes	Yes
PWM sound	Yes	Yes	Yes	Yes
External DAC needed?	Yes	Maybe	No	No
MIDI support	No (requires module)	No (requires module)	Yes (USB or Bluetooth)	Yes (native USB-MIDI)

The table above shows a comparison in the microcontroller's ability to utilize each of the sound generation methods. Their differences are reliant on the level of processing each microcontroller has access to. Additionally, the comparison is affected by their ability to communicate with external hardware. This is situational in cases where an external DAC is required or when an external synthesizer is needed for the MIDI method. It's important to note that all options have the ability to generate sound via Pulse Width Modulation. This method is the most primitive but is a potential backup in case the audio generation needs to be simplified. Both the ATmega328 microcontroller and the ATmega2560 microcontroller are the weakest in this department. They both lack a Native DAC and intuitive MIDI support. To leverage a synthesizer, they would need an external module to communicate with the microcontroller. The MSP430 is a little better than the ATmega. Specifically, the MSP430FR6869 features a native DAC while some of the other MSP430 models don't. Unfortunately, it would also need an external module to synthesize audio via MIDI. However, this might not be too big a downside considering its incredibly low processing power. It would have no need to outsource audio generation when it already takes such little power to operate. From its base specifications, the ESP32 is already in a stronger situation. It can leverage native DAC and MIDI support via USB or Bluetooth. This wireless potential is incredibly strong for the purpose of minimizing cables in a wet environment. The Teensy4.0 is also in a strong position. Like the ESP32, it can use native DAC and MIDI. Additionally, its USB capabilities can directly communicate with a synthesizer to the port on its board. This would minimize development time by having a direct connection to an external synthesizer. Ultimately, under the context of sound generation, the ESP32 and Teensy4.0 feature the best capabilities.

3.2.1.6 Comparison of Microcontrollers

Table 3.2.1.6.1: Comparing Microcontrollers

Feature	ATmega 328 (Uno)	ATmega 2560 (Mega)	MSP430 FR6869	ESP32	Teensy 4.0
Cost	20.00 (Mouser)	48.40 (Mouser)	24.00 (DigiKey)	8.00 (Mouser)	23.80 (Adafruit)
Size (board)	68.6 x 53.4 mm	101.52 x 53.3 mm	89 x 58 mm	51 x 25.5 mm	35.56 x 17.78 mm
Manufacturer	Microchip	Microchip	Texas Instruments	Espressif Systems	PJRC
ADC Resolution	10-bit 8 inputs	10-bit 16 inputs	12-bit 16 inputs	12-bit 18 inputs	2 x 12-bit 10 inputs
PWM Channels	6	15	8	16	31
Number of GPIO Pins	23	86	83	34	40
Communi-cation Interfaces	1 x UART 1 x I2C 1 x SPI	4 x UART 1 x I2C 1 x SPI	2 x UART 2 x I2C 2 x SPI	3 x UART 2 x I2C 4 x SPI	3 x UART 3 x I2C 3 x SPI
Power Consumption, Active Mode (per 1 MHz)	200uA	500uA	100uA	~200mA	100mA

Best Feature	Simple, low power	Many I/O and PWM	Ultra-low power, DAC	High memory, DAC	Fastest, USB MIDI

3.2.1.7 Selection of Microcontroller

To best suit the project's requirements, the microcontroller we have chosen is the ESP32-WROOM Development Board. The ESP32 seemed to be the strongest contender amongst the microcontroller options. It is fast, has a good amount of I/O pins, features a native DAC and MIDI potential, and is incredibly affordable. This specific model was partly chosen due to experience with this board and similar models. Members of the team have used this microcontroller in previous projects and its familiarity will aid in the development of Aqua Strings. And this isn't even considering its extensive capabilities. This board features dual Tensilica LX6 cores clocked at up to 240MHz, creating a very powerful processor for its size. Additionally, it features 512 kilobytes of SRAM. This board has access to 30 pins, 15 on each side. It supports essential peripherals like ADCs and DACs alongside potential communication protocols like UART and I2C. Ultimately, it balanced the constraints of the project the best while providing the most features.

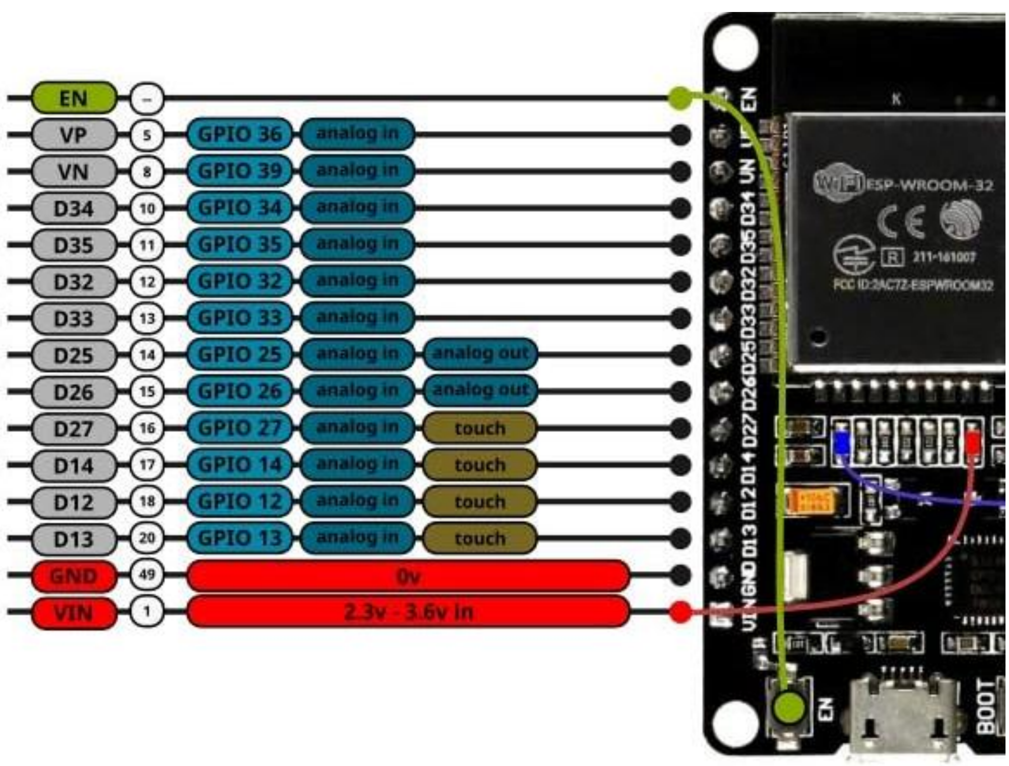


Figure 3.2.1.7.1: ESP32 WROOM Left Side Pinouts

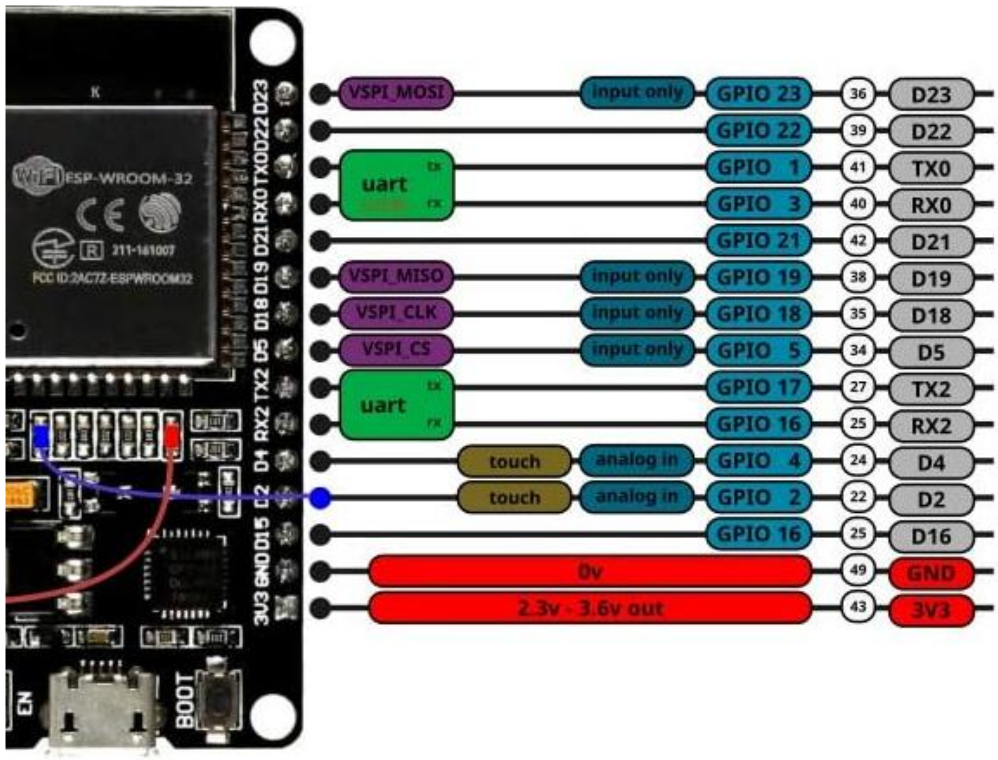


Figure 3.2.1.7.2: ESP32 WROOM Right Side Pinouts

3.2.2 Programming Language Selection

Table 3.2.2.1: Comparison of Programming Languages

Language	*Dev Difficulty*	*Power Eff.*	*Exec Speed*	*Libraries*	*Docs Available*	*Learn Curve*
ESP-IDF	High	Great	Great	Good	Great	Difficult
Arduino Framework	Medium	Good	Good	Great	Great	Moderate
MicroPython	Low	Poor	Fair	Good	Good	Easy
JavaScript	Low	Poor	Poor	Fair	Fair	Medium
Rust	High	Great	Great	Fair	Good	Moderate

In developing Aqua Strings, our interactive waterfall display project, the selection of a programming language is just as critical a decision as the selection of hardware. With the ESP32-D0WDQ6 microcontroller already selected due to its high processing capability, on-board wireless capability, and extensive feature set, the next task is to select the language that will unlock its full potential. This decision influences not just the ease of development but also determines the responsiveness of the system, stability, and ability to handle the complex interaction between sensor input, real-time sound synthesis, and dynamic UI.

Considering the seriousness of our project, where every pause of the flow of a water stream must produce a musical note with zero delay, the programming language used must allow for quick processing, precise timing, and intelligent resource utilization. Our evaluation examines some top contenders: the sprawling Espressif IoT Development Framework (ESP-IDF), the Arduino platform, MicroPython for rapid prototyping, JavaScript with Espruino for event-driven style, and Rust with high performance and good memory safety guarantees. There are trade-offs for each language's benefits. For example, ESP-IDF has extensive hardware control and performance optimization but with the requirement of intimate knowledge of C, whereas Arduino is easy to use and has a large user base at the potential cost of utilizing the chip's advanced features to their highest capability.

Also, MicroPython excels in usability and rapid iterations but may not be able to cope with the real-time demands of dealing with ongoing sensor inputs. JavaScript through Espruino provides an event-driven, natural syntax, but the performance may not be adequate to meet the strict demands of our system. Rust, however, provides efficiency and safety, although its relatively new ecosystem for embedded systems may introduce integration challenges.

In the following pages, we discuss these alternatives in more detail, as they relate to development complexity, availability of community resources, and potential for levels of hardware control. By comparing the strengths and weaknesses of each contender, we aim to choose a programming language that not only meets our technical needs but also allows for scalable, sustainable development. This single design ensures that the finished system will deliver an immersed, real-time interactive experience.

3.2.2.1 C/C++ with ESP-IDF

C was created in the early 1970s when Dennis Ritchie developed it at Bell Labs to be used as an extension of the B language. C was originally developed in Bell Labs to allow the user to have low-level memory access while giving some of the benefits of a high-level language as well, making it ideal for embedded systems programming. The C programming language was standardized in 1989, also known as ANSI C.

In 1979, C++ was created by Bjarne Stroustrup, introducing object-oriented features while keeping the programming language's compatibility with native C. It was originally known as "C with Classes" until being standardized in 1998 and given the name C++, with the "++" representing an upgrade from C.

ESP-IDF (Espressif IoT Development Framework) was created for the ESP32 microcontroller in 2016. It was the official software development framework for ESP32 products using the RTOS operating system, which was created in 2003. Since its initial release, the Espressif team has built ESP-IDF out with more helpful libraries, tools, and APIs, allowing for more capabilities on the ESP32.

The Framework is built on FreeRTOS, allowing for real-time task scheduling, enabling the user to have more precise control over its prioritization and the timing of execution. A benefit of using the official ESP32 development framework is that we will be able to achieve better performance than many alternative frameworks, as we would be directly accessing our hardware without unnecessary abstraction layers interfering.

Using this framework would also allow for the best use of memory allocation, maximizing our available RAM for our project. The Espressif IoT Development Framework has very good documentation and online resources to help us through development.

ESP-IDF provides extensive access to all the needed ESP32 hardware features we would need for this project. This also gives us fine control over hardware timers, sensor polling, and interrupt handling, which will come in handy for low latency for the audio response after a string of water is broken.

ESP-IDF also allows for more advanced power management by enabling us to optimize battery life through selectively choosing what components are necessary and accessing deep sleep modes when needed.

However, ESP-IDF does have some glaring downsides, one being how steep the learning curve is. ESP-IDF is a verbose framework requiring more boilerplate code to get basic features and operations to work. Being a lower-level programming framework, it requires more manual management of hardware resources and memory. This can lead to more complexities, bugs, and a much longer development time.

Programming in the ESP-IDF framework requires proficiency with the C/C++ coding language, a deep understanding of embedded systems concepts, along with understanding the principles of using RTOS. In the case of our project, this would mean allocating more time for initial development and any testing and calibration, potentially prolonging a working prototype.

3.2.2.2 C++ with Arduino Framework

Arduino was created in 2005 by Massimo Banzi, David Cuartielles, Tom Igoe, Gianluca Martino, and David Mellis. The idea behind Arduino was to create a basic tool that was accessible to students with no previous electronics or programming background. The first Arduino board was released in 2005 alongside the Official Arduino IDE that was forked from the wiring project. Being made for Arduino, the Arduino IDE was introduced to lower the hardware complexities and make C/C++ easier to program for microcontrollers by less experienced designers.

Official Arduino Support for the ESP32 began in 2016. This project attempted to bring the ease of programming on the Arduino boards to the more complex ESP32 line of microcontrollers, allowing for two separate microcontroller platforms to share the same platform. Arduino for the ESP32 is actively updated with stability features and library support. This makes the Arduino framework a more accessible entry way for programming on the ESP32.

The Arduino framework adds an additional compatibility layer on top of the original ESP-IDF framework mentioned in the section above. This compatibility layer allows us to strike a balance of having easier to understand code but at the same time having a lot of the benefits of using the original ESP-IDF framework. Another large benefit of using the Arduino Framework is the access to numerous prebuilt libraries for popular sensors, LED control, and pumps. These libraries would mean that we wouldn't have to create these functions from scratch, and we could add to our project to significantly reduce development time. Most of these libraries are fairly well documented and have many online resources to reference.

The Arduino IDE also provides a very easy to use development environment with simple compilation and uploading, making it easy for team members with varying amounts of programming knowledge to get involved and understand what's going on. Another large advantage of this framework is the large community behind it, which means that many niche problems we find during development are very likely to already have published solutions somewhere on the internet, which will also help to reduce debugging time.

The Arduino Framework also has high cross-platform compatibility, meaning that our code will have high portability if we intend to switch to another Arduino Framework supported microcontroller in future versions of the project.

The Arduino Framework has its downsides. Due to the compatibility layer added on top of the original ESP-IDF development framework, we will incur small performance penalties; however, it should be noted this is nowhere near the inefficiency of using something like MicroPython. Another issue we'd face using this framework is the limited access we would have to more advanced features that Arduino simplifies and less control over certain timings. These features may be detrimental to achieving precise pump timings needed for this project.

Due to the simplification of the ESP32-IDF framework, we will have limited ability to optimize aspects of the system. Additionally, this simplified programming model may not be ideal for running operations in parallel with one another, which would be used for running multiple water strings or having the pumps activating at different speeds to balance out the water reservoirs.

3.2.2.3 MicroPython

MicroPython was created by Damien George with a Kickstarter campaign going up in 2013. MicroPython was originally written as a lighter version of Python 3 to be used in the realm of embedded devices and, more importantly, microcontrollers. Its first implementation was on a specialized MicroPython dedicated board. Going back to the source of MicroPython, Python was created by Guido Van Rossum in the late 1980s and was published in 1991. Python is famous for its readability and has quickly become one of the world's most versatile and used languages.

Official MicroPython support for the ESP32 began in 2017, with the primary port being worked on by the Espressif and MicroPython team. Over time, the ESP32 port has improved with support for additional chip features and performance and stability improvements. A big use of MicroPython is educational use for its very easy readability and its simplicity, which will greatly help in lowering development time and making it more accessible to team members that may not have as much coding experience or more experience with Python.

Python's simple syntax and dynamic typing eliminate a significant amount of boilerplate code that is used in C/C++. The implementation of MicroPython introduces a Python interpreter that allows the user to control the hardware through Python. Another plus of using the Python development environment is using the quick development tool such as the built-in REPL (Read-Eval-Print Loop), which allows the user to utilize immediate testing on their hardware without having to worry about compilation cycles. This allows the user to adjust their parameters and see real-time results, which comes in handy for things like calibrating laser sensors or tuning the water pump and flow system.

MicroPython also includes many built-in modules for embedded use, such as modules for communicating with popular communication methods such as I2C, SPI, and UART and hardware peripherals. The language also includes automatic memory management with garbage collection, which eliminates common memory-related bugs such as memory leakage or dangling pointers that are common occurrences when coding in C/C++. For our use case, this could mean more stable long-term operation without memory-related crashes. MicroPython also features a modular approach, which will allow us to make clean separation within our code base for our various subsystems such as Audio, water flow, and sensor detection, making maintenance easier.

However, MicroPython doesn't come without its tradeoffs that could make a big impact, particularly for our Aqua Strings project. As we are using an interpreter language such as Python, this leads to significantly slower execution speed compared to compiled C/C++ code. This could present a big issue when it comes to time-sensitive tasks such as playing the audio response in reaction to a water string being broken. Having too heavy of a latency on the sound after a string is played could greatly affect the user experience.

Along with this latency, another downside of using an interpreter on the microcontroller is the memory resources needed to hold the interpreter. In MicroPython's case, this would be around 356KB of flash memory and at least 16KB of RAM out of the ESP32's 520KBs of RAM to hold just the interpreter. One of the biggest concerns of using MicroPython for our project is that due to the implementation of the automatic garbage collection system, timings can become quite unpredictable. When trying to create a responsive system giving the user near-instant feedback of playing a string, possible random pauses and jittering audio due to delay in execution timing would not be ideal.

3.2.2.4 JavaScript (Espruino or Moddable SDK)

Brendan Eich developed JavaScript in 1995 at Netscape to enhance interactivity in web browsers. Initially called Mocha and later LiveScript, the language was renamed JavaScript to align with Java's rising prominence, though the two share no technical ties. Standardized as ECMAScript in 1997, JavaScript evolved through iterative updates, becoming a staple of web development. Its expansion into embedded systems began years later. In 2013, Gordon Williams introduced Espruino via a crowdfunding campaign, enabling JavaScript execution on microcontrollers by embedding an interpreter directly into firmware. By 2017, Espruino extended compatibility to ESP32 chips, allowing developers to prototype IoT applications using familiar web syntax. Around the same period, Moddable SDK emerged, prioritizing modern JavaScript standards (ES6+) and modular toolchains to merge web development workflows with embedded hardware design. Both frameworks aim to simplify microcontroller programming but can introduce trade-offs when applied to time-sensitive projects like Aqua Strings.

For teams with web development experience, JavaScript reduces initial barriers to firmware coding. The language's event-driven model aligns with interactive systems, where actions like interrupting a water stream must instantly trigger audio feedback. Espruino's interactive coding environment REPL (Read-Eval-Print Loop) supports real-time adjustments, such as tweaking sensor thresholds or refining sound delays without recompiling code. This agility accelerates prototyping, particularly for calibrating laser sensitivity or pump response times. Moddable SDK complements this with tools like xsbug, which monitors memory allocation and execution flow, aiding optimization. Native JSON handling also simplifies data management, enabling future expansions like user preference storage or remote control via Wi-Fi.

Despite these strengths, JavaScript struggles with real-time constraints. Interpreted execution introduces latency: tests show sensor interrupts on ESP32 take 2–3 milliseconds longer to process in Espruino than in C, risking audible lag during rapid interactions. Memory consumption poses another hurdle. Dynamic data types and automated garbage collection strain the ESP32's 520 KB RAM, risking instability during prolonged use, especially with multiple sensors and audio buffers active. Hardware integration demands extra effort, as most drivers for components like lasers or pumps are written in C/C++, requiring hybrid codebases that blend JavaScript with low-level modules.

Community support for embedded JavaScript remains limited compared to Arduino or MicroPython. Few pre-built libraries exist for peripherals such as I^2S DACs or solenoid valves, forcing teams to adapt C libraries or develop custom solutions. Debugging timing conflicts, like overlapping interrupts between water-level sensors and pump controllers, becomes cumbersome without advanced tools like cycle-accurate simulators. Power efficiency also suffers: Espruino's interpreter draws 15–20% more current than equivalent C code during idle states, a critical issue for battery-dependent setups.

While JavaScript frameworks excel in rapid prototyping and lowering entry barriers, Aqua Strings' demand for precision and efficiency prioritizes languages like C or MicroPython. These alternatives offer tighter hardware control and predictable performance, essential for maintaining seamless user interactions despite their steeper learning curves. JavaScript's role may shine in early-stage experimentation but falters under the rigorous demands of a polished, real-time system.

3.2.2.4 Rust

Rust was created as a personal project in 2006 by Mozilla programmer Graydon Hoare, and Mozilla officially picked up support for the project in 2009. The first stable release was released on May 15, 2015. The main goal in the development of Rust was to remove intense memory management while retaining the performance of C and C++.

Rust first started being integrated into the embedded world around 2016–2017 when the Embedded Devices Working Group was established within the Rust project. Seeing as it was meant to be high-performance, it makes sense to make it usable in an application with resource-limited microcontrollers. Official Rust embedded support was started in 2019–2020, with the initial releases only allowing limited hardware access. Since the initial release, however, the ecosystem has expanded its tooling, documentation, and library support. In 2021, Espressif, the company behind the ESP32, officially released Rust support on their chips. Rust has begun to gain traction in the embedded field for its reliability in applications where safety redundancy is important.

With how relatively new Rust is as a modern programming language, it doesn't have the development toolchain for the ESP32 that we see in other options such as Arduino and ESP-IDF. Using Rust could provide many advantages to our project, such as guaranteeing memory safety at compile time without having to worry about garbage collection like you would in C/C++. We could get comparable performance while eliminating the need to worry about common bugs and issues using the Rust ownership model and it borrow checker.

Another feature built into Rust that will benefit us is its advanced type system, which helps to prevent data races and similar concurrency bugs. This could be very helpful when implementing multiple tasks running in parallel. For example, in our project, we could have polling running for the laser sensors while simultaneously managing the reservoir water level management and pump flow control. Rust also offers modern programming language features such as pattern matching, zero-cost abstractions, and a macro system that we could utilize to simplify the development of complex functionality. The language is known for its robust error management, which could lead to more reliable operation for our very water-sensitive electronic system.

With safe Rust code, entire classes of undefined behavior that C/C++ programming is rampant with are eliminated at compile time, making debugging quicker and the system more stable. With all these advantages, using Rust in our ESP32 development comes with some issues. The ESP32 in the Rust community is still developing compared to well-established alternatives such as Arduino and ESP-IDF. Although operational, the available frameworks and libraries are less mature and will feature more workarounds for ESP32-specific features.

Rust has a highly vertical learning curve, with hard-to-grasp concepts like ownership and borrowing that will require significant investment in learning. This will push the initial development time frame as members become accustomed to the language. The Rust ecosystem, although growing rapidly, still falls behind Arduino or ESP-IDF in ESP32-specific examples, tutorials, and community support.

On the practical front, Rust's expressive type system and safety checks translate into longer compilation times, which slows the development process. Rust on ESP32 embedded libraries is less mature than Arduino or ESP-IDF, with fewer high-level abstractions for mundane tasks. Library support for a single sensor or peripheral we wish to utilize in our project is similarly weaker, with additional custom implementation effort potentially required. Finally, installation and configuration of the Rust toolchain for ESP32 development is more complicated than with other options like Arduino, introducing overhead to project Initial Development.

3.2.2.6 Programming Option Selection for Project

Following close consideration of all the programming options for the ESP32, we have decided to use C++ with the Arduino Framework for our Aqua Strings application. This was chosen for a variety of key factors relevant to our specific application requirements and team expertise.

The Arduino framework provides the optimal combination of development speed and performance for our interactive waterfall display. Though ESP-IDF would provide marginally improved performance, the Arduino ecosystem's streamlined API and rich library environment will save us a huge amount of development time, letting us concentrate on the specific challenges of our water-based instrument instead of low-level implementation details. The stringent timing requirements of our sensor detection and audio response system require a compiled language over interpreted alternatives such as MicroPython or JavaScript. Arduino's C++ implementation provides us with nearly native performance for these time-sensitive operations but still offers helpful abstractions for common tasks.

While Rust also offers comparable performance with additional safety features, its greater learning curve and less mature ESP32 support would introduce unnecessary risk to our development timeline. A second reason is that several of our members are already familiar with the Arduino environment, reducing the learning curve and allowing for faster progress. The extensive Arduino community and the vast number of sensor interfacing, audio output control, and water flow system control libraries provide handy resources that will help us avoid typical pitfalls.

In our specific scenario, Arduino offers the best compromise between control and abstraction. It gives us sufficient access to the hardware capabilities of the ESP32 while simultaneously providing us with high-level functions that allow us to quickly develop our code. The small performance difference between Arduino and ESP-IDF will not impact user experience.

As we proceed with our project, we can opt to use direct ESP-IDF calls in the Arduino environment for performance-critical sections of code if necessary. This hybrid approach would give us the best of both worlds, Arduino's ease of development for most functionality and ESP-IDF's performance for more custom solutions.

3.2.3 Speaker Selection

Fundamentally, Aqua Strings' main objective is to be a playable instrument. There is a simple relationship one expects to occur when they play an instrument: When you interact with it, sound comes out. This can happen from a variety of different means: the contact between a mallet and wooden bar, the air traveling through a pipe, or the vibrations from a string. Regardless of how, this core relationship exists with all instruments. Aqua Strings will be no different. However, laser beams and water columns don't exhibit the same musical properties as a taut and tuned harp string. We've already discussed the potential ways to generate audio, but we need a means to play this noise. A normal instrument would use the physical properties of its materials to produce vibrations. To achieve the same effect, we will need to interface with an audio output device to play specific audio signals. When the sensor triggers a detection from a "string", it will communicate with the microcontroller to send an audio signal to an external device. This device needs to be able to produce an acceptable sound quality. The notes that the harp will play should be of distinguishable tone and volume. If necessary, the speaker can leverage the power of the external amplifier if it does not have one built-in. The speaker must also be within a certain size to allow the device to be concealed within the harp. From these factors, the following speakers will be considered: Passive Speaker (3W), Active Speaker (3W-10W), Exciter Speaker, Piezo Speaker, and High-Fidelity Audio Speaker (10W-20W).

3.2.3.1 Passive Speaker (8Ω, 3W)

Passive Speakers are the simplest option of all sound generation options. It consists of a diaphragm, voice coil, and magnet, which work in tandem to produce sound. When an audio signal is passed through the coil, it creates a varying magnetic field around the permanent magnet. The interaction from the magnet on the field oscillates the coil, which drives the diaphragm to vibrate and produce sound waves. And unlike active speakers, they do not possess a built-in amplifier. An external amplifier will be required to drive a passive speaker because a microcontroller, like an ESP32, will not be able to supply enough power by itself. These are low cost and commonly available in a variety of sizes and power ratings. For the sake of this comparison, we will look at passive speakers rated at 3W. However, there are plenty of alternatives at 5W and 10W ratings. One key advantage is that the lack of an amplifier means we have complete control over the external amplifier we can use. As such, we have more flexibility in tuning the speaker's performance. There is also the possible of incorporating an amplifier into our PCB design, as an amplifier for a speaker in this application should not be too complex. The double-edged nature of this trait is that the speaker lacks the ability to function on its own. Overall, the advantages of passive speakers are apparent: low cost, availability, compatibility, and versatility. For such reasons, a small 8Ω, 3W passive speaker would be a great choice for this project.

3.2.3.2 Active Speaker (8Ω, 3W)

Active Speakers are the next progression of speakers when considering sound generation options. Unlike passive speakers, they feature a built-in amplifier. This internal amplifier circuit boosts low-power audio signals given by the microcontroller. This provides a number of advantages over its predecessor. For one, they can be powered by the ESP32 through a voltage regulator (which would be required anyhow). Additionally, they can be interfaced directly with the microcontroller's Digital-to-Analog Converter or Pulse Width Modulation output. The passive speakers have this capability as well, but the Active Speakers can do this via 3.5mm audio jack or USB. As such, this device could be as simple as a plug-and-play with greater integration. Some models even include extraneous features like volume control knobs or equalization settings that could provide increased sound customization options. Another advantage is that active speakers can deliver clearer and louder audio. This would improve the playback of the music of the harp. As a result, these models typically require more power to operate and may not be ideal for battery power. A key disadvantage of these speakers is that, in addition to a voltage regulator required to power the device, an external module will be required to interface these speakers. Having the ability to connect via 3.5mm audio jack or USB is a nice option if our microcontroller had those ports. However, a small ESP32 Devkit only has one port: a micro-USB connection to power and program. Unfortunately, in our case, our microcontroller cannot leverage this advantage. We will need an external module regardless of whether the speaker has an internal amplifier or not. For this reason, a passive speaker seems to be the better option. If both products require external circuitry to properly operate, it only makes sense to choose the one that is more affordable and more available. However, there is one option of connection that we have not considered. The ESP32 can leverage the power of Bluetooth to wirelessly connect with devices. If we were to connect an active speaker via Bluetooth, we would surpass the need to connect via audio jack or USB, reducing the additional circuitry required to operate. This method would also allow us to place the speaker anywhere within the harp (or outside it) with little concern for its connection. However, two major considerations would arise for utilizing Bluetooth in this way. As previously mentioned, latency is a serious concern for this project. Our specification goals require quick processing of signals and playback. Wireless connection via Bluetooth risks latency between the microcontroller and speaker. While this would likely be in the milliseconds, the longer the delay, the more the experience is diminished. When an instrument is played, the soundwaves are near instant. We want Aqua Strings to be on this level. Additionally, a wireless complication would complicate the software end of development, as the audio transmission now needs to occur via Bluetooth. Before, the speaker would simply need to connect to a few specific analog outputs from the ESP32. Now, the programming would need to utilize Bluetooth libraries to interface with the device. And this doesn't even consider that the speaker would still require a power source. Ultimately, an active speaker is still a solid potential option, but its complexity is to be considered alongside its greater audio fidelity.

3.2.3.3 Exciter Speaker

Exciter Speakers are a special type of speakers that conduct their sound waves through solid surfaces. Instead of traditionally emitting sound through the medium of air, this speaker turns the surface into a sound-producing element. Fundamentally, an exciter speaker is very similar to a passive speaker. It consists of similar elements, like a voice coil and a magnet, and the physical reaction that produces audio is the same. However, unlike a traditional speaker, the oscillating coil doesn't drive a speaker cone. Instead, exciter speakers possess a mounting plate that transfers the vibrations from the coil to a surface. The surface itself then acts as the speaker's diaphragm, producing sound. This would be the most immersive of the speaker's options, as the harp's sound would be resonating from its frame. That is one of its biggest advantages: the unique and immersive sound that would change characteristics and resonance based on the shape of the frame. However, that is one of its biggest potential concerns. At this stage in the design, the frame of the harp is yet to be finalized. Prototypes of its general shape exist, but we have no idea how the surface will conduct sound in such a configuration. There is also the possibility that the large amount of water from each reservoir would absorb the soundwaves and dampen the volume. Additionally, vibrations produced in the water could disrupt the flow of the water columns. It is tempting to consider an option as interesting as this, but we have no idea how it will sound until we finalize and begin testing the frame. At this stage in the design, there is unfortunately too much we do not know about the frame to understand how well this application would function. However, this consideration is worth returning to because of how experimentation-dependent it is. Not only does the material and size of the mounting surface impact clarity, as does the mounting spot within the frame. Determining its application would best occur later in development. As a result, we will move forward with another option in the meantime. However, provided there is room in development, the exciter speaker will be considered for its unique and organic sound.

3.2.3.4 Piezoelectric Speaker

Piezoelectric (piezo) speakers are a type of speaker that generates audio using the piezoelectric effect. Unlike traditional speakers that rely on a voice coil and a magnet, they utilize a thin piezoelectric ceramic disc that produces vibrations when subject to an electrical signal. This occurs according to the piezoelectric effect, which is when a voltage is applied to a piezoelectric material (like quartz), causing that material to rapidly deform. This deformation causes mechanical vibrations that generate sound. These vibrations tend to produce high-pitched tones and beeping sounds, such as those commonly present in alarms and watches. A piezo speaker is an incredibly simple device, and as such, has a host of benefits. For one, it is extremely power-efficient, requiring little current to operate and is ideal for battery-powered situations. It is compact and requires little room to function, meaning it can be placed throughout the harp's frame. While limited it frequency, the tones these speakers produce are sharp and clear. This could be useful for ensuring the audio is heard despite the sound from the other moving components (i.e. rushing water, water pump operation). And many piezo speakers can run directly off the microcontroller's Pulse Width Modulation output, meaning it doesn't generally require an external amplifier to operate. However, by being such a simple and efficient device, it possesses several limitations too. One of its greatest disadvantages is its limited sound quality. While it is effective at simple tones, it cannot achieve a fuller range of audio due to its means of generating sound. Specifically, it would struggle at producing lower-pitched tones and any level of bass. Additionally, because their audio is so biased towards high frequency, they are great for beeps and chimes, but not as applicable towards more complex musical tones. If we wanted the sound of a string being plucked to have a complex, vibrating tone, we are unsure if such a speaker could produce that note. Another disadvantage is that some piezo speakers, despite operating very efficiently with a low current, may require higher voltages to boost their circuit for proper volume levels. This voltage range could reach 12V or above, which would certainly require a voltage regulator. For the applications of this project, if we wanted the output of the harp to be short, percussive, and high-pitched, we would choose a piezoelectric speaker. However, Aqua Strings at its core is resemblant to a harp and its audio output should reflect that. Confining the music to high-pitched beeps would limit the project's effect and stifle the experience. For this reason, piezoelectric speakers will most likely not be considered as the means of generating the tones and audio for this project.

3.2.3.5 High Fidelity Speaker

High fidelity (hi-fi) speakers are the most advanced option to produce the highest level of quality. They feature much more complex electronics than the previous speakers to produce greater audio quality. Specifically, they consist of multiple driver components such as woofers for lower frequencies, tweeters for higher frequencies, and midrange for the main body of the sound. When combined with the microcontroller's Digital-to-Analog Converter and an amplifier, the hi-fi speakers could most faithfully produce musical tones. This option is similar to what one might purchase for their computer or television audio system. Their advantages mainly come from their complex hardware. They can produce a rich and superior sound with support across the full range of frequency. They would also be the most ideal for music playback, as this higher quality could sound as close to a genuine instrument as possible. It also could be expanded upon and upgraded with additional units such as subwoofers or external amplifiers. If this project was entirely audio focused, then this would be a definite pick. However, that is not our only focus. We must balance the project's other features and consider its limitations. And that is where hi-fi speakers' disadvantages begin to come in. For one, they consume a very large amount of power compared to their alternatives, so much so that they might need to run on a different power source. Additionally, they are large and bulky. They could not be placed within the harp's frame and would simply need to sit outside the instrument. This would take away from the harp's effect as the audio playback would occur away from the strings. These speakers also tend to be rather expensive, some ranging almost ten times as much as some passive speakers. This is outside the range of our budget for the speaker. Ultimately, hi-fi speakers are overkill for the level of audio quality we are expecting for this project. While we do want the instrument to play with a reasonable level of richness and clarity, we do not want to sacrifice the rest of the project to achieve it. Unfortunately, high fidelity speakers will most likely not be considered for this project because of their high-power consumption and unnecessary level of audio quality.

Table 3.2.3.5: Comparison of Speakers

Feature	Passive Speaker	Active Speaker	Exciter Speaker	Piezo Speaker	Hi-Fi Speaker
Cost (general)	~ \$3 - \$8	~ \$10 - \$20	~\$3 - \$20	\$0.5 - \$3	\$30 - \$100
Sound Quality	Good	Good - Excellent	Surface-dependent	Poor - Good	Excellent
Size	Small - Medium	Medium - Large	Small	Very Small	Very Large
Complexity to Integrate	Moderate (need amplifier)	Moderate (need 3.5mm or Bluetooth)	Moderate (surface/ frame dependent)	Very Low (near plug and play)	High (need amplifier/ external power)

Power Consumption	Moderate (3 – 10W)	High (10 – 30W)	Moderate (1 – 10W)	Very Low (0.1 – 1W)	Very High (20 – 100W)
ESP32 Compatibility	Yes (with amplifier + module)	Yes (with amplifier + module/BT)	Yes (with amplifier)	Yes (PWM output)	Yes (with DAC + amplifier)
Best Feature	Simple application, average sound quality	Higher-than-average quality, Bluetooth	Unique sound profile, immersive	Incredibly simple, low power	Excellent audio quality, great range
Suitability for Aqua Strings	Good	Good	Experi-mental	Limited	Overkill

3.2.4 Water String Detection Laser & Sensor Selection

For the Aqua Strings project to become fully functional the sensors used to detect an interruption in each water string need to be reliable, affordable, practical and compatible with the other chosen electronics. In section 3.1 the different types of sensors that could be considered were researched and our findings were compared leading to visible LED lasers being selected due to their numerous advantages, including the added visibility when aligning the beam and the receiver. Now that the type of sensor has been selected, the next step would be to compare specific parts and choose the proper part based on a multitude of factors such as cost, delivery time, wavelength (color of beam), performance, device specs. Similarly, the photodiodes also need to be compared and selected based on a similar list of qualities. They must have a sensitivity range that the laser beam falls into, which is roughly between 400-580nm since green and blue laser have been chosen due to their reduced absorption in water. The majority of these options are not inherently waterproof, for both laser transmitters and receivers, it is important to note the costs that come along with waterproofing these materials verse paying the price of these already waterproofed components. This section will lay out each component and the advantages and disadvantages it'll bring to our project.

3.2.4.1 Laser Beam Component Selection

This project will have a handful of electronic components that will need to be powered so finding a component with a low power demand while also maintaining a strong output at an affordable price is a main priority. Even though green and blue lasers have slight differences in visibility and their interactive properties it is still important to note and compare those discrepancies. Green lasers are typically a bit more visible to the naked human eye, which gives these lasers a small advantage when aligning and implementing the system. Blue lasers are still sufficient in terms of maintaining the functionality of the project and are typically a bit cheaper compared to green lasers. Both disadvantages are basically negligible, but they are still factors that exist.

3.2.4.1.1 Green Laser – GH05210H2K

The GH05210H2k is a laser diode that produces a laser beam at a wavelength of 520nm meaning it falls on the visible light spectrum as a green color. Due to this green color, the beam will have great visibility which will help with alignment (as mentioned previously) and will add a color to the water string enhancing user experience. This specific is a suitable option for our project. It was found online for $8.00 on the website Laser Tree however delivery added a few more dollars depending on how fast the product will be shipped, bring the overall cost to about $12.00 roughly. At this cost, this laser would operate as expected with its performance meeting expectations and needs. Its cost is slightly high, but it does fully out-rule this beam from the equation.

3.2.4.1.2 Green Laser – GM532-50B

The GM532-50B is a green dot laser diode module with slightly long dimensions when compared to the size of the GH05210H2K laser diode. This particular model is a dot laser meaning the laser beam isn’t as visible as other options but the photodiode on the receiving end would still be able to read the input as the same since the green dot appears on the end. An advantage to this would be that the user wouldn’t see the laser until they swipe their hand across the water string, and it would appear on their hand, giving them an illusion of how the water being there. This, however, doesn’t affect the functionality of the project, so it is more so just a cosmetic design the team could make. These laser beam modules were found on Amazon for $10.00 per unit and delivery cost is free since our team members have an Amazon Prime subscription which includes free shipping. This puts the overall cost per unit still at $10.00, which is less than the GH05210H2K green laser diode making it a more affordable option. Performance measures are about the same with similar power requirements (see the table in this section) but this module is slightly more appealing due to the small difference in cost.

3.2.4.1.3 Blue Laser – B0CYL53LVG

The B0CYL53LVG is fairly similar to the previously mentioned laser diodes but instead it produces a laser beam at a wavelength of 405nm, which is a blue color on the visible light spectrum. This specific model can be purchased as either a line beam, dot beam or cross beam. These different line types only serve as cosmetic choices and do not affect the functionality of the project. Blue beams act similarly to green beams since they have a reduced absorption rate within water but there still is a slight reduction in visibility to the user. Even with this slight difference there is no change in the performance of the overall project. These laser modules were found for $8.80 per unit on Amazon and delivery costs are already included since our team members are prime members, leaving the total per unit price at $8.80. Since this product is also on Amazon its delivery time is only two days, beating out other websites. This option is a solid choice for our blue laser beams since they are available in multiple different line types along with its lowered cost.

3.2.4.1.4 Blue Laser - B07M9DTSF7

The B07M9DTSF7 is another blue laser diode module at a wavelength of 405nm. This model comes as a blue dot beam meaning the color is mainly seen at the end of the beam when it hits the receiver (photodiode) on the opposing end, there's no functionality issues. This module is quite identical to all the other laser modules listed in this section since it has relatively the same dimensions and performance. This transmitter was found on Amazon for a price of $11.99 and since it is ordered from Amazon it would have shipping fees already included. Its reliable power output and high stream stability make it a contender for actually being implemented into our Aqua Strings project. This higher cost, however, is a drawback so other options are likely to be chosen first before our team chooses the B07M9DTSF7.

3.2.4.1.5 Red Laser – 1528-1391-ND

The 1528-1391-ND is another red laser beam which means the mean has a wavelength of 650nm on the visible light spectrum. In previous sections it was mentioned that green and blue lasers would most likely be our best option since there is a reduction in the absorption rate of the beam into the water. Red beams do have a higher absorption rate, but visible light beams are also rated for a long distance which is about 6 feet (dependent on the specific laser transmitter) compared to the 1.5 feet for IR lasers. The draw factor to red laser diodes is how much cheaper they are compared to other colored beams since they are more widely produced. Our team has decided to purchase a red beam along with our green and blue laser beams to run our own experiment to see how much more the red beams are absorbed and if it's worth using 650nm beams instead. These specific transmitters were found for $5.95 on DigiKey, not including shipping. This is only one option of the many that were found and there are packs of red beams that can lower the unit price if purchased for all 8 water strings.

Table 3.2.4.1.5.1: Laser Comparison

Specification	Sensor 3.2.4.1.1	Sensor 3.2.4.1.2	Sensor 3.2.4.1.3	Sensor 3.2.4.1.4	Sensor 3.2.4.1.5
Color (Wavelength)	Green (520nm)	Green (532nm)	Blue (405nm)	Blue (405nm)	Red (650nm)

Power Output	15 mW	5 mW	5 mW	20 mW	5 mW
Voltage	5.8 V	3 - 3.7 V	3 – 5 V	3 – 5 V	2.8 - 5.2 V
Current	35 mA	200 mA	--	< 120mA	25 mA
Laser Type	Dot	Dot	Line, Cross, Dot	Dot	Dot
Dimensions	--	1.3” L x 1.3” W	12mm x 30mm	14mm x 45mm	10 mm x 31 mm
Operating Temperature	-10°C to 60°C	0°C to 50°C	15°C to 35°C	10°C to 40°C	-10°C to 40°C
Cost	$8.00 + shipping	$10.00	$8.00	$11.99	$5.95 + shipping

*See each data sheet for more information

3.2.4.2 Photodiode Component Selection

For an accurate detection system, a reliable photodiode is needed on the opposing end of the laser beam that is traveling through the water string. Photodiodes are made up of semiconductors which convert light into a form of electrical current using the photoelectric effect. When a beam comes into contact with the photodiodes p-n junction, it will then generate electron hole pairs causing current to flow. These diodes are highly effective for light detection because the amount of current that will be produced from these sensors is directly proportional to the intensity of the light beam it is reading. For applications where photodiodes are used to detect interruptions between a laser beam and a receiver, these photodiodes play a crucial role since they record whether they are in contact with the beam or not. When there is no interruption, the photodiode maintains a constant current value with no pattern change. When there is an interruption there will then be a fluctuation in the amount of current that is flowing causing the system to note there was an interruption. The microcontroller will read this occurrence and act accordingly, in this case it will trigger a note to play out of the speaker system. Due to the instantaneous reaction time and sensitivity, photodiodes remain a great choice when needing to read input based on the visibility of a laser beam.

3.2.4.2.1 Part 475-BPW34-ND

The 475-BPW34-ND is a mass-produced silicone PIN photodiode that is widely known for its fast detection time and sensitivity. This specific photodiode has an operation wavelength range that includes the visible light to the near sided inferred spectrum, which includes all the listed laser diode parts in section 3.2.4.1. One of the main advantages is its relatively low cost, which was found at $1.14 per unit on DigiKey, making it an affordable choice in relation to the needs of our project. Another advantage is its small dimensions and high efficiency which allows for a straightforward integration into the system. However, one disadvantage is how the component isn't inherently waterproof which would require extra waterproofing measures to be taken on our end or having to isolate the component from the water completely. This photodiode has a sensitivity to a wide range of wavelengths on the spectrum, incorporating the project's needs, but may require extra steps when working with water.

3.2.4.2.2 Part 475-SFH213-ND

The 475-SFH213-ND is another photodiode that has a sensitivity range within the visible to inferred spectrum, but it does have a peak sensitivity in the inferred range, meaning it is more suited for IR beam rather than visible light. This doesn't mean it wouldn't work but it may lead our team towards other components. An advantage to this diode is its low cost, which was found at $0.85 per unit on DigiKey, making it one of the cheapest listed items here. A function of this diode to note is its function with low dark current in low light areas but our team doesn't have to worry about low light areas when assembling our project. Just like the previous photodiode, this component is not manufactured to be waterproof so it would need additional waterproof measures for it to be submerged in water. The 475-SFH213-ND most likely won't be the option chosen for out water string detection since it seems not to meet our needs as well as the other options that were researched.

3.2.4.2.3 Part 751-1013-ND

The 751-1013-ND is considered to a be a premium photodiode since it offers a higher sensitivity and accuracy when compared to other options. It serves as a strong component for this type of interruption detection due to its stable and high-performance readings. One of these photodiodes will cost $11.38 per unit from DigiKey making it the most expensive option by far out of our listed options. Our project only consists of sending a laser beam about a foot distance to which it will be then read so this type of diode may be overkill and an unnecessary purchase. Also at this price point, this photodiode does not come manufactured to be waterproof so there would be additional costs needed to make this option capable of being submerged.

3.2.4.2.4 Part B07VS3FLLF

The B07VS3FLLF is the fourth option of photodiodes, and it is a high sensitivity diode that is designed for general light detection, perfect for the needs of Aqua Strings. These photodiodes are the cheapest out of all the options listed and can be purchased at $7.29 for 20 diodes, making the unit cost be about $0.36. These packages can be purchased with Amazon which includes fast free shipping unlike DigiKey (where the other three options would be purchased from). The downside to these photodiodes is their lack of documentation compared to the other options so by purchasing them our group would be taking a gamble at the reliability since there is much information out there about the uses of this model. It also lacks waterproofing options when being manufactured so it would also require additional costs and steps if the component were used in or around water. These photodiodes are very cheap and affordable but due to their lack of testing with this type of application it may not be a top choice for our project when we can find a more documented component that is relatively the same price.

Table 3.2.4.2.4.1: Photodiode Comparison

Specification	Photodiode 3.2.4.2.1	Photodiode 3.2.4.2.2	Photodiode 3.2.4.2.3	Photodiode 3.2.4.2.4
Wavelength Range	430nm – 1100nm	400 nm – 1100 nm	420 nm – 675 nm	400 nm – 1100 nm
Peak Wavelength	850 nm	850 nm	565 nm	940 nm
Reverse Voltage	32 V	50 V	10 V	0.5 V
Current	Dark, 2nA	Dark, 1nA	Dark, 2nA	5 mA
Viewing Angle	120°	20°	100°	40°
Dimensions	5.4 mm	37 mm x 5.9 mm	--	26 mm x 0.5 mm
Temperature	-40°C to 85°C	40°C to 100°C	-40°C to 125°C	--

Response Time	20ns	5 ns	--	--
Active Area	7 mm^2	1 mm^2	--	--
Cost	$1.14 + shipping	$0.85 + shipping	$11.38 + shipping	$7.29 ($0.36 pu)

3.2.5 Water Level Sensor Selection

Water level sensors play a crucial role in the functionality of the Aqua Strings project since they ensure both the upper and lower reservoirs have at least the minimum amount of water needed for smooth operation. This project is focused on the ability to swipe a hand through strings of water and for that water to be flowing the whole system needs to have water balanced throughout without any water pooling in one specific location. This requires the water pump, that will be implemented, to work when needed and not overwork itself. To guarantee the water pump won't be over pumping water from the lower to upper reservoir by the utilization of water level sensors. These sensors will control the on or off state of the water pump depending on the amount of water in each reservoir, ensuring proper use. There are various types of water level sensors including resistive, capacitive and float designs, all have different types of uses and applications but will manage the flow of water. Choosing the right sensor type will ensure the water flow for the water strings works as expected aiding to the user’s experience.

3.2.5.1 Part 1528-4965-ND

The 1528-4965-ND is a digital water level sensor that works by reading the resistance in the water. The sensor itself consists of exposed interlocking traces that are considered an open circuit when not in contact with water but when the sensor is submerged the water completes the circuit, allowing current to flow. When the current starts flowing the microcontroller attached will take note of this and flag this detection allowing for the water pump to be properly controlled. It is a simple and direct detection method that could be easily implemented for our needs. However, if these sensors remain in the water consistent, they become prone to corrosion and degrading over time which reducing the accuracy of the device. This type of sensor is on the cheaper side making it a great option for the Aqua Strigs project but due to the possibility of corrosion over time our team would need to make sure to take these sensors out of water when not in use.

3.2.5.2 Part 42AK5700

The 42AK5700 is another digital water level sensor that operates by measuring capacitance or resistance to determine the level of a liquid. Digital sensors do not rely on moving mechanical parts unlike float sensors, which makes it more intuitive. This specific model operates at a 5-volt DC and outputs either a high or low value depending on the input the sensor reads. The microcontroller then reads then output and can act accordingly, such as adjusting the state of a water pump. However, this specific component is documented as thoroughly as out other digital sensor option which can cause issues when implementing the sensor comes around. With this lack of documentation, it is uncertain to tell if it is fully waterproof or if only a portion is, which is another factor to consider. While this option produces a reliable output that the microcontroller would easily be able to read, other factors such as the documentation and accreditation of this sensor may not make it the top chose our Aqua Strings.

3.2.5.3 Part 2010-1043-ND

The 2010-1043-ND is a float sensor that works by mechanically monitoring the position of a floating object and switch the flow of water either on or off according to its position. This model does not have any electronic or digital component to it and operated solely on mechanical pieces which can make the design of the system more simplistic. This straightforward mechanical approach it very reliable and resistant to electrical malfunctions, unlike the digital sensors. These electrical malfunctions could include any false triggering due to water temperature, water impurities, or corrosion of electrical parts. A major advantage to these sensors is it waterproof design since it does not use electronics, making an ideal option for in water uses. However, due to its reliance on the movement of different mechanical parts this affects the response time slightly, which may not hurt the functionality of the system but still a factor to consider.

3.2.5.4 Part B07G13JB57

The B07G13JB57 combines both digital and float technology into one sensor. This sensor works by using a mechanical float switch to detect water level but instead of using a physical switch to block off water flow it uses a digital signal the microcontroller can read to turn the water pump on or off. This design is intended for water use meaning it is fully waterproof since the sensor itself is mechanically based and the connecting wires are properly protected. Resistive and capacitive sensors take input through the completion of a circuit where with this combination of design its input is mechanical, and output is electrical. One of the main advantages of this sensor is its durability but overtime it is still subject to normal wear and tear. This would be a great option for the Aqua Strings project since it takes the best parts of both resistance/ capacitance sensors and mechanical float switches and combines them into one reliable sensor at a reasonable price.

Table 3.2.5.5 Water Level Comparison

Specification	Sensor 3.2.5.4	Sensor 3.2.5.4	Sensor 3.2.5.4	Sensor 3.2.5.4
Detection Type	Digital	Digital	Switch	Digital Float
Output Signal	Digital (High/Low)	Digital (High/Low)	Open/ Closed Circuit	Digital (High/Low)
Voltage	3V – 5V DC	5V DC	--	5V DC
Fully Waterproof	No	--	Yes	Yes
Dimensions	64mm x 20mm x 7mm	20mm x 133mm	53mm x 24mm	19mm x 45mm
Temperature	--	-40°C to 105°C	-20°C to 80°C	-20°C to 80°C
Cost	$1.95 + shipping	$8.95 + shipping	$3.65 + shipping	$9.90 ($3.30 pu)

3.2.6 Water Pump Selection

A key element for our Aqua Strings project is incorporating continuous water movement. The water pump in Aqua Strings serves the purpose of providing consistent transportation of the water from the bottom reservoir back to the top reservoir. This water flow continuity is very important in creating stable water streams not only to generate stable water streams for a fountain visual, but also to maintain a high accuracy of water detection to successfully execute the water's interactive feature. The design of our project includes an upper reservoir that has water piping for facilitating the eight vertical streams of water. Our water pumps will be located on the bottom portion of the project, and it will be constantly recycling the water that has just been released from the waterfall back to the top portion to be utilized again.

During the selection process of an appropriate water pump, there are a variety of technical specifications that need to be evaluated. One of the primary considerations is the water pump's flow rate, which is responsible for the speed and quantity of water moving through the system. The approximate height for the project is about two feet tall, with around two gallons of circulating water across 8 small streams. A typical residential home sink can be found with a flow rate of 1.5 to 2.2 gallons per minute (GPM). With this taken into account, an appropriate flow rate to maintain a steady stream for our project should be a slightly lower amount. As the quantity of water requirement is not a large quantity, we expect to utilize a less powerful water pump than for high volumes of water. Having an estimated flow rate of about 1 gallon per minute (GPM) is an accurate and also useful specification for selecting an optimized water pump. In addition, adjustability of the flow rate is a crucial component. Our project's stream pressure for all 8 waterfalls requires minor adjustments and changes to create just the right stream pattern for sensor detection. Having such flexibility to make small adjustments is important to create the visual effect and sensor performance.

Another very crucial parameter is the head height of the water pump, which is the ability for the water to push up vertically against gravity. Since Aqua Strings is about 2 feet tall, the head height of the pump should be able to support at least three feet. The reason for this is that the pump has to take into account the loss in pressure from the tubing of the frame. An adjustable head height for a water pump will also be useful as it will allow easy calibration throughout our testing process of water pressure.

As the main function of Aqua Strings is to produce a musical tone from hand movement, it is important to consider that the water pump operates at a quiet noise level, to prevent the background noise from interfering this the sound output of the harp. Even though the noise of the musical output tone can be adjusted with selection of the audio system, it is overall extremely important to minimize the operational noise whenever possible to create the optimal auditory experience for users. Additionally, noise of a water pump correlates with the size and GPH capacity, so selecting a smaller water pump has a positive correlation with noise and cost.

3.2.6.1 Condensate Water Pump

A condensate water pump is a specialized type of pump designed primarily for handling the collection and movement of condensate water, often found in heating, ventilation, and air conditioning (HVAC) systems, dehumidifiers, and refrigeration units. Condensate pumps are optimized for low-flow applications where water is collected intermittently and needs to be transported to a designated drainage or recirculation point. For our water harp project that involves continuously moving water from the lower reservoir to the upper reservoir to maintain consistent water streams, a condensate pump has qualities that would allow it to be a viable option.

The operation of a condensate pump involves an internal reservoir or sump where water accumulates. Once the water reaches a certain level, a float switch or sensor is triggered, activating the pump motor. The pump uses an impeller mechanism, similar to other centrifugal pumps, to generate the required pressure to move the water through a discharge line. However, condensate pumps have a piston-style mechanism, which is designed to manage smaller volumes of water at lower flow rates. This is achieved by creating suction that draws water into the pump chamber, where the impeller then pressurizes the water and pushes it through the outlet. Many condensate pumps also include a check valve to prevent backflow, which is critical in maintaining the directionality of the water flow within a closed-loop system.

When considering a condensate pump for Aqua Strings, the critical specifications include flow rate, head height, and activation mechanism. Condensate pumps are generally designed for flow rates ranging from 0.5 to 2 GPM and head heights up to 20 feet. For Aqua Strings which requires a pump with a flow rate around 1.5 GPM and a head height of approximately 3 feet, a properly sized condensate pump would be able to meet these needs. The intermittent operation mode of most condensate pumps that is triggered by the float switch could be adapted for continuous operation if the pump allows for manual override or if the reservoir is designed to keep the pump running steadily. This change would ensure that the water streams remain consistent and uninterrupted, which is crucial for the accurate functioning of the motion sensors and the overall musical experience of the water harp.

One of the strengths of a condensate pump is its ability to handle small volumes of water efficiently while maintaining a compact form factor, which would be beneficial as the pump must fit within the lower reservoir without occupying excessive space. Additionally, condensate pumps are typically designed for quiet operation, which is also a viable option considering our project is sound based. The built-in float switch also adds a level of automation and safety as it prevents the pump from running dry and potentially overheating.

However, there are some limitations to using a condensate pump for our project. The primary concern is that condensate pumps are not inherently designed for continuous operation. They are intended to activate sporadically when water accumulates to a specific level, and prolonged use could lead to premature wear on the motor and internal components. Additionally, the flow rate control on condensate pumps is often limited, as they are engineered for specific drainage applications rather than dynamic water features. This could pose a challenge in fine-tuning the water streams of Aqua Strings, where adjustability is needed to balance the flow for optimal sensor performance and visual effect. Another consideration is the pump’s sensitivity to small pieces of debris. Since condensate pumps often deal with relatively clean condensate water, they might not be adaptable with less clean water. In Aqua Strings, where water is being recycled continuously, the risk of small particles or impurities entering the system is higher, potentially leading to clogs or reduced performance is using a condensate pump.

While a condensate pump could technically fulfill the requirements of Aqua Strings in terms of flow rate and head height, its limitations in continuous operation and flow adjustability does make it a less ideal choice compared to a traditional submersible fountain pump. If a condensate pump were to be used, there would be additional design considerations that would be necessary like implementing a bypass to maintain constant water flow or integrating filtration to prevent debris buildup. Ultimately, the decision would hinge on balancing the pump's compact size and quiet operation against the need for reliability and precise flow control in a dynamic water-based musical instrument.

3.2.6.2 Submersible Water Pump

A submersible water pump is a specific type of centrifugal pump that is designed to operate in fully submerged water. Traditional water pumps rely on suction of water, but submersible pumps operate by pushing the water to the surface by converting the rotational energy into pressure energy. This process is achieved through the operation of an internal impeller, which is connected to a sealed electric motor. When this motor is activated, the impeller rotates and creates a low-pressure area at the pump's inlet. Water is then drawn into the pump and leaves through a volute, where the water is then directed through the outlet and into the connected tubing system. This mechanism allows the pump to efficiently move water vertically, overcoming gravity and reaching the top reservoir of our project.

Specifically for Aqua Strings, a water pump with a flow rate of approximately 1.5 gallons per minute (GPM) and a head height of about three feet was identified as optimal for achieving the required performance criteria for the consistent flow of eight strings of water. The 1.5 GPM flow rate translates to approximately 90 gallons per hour (GPH), providing enough volume to create visible and even water streams without causing inconsistencies that could interfere with the motion sensors' accuracy. The three-foot head height capacity is just as important, as it defines the maximum vertical distance the pump can move water while maintaining the necessary pressure. Given that our project stands about two feet tall, the three-foot head height offers a margin of safety in order to account for pressure losses due to friction within the PVC tubing or potential resistance from flow control precautions. This head height specification also allows for reliable delivery of water to the upper reservoir, ensuring all eight streams remain uniform and responsive to user interaction.

One of the potential water pumps under consideration for Aqua Strings is the "Smartpond" brand pump, which meets these precise specifications. The Smartpond pump is designed for small water features and is both compact and efficient, aligning well with the space and power constraints of the Aqua Strings design. The compact size of the pump allows it to fit comfortably within the bottom reservoir without obstructing water collection or requiring a complex installation. In addition, the Smartpond pump features adjustable flow control, which is crucial for fine-tuning the water output to achieve the desired stream stability. This adjustability allows our team to calibrate the water flow during testing and setup, ensuring the water streams are both visually appealing and functionally effective in triggering the sensors accurately. Submersible pumps like the Smartpond model offer the advantage of quiet operation. Since the pump is fully submerged, the surrounding water acts as a natural sound dampener, which is optimal for minimizing the mechanical noise that could interfere with the musical output of Aqua Strings. As detailed previously, creating a quiet operation is particularly beneficial for a musical instrument, where maintaining an unobstructed auditory experience is important for user experience.

Beyond the performance, submersible pumps are also advantageous for their efficiency and ease of maintenance. The Smartpond pump, like many modern submersible pumps, is designed to be energy efficient, and is beneficial for our project because we would require operation with limited power capacity. The pump's design typically includes a sealed housing to prevent water intrusion into the motor which is beneficial to safety and durability. Routine maintenance for submersible pumps is minimal, compared to other pumps in the market. Cleaning for submersible pumps is limited to small maintenance of the intake screen, to prevent potential blockages from debris. This low-maintenance requirement will allow our team to focus on the project's performance with hardware and sensor accuracy, rather than frequent servicing of the water pump.

Chapter 4: Standards and Design Constraints

Definitionally, a design standard refers to a certain set of guidelines or specifications that ensure a project meets a certain level of quality, safety, and performance. For our Aqua Strings project, these standards are crucial for ensuring that our design stays as reliable and functional as possible. Design constraints, on the other hand, represent limitations that then affect the design process of our project. Constraints can come in many forms, such as time, budget, resources, or technical limitations, and need to be managed to ensure the success of the project. In the case of our project that is primarily electrical-based, our group must adhere to standards set by organizations like IEEE (Institute of Electrical and Electronics Engineers) for our PCB to ensure that our design complies with industry regulations. Additionally, safety and manufacturability play a significant role, as our design must be safe, practical and cost-effective to produce. The main constraints in our project are time and finances, both of which add limits on how quickly we can complete the design and how much we can invest in materials, components, and testing.

4.1 Design Standards

4.1.1 PCB Design Standards

In order to have a well fabricated PCB, there are a few design standards set by our selected manufacturer, JLCPCB, that our group must adhere to. These key specifications have an impact in our design choices and must be taken into account when designing our PCB to send out for manufacturing. IPC-2221 standard is the guideline that dictates the general PCB design requirements that include the material selection, trace routing, spacing, and hole sizes. More specific standards, such as IPC-2222, focus on only rigid PCBs, which we will not be utilizing. Another critical standard is IPC-6012, which defines the performance and qualification requirements for high-reliability PCBs. This standard makes sure that all of the boards meet quality durability expectations, which is especially important for our senior design project, for the quality of our hardware integration.

Overall electrical performance standards are also crucial in PCB design to maintain signal integrity and power efficiency. IPC-2152 provides guidelines on appropriate trace widths and thicknesses for handling different current levels, preventing overheating and unexpected voltage drops across the board. For manufacturability, the IPC-7351 standard provides rules for surface-mount component footprints, and IPC-A-600 defines the acceptance criteria for PCB fabrication. Additionally, ISO 9001 and ISO 13485 certifications ensure that PCB manufacturers follow quality management practices to produce consistent, high-reliability boards. JCLPCB is an optimal choice for our group because it is a company that has consistency in creating reliable, manufacturable, and high-performance circuit boards that meet all of the PCB standards discussed above.

4.1.2 IEEE Standards

IEEE (Institute of Electrical and Electronics Engineers) standards are a globally recognized standard of regulation for electrical and electronic systems. These standards cover many industries, however for our project we will be focusing on hardware design, power systems, signal processing embedded systems. By adhering to IEEE standards, our project is benefitting from reducing the risk of malfunctions and improving its long-term performance.

IEEE 1451, which standardizes the smart sensors and transducers, is very relevant to our project's laser sensor system as it gives protocols for sensor communication. This ensures that the motion detection data is consistently being transmitted to the microcontroller. Once the sensors detect movement, the data must be processed, and it makes this standard essential for floating-point arithmetic in digital signal processing. IEEE 1149.1 standard provides a set structure for diagnosing faults within digital components. Through this, it ensures that important hardware components, such as the microcontroller, are consistently being monitored and working as expected. In addition to this, IEEE 1687 (IJTAG) facilitates the testing of the embedded components within the PCB for accurate mentoring and detecting specific faults.IEEE 1241 defines standards for ADC's, ensuring that sensor signals are accurately converted into digital data for processing. This standard helps maintain precision in detecting and interpreting interactions with the lasers, which is better overall responsiveness. Lastly, IEEE 1620 ensures safe and efficient power conversion within the PCB. This standard helps regulate voltage levels and maintain power integrity, preventing fluctuations that could impact the microcontroller performance and sensor accuracy.

4.1.3 Safety Standards

Safety is a critical consideration for our senior design project, as there are a few hazardous components that our team must be mindful of. Aqua Strings involves the simultaneous use of water, electronics, and lasers, all of which pose potential dangers if our group is not being mindful. The integration of water and electrical components requires strict adherence to IEEE and IEC electrical safety standards. IEC 60529 is the standard for water resistance, which ensures proper insulation and protection against short circuits. Encasing electrical components in waterproof housings and using sealed connectors will be essential to prevent water from coming into contact with the PCB, microcontroller, and power supply. Additionally, proper grounding and the use of low-voltage DC power sources will minimize the risk of electrical shock. Circuit protection mechanisms, such as fuses and surge protectors, will further enhance safety by preventing overcurrent conditions that could damage components or create fire hazards.

Beyond electrical safety, the project must also account for laser safety, as the system utilizes lasers to detect motion within the water strings. Following the laser safety standard, IEEE 60825-1, will ensure that the chosen laser modules operate within safe power limits, reducing the risk of a potential eye injury. The lasers used will be Class 1 or Class 2, which are considered safe under normal operation and do not pose significant harm unless directly stared into for extended periods. Additionally, proper alignment and shielding will prevent accidental exposure to laser beams, ensuring that they are directed only down at the intended point of the bottom of the harp. Clearly marking laser areas and providing safety instructions for users interacting with the system will further mitigate risks.

4.2 Constraints

4.2.1 Time

The largest constraint that our team has to consider with our senior design project is the limited time. Our Senior Design semester takes place in the Spring and Summer term, and our group only has twelve weeks to bring our water harp fountain concept to run successfully and ready for demo. Unlike a traditional timeline with 14 weeks for Senior Design 2, this compressed schedule offers no possibility for extensions and has a shorter fixed deadline that we must meet to complete the project and pass the class.

Our team has already taken a few proactive steps in the beginning of the semester by forming our group, creating a project design, and gathering research. These early actions and overall accountability from each member will help reduce some of the time pressure as the semester moves along. Our project involves multiple complex and time-consuming tasks, including the design of electronics and water reservoirs, setting up motion sensors, and integrating sound output when the water is touched. Each of these tasks presents its own challenges and building the water reservoirs requires careful planning and thought to ensure water flow and safety. Sensor testing and calibration will take work and time to make sure the system accurately detects interactions, as well as the sound system needed to be properly integrated. These elements all need thorough testing, debugging, and troubleshooting, that are all heavily taken into consideration with the timeframe.

Some unexpected problems such as component shipping, testing failures, or overall delays in trouble shooting efforts could complicate our planned schedule. A specific concern is the potential delay in receiving critical components, like the PCB, due to supply chain issues or shipping delays. If parts arrive late, it could slow down our progress on certain project aspects, and this would consume valuable time that we cannot afford to lose. The risk of these time constraints is that our project might become rushed, leading to compromises in quality or overall success in the course. Our group will continue to be proactive in organization, time management, and communication to overcome the time constraint of our project.

4.2.2 Economic

Our project operates under an economic constraint due to the lack of an external sponsorship or funding. Unlike some projects that receive financial backing from companies or university grants, our group is responsible for covering all costs for our design. In order to manage this, each group member has agreed to split the total estimated cost of around $400 equally among the four of us. While this approach ensures a fair and equal distribution of expenses, it also means that all of us are aware of personal financial limitations when it comes to purchasing items. This makes financial decisions a priority throughout our Senior Design project.

One of the key challenges we face is balancing cost efficiency with the need for backup materials. While it is important to minimize any unnecessary expenses, we also recognize that there are risks associated with having no extra components in case of unplanned damage or failure at any point of the semester. However, since we are working with limited funding, we must carefully determine which materials are essential to purchase in surplus and which can be limited to the exact quantity needed. Our group has held multiple discussions on our financial plan with how to optimize our budget while maintaining enough flexibility to account for unforeseen issues.

Additionally, our budget impacts our ability to test as freely. Ideally, extensive testing with multiple components and materials would allow us to refine our design and troubleshoot issues more effectively, but this would mean additional material costs. Since we want to avoid unnecessary purchases, we must be selective in our testing approach, prioritizing the most critical aspects of our design while minimizing unused materials. This economic limitation pushes us to be more precise in our initial design and creating a more budget-friendly project.

Chapter 5: Comparison of ChatGPT with other Similar Platforms

As artificial intelligence increasingly enters engineering workflows, various AI-capable platforms have become important tools for research, problem solving, and design enhancements. This chapter will look at the the comparative strengths and weaknesses of ChatGPT, Claude, Gemini, and Bing AI, particularly toward engineering design, through the Aqua Strings interactive waterfall display project. Each platform was distinctly useful at different points in the design process, including technical research, component selection, troubleshooting, and software design. This section analyzes the benefits and limitations of these platforms to better understand how AI can contribute to engineering innovation while showing the significance of having a human touch to verify and develop solutions from AI.

5.1 Introduction to AI Platforms in Engineering Design

In the rapidly evolving field of engineering design, artificial intelligence platforms have been a goldmine of tools for conceptualization, research, and problem-solving. In the creation of the Aqua Strings interactive waterfall display, our team made use of several AI platforms to enhance our design process. This chapter explores the relative strengths and weaknesses of ChatGPT, Claude, Gemini, and Bing AI, focusing on their specific applications in engineering design uses.

Table 5.1.1: Comparison of A.I. Assistants

Platform	Strengths	Weaknesses	Impact/Best Application
ChatGPT	- detailed technical expertise and precise descriptions. - Robust code generation for microcontroller coding. - Effective iterative dialogue and context recall.	- Sporadic "hallucinations" and errors. - Stale knowledge cutoff, without any newer component data. - Limited capacity to scan images.	- Supplied summarizations on methods of water flow. - Supplies formalized troubleshooting for laser detection issues. - Effectively generated functional code for the ESP32 microcontroller.
Claude	- Excellent for lengthy reports and	- Less wordy and less direct in making specific	- Assisted in breaking down engineering trade-offs and

	summarization of multiple sources. - Better at identifying boundaries in technical expertise. - Subtler solutions to design trade-offs.	recommendations. - Worse at generating specialized microcontroller code. - Constrained in giving alternative engineering solutions.	refining design concepts.
Gemini	- Contains active search features for modern component specifications. - Enhanced image analysis for mechanical sketches and circuit schematics. - Makes comparative component analysis with exact references.	- Inconsistency in delivering complete technical descriptions. - Periodic context retention issues in long conversations. - Less optimized user interface for repeated design sessions.	- Played a major role in component selection by providing real-time data on specs, prices, and availability.
Bing AI	- Real-time web search access for price and availability data. - Very good summarization of technical reports and product suggestions.	- Less strong for complex reasoning in tailored engineering solutions. - Less ability for code generation. - Generally, overstates commercial solutions at the expense of fundamental engineering principles.	- Supported market analysis and component testing by providing new product information and comparison analyses.

5.2 Comparative Analysis of AI Platforms

ChatGPT, created by OpenAI, provides comprehensive knowledge in technical fields with robust code generation for microcontroller programming and precise technical descriptions for advanced subjects. Its context retention throughout a conversation was useful for iterative design conversations. ChatGPT sometimes "hallucinates" or produces sounding-plausible but erroneous technical specifications. Its knowledge cutoff also limits knowledge of newer components or technologies, and it sometimes provides extremely vague solutions to specific engineering problems. We also saw limitations in its image examination capability for examining photos of circuit designs or mechanical components, compelling us to describe our designs as text.

Claude, which was built by Anthropic, shows greater context sense for lengthy engineer reports and provides more nuanced responses for design trade-offs and engineering considerations. We found Claude better at identifying limits in technical information and superb at synthesizing information from multiple sources. Claude is sometimes less assertive, however, in proposing specific technical recommendations and can be verbose in responses. We found it less capable of generating code for specialized microcontroller use and somewhat limited in providing alternative solutions to engineering issues on other platforms.

Gemini (formerly Bard) from Google offers enhanced search integration for up-to-date component specifications and enhanced image analysis for mechanical drawings and circuit diagrams. It excels at providing comparative component analyses and more precise references to technical sources. Its weaknesses are that it sometimes is not consistent in providing extensive technical descriptions and gives less comprehensive answers to multi-faceted engineering queries. We also experienced occasional difficulty maintaining context in extended technical discussions, and its interface was less well-suited to round-the-clock iterative design sessions than ChatGPT or Claude.

Microsoft Bing AI benefits from direct web search access, with real-time data on factors like up-to-date price and availability information. It is especially effective at suggesting individual product models with links and summarizing technical reports effectively. However, Bing AI is less able to perform complex reasoning for tailor-made engineering solutions and has fewer capabilities for generating code. We found that it overemphasizes commercial fixes at times instead of principles and has less consistency in the level of response to technical questions when compared to special AI platforms.

5.3 Impact on the Aqua Strings Project

AI platforms significantly accelerated our research process during the initial discovery stage of the Aqua Strings project. Rather than spending hours surfing through disjointed sources, we were quickly able to access synthesized information on water flow dynamics, sensor technologies, and microcontroller integration methods. For example, in looking for laminar flow techniques to employ in our strings of water, ChatGPT provided a broad overview of numerous techniques like perforated materials, honeycomb flow straighteners, and nozzle design and identified critical considerations that directed our subsequent study into specific flow conditioning techniques.

In selecting components, we found AI platforms to be very varied in their utility. For current component specs and costs, Gemini and Bing AI's web search feature provided the best and most up-to-date information. In comparing water pump options, Gemini proved particularly helpful in comparative analysis by model, such as technical information, current price, and stock availability. All of this information greatly aided our component selection, allowing us to focus on testing rather than extended market research.

For solving technical problems, we found ChatGPT very useful in producing possible solutions and troubleshooting strategies. When we had problems with laser detection via water columns, ChatGPT provided systematic analysis and mitigation methods, proposing changes to laser power, photodiode sensitivity thresholds, ambient light shielding, and other wavelengths. This overall troubleshooting method offered several directions to pursue, leading us to successfully utilize green lasers with collimating optics and ambient light shields for our end product.

In programming support, we experienced vast disparity in the capability of various AI tools. ChatGPT exhibited greater proficiency in producing functional code for our ESP32 microcontroller under the Arduino framework. It provided nicely structured code samples with good comments explaining the logic and implementation details. These code structures formed the foundation of our control system, allowing us to adapt them to our specific implementation needs while conserving considerable development time compared to writing each function from the ground up.

5.4 Limitations and Potential Drawbacks

Despite their strengths, our group also encountered important limitations when using AI platforms for engineering design. All platforms at times contained inaccurate specifications or overly simplified engineering principles. As an example, while describing waterproofing solutions for our electronics, Claude suggested "standard silicone spray coating" which would have been insufficient for our submerged components. We also noticed how sometimes AI systems would offer recommendations without taking into account relevant constraints or trade-offs, such as recommending some photodiodes without checking if they would be compatible with our selected microcontroller's input voltage levels.

Too much reliance on AI recommendations occasionally led to "design fixation," where our group fixated on a particular solution recommended by the AI rather than venturing further out to discover more creative ones. This was particularly clear in our early waterproofing design concepts, where we first pursued the very first viable solution suggested rather than investigating multiple methods. Further, while AI tools accelerated many aspects of research, they also created time management problems as team members sometimes spent too much time iterating with AI tools rather than moving on to prototyping and testing.

5.5 Best Practices for AI Integration in Engineering Design

We gained experience through the Aqua Strings project, which taught us several best practices on how to integrate AI platforms successfully into engineering design processes. We realized the importance of verifying technical specifications and guidelines from multiple sources, such as manufacturer datasheets and technical publications. Following the rules of crafting explicit, well-structured prompts which specify constraints, requirements, and desired level of detail consistently produced more useful results. We also benefited from having AI platforms as co-design collaborators through iterative optimization, challenging assumptions and exploring alternatives at each step. Finally, complementing AI assistance with traditional engineering resources like textbooks, technical reports, and expert opinions remained crucial to ensuring design decisions.

5.6 Conclusion

AI platforms have been instrumental in enhancing our engineering design process for the Aqua Strings project, accelerating research, guiding component selection, aiding problem-solving, and supporting software development. Every platform has distinct strengths and limitations, and an integrated approach utilizing multiple AI platforms might be ideal for advanced engineering activities. While these platforms proved to be useful design partners, they cannot replace rudimentary engineering skills, good thinking, and in-the-shop testing. The ideal approach blends AI assistance with traditional engineering methodology and rigorous validation, using these platforms to complement human imagination and problem-solving rather than replace it. Having experienced both the power and vulnerability of AI tools in engineering design, we could make the best use of these software packages to save time while maintaining the integrity and creativity of our Aqua Strings interactive waterfall display project.

Chapter 6: Hardware Design

Hardware design plays a crucial role in the overall success of any engineering project because it involves the physical components and structures that make the system function as it is intended. This chapter of our project includes the organization and integration of all necessary parts, such as sensors, pumps, frames, and wiring, ensuring that each component works in harmony within the system. The hardware design must consider factors like durability, manufacturability, and compatibility with other parts of the project, all while meeting the performance and safety standards. The hardware design is also essential for enabling the system's functionality for the recirculation of water, the interaction between the laser sensors and water strings, and the safe operation of all electrical components. A well-thought-out hardware design achieves having all components are properly housed, protected, and positioned, and also takes into account the constraints such as size, cost, and manufacturability. Ultimately, hardware design is key to ensuring that the system operates efficiently, reliably, and safely, contributing significantly to Aqua String's overall success.

6.1 Design Overview of Aqua Strings Hardware System

One of our initial designs consisted of including a ramp runoff with dividers that would separate the flowing water into eight different sections, one for each water string and laser beam. In the below figure, the design is laid out to show the side profile of the system and how the recirculation of the water would occur. These hardware components, including the laser beam transmitter and receiver are also displayed showing a portion of each component either being exposed to water or fully submerged in the water.

As seen by the figure below, the hardware components of Aqua Strings are mostly located within the top half of the frame. The only exception is the submersible water pump that will be located on the bottom left of the lower reservoir to pump the water back up for the closed loop system. At the top of the frame, there is a fully dry zone to hold the laser sensors, with the transmitters and receivers aligned across the water streams. This dry compartment also contains the PCB, where all sensor wiring is routed for centralized processing. Next to the PCB, the speaker is mounted within the same dry area, positioned in a way that is close to water sensitive electronics. The mode switch is located on the exterior of this compartment next to the speaker to once again provide safety and proximity to the PCB.

The water pump is positioned at the bottom of the frame, fully submerged in the lower reservoir. A tube runs vertically along the structure, directing water from the lower reservoir back up to the upper reservoir. The ramp for water flow is situated beneath the dry compartment, guiding the water downward in distinct sections. Support beams on either side provide structural stability, maintaining separation between the wet and dry zones.

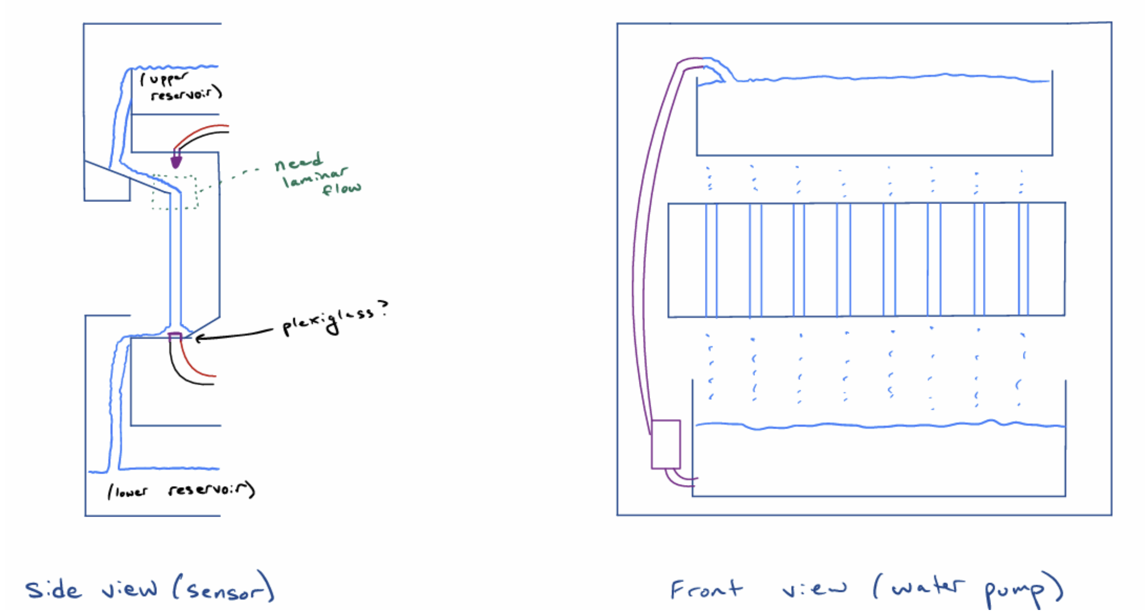


Figure 6.1.1: Aqua String Side and Front Sketch

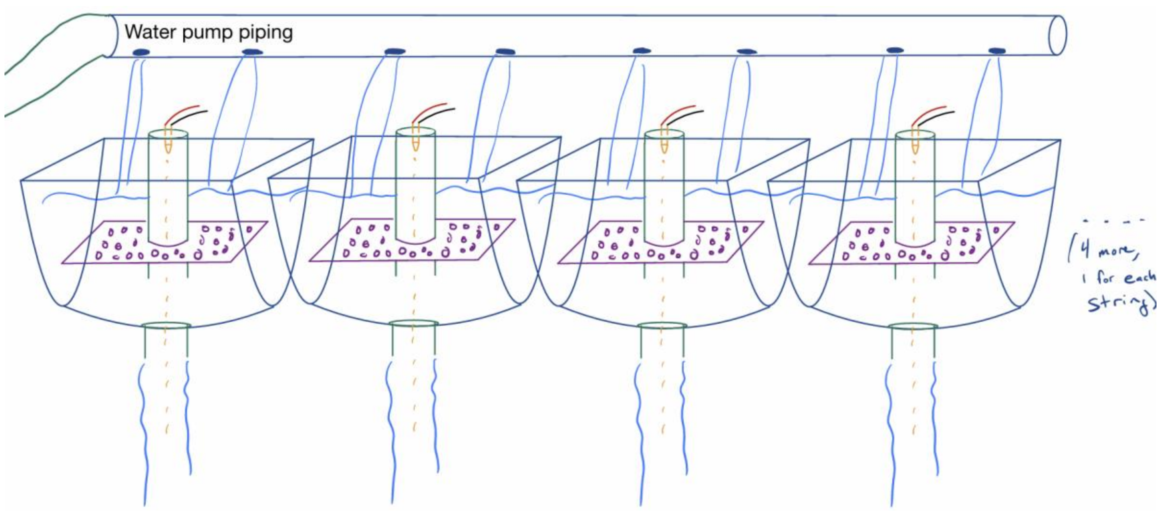


Figure 6.1.2: Aqua Strings Top Sketch

Chapter 7: Software Design

The Aqua Strings system's software design is organized to provide uninterrupted operation, user engagement, and ease of managing system states. This chapter describes the software architecture through important diagrams that focus on system functionality and user engagement. The main program design describes the initialization and running of components such as the ESP32 microcontroller, water pump, laser sensors, and audio system with different modes to control the functions. The use case diagram illustrates user engagement with the system and how individuals will interact with the system to generate musical notes and visuals. Finally, the system state diagram describes the operational states and transitions in the system. This ensures that the responses of the system are clear, faults are managed, and the system can adapt in real time. All of these come together to develop the Aqua Strings software to provide smooth performance and good user experience.

7.1 Main Program Design:

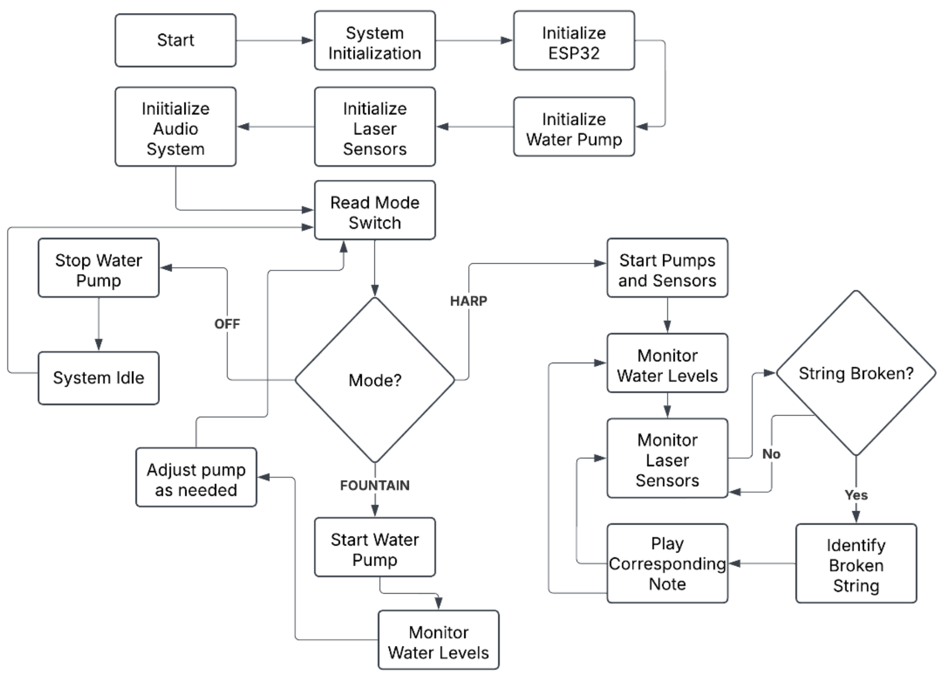


Figure 7.1.1: Main Program Block Diagram

The Main Program Flowchart illustrates the working flow of the Aqua Strings system from initial complete initialization of all the primary components like the ESP32 microcontroller, water pump, laser sensors, and audio system. Once initialized, the system proceeds into its main working loop, continuously checking the mode switch position to determine the appropriate operating state. OFF setting makes the system shut down the water pump and idle down; FOUNTAIN setting makes the system switch on the water pump for effect and switch off sound interaction; HARP setting makes the system switch on both water pump and laser detection system for full interactive capacity. The system checks the levels of water in both reservoirs during operation continuously to provide optimum flow conditions and adjusts the pump accordingly. In HARP mode, it scans all of the laser sensors at once for breaks, recording what water string has been broken when it senses one and producing the resultant musical note via the audio system. This systematic sequence offers responsive input without sacrificing water system integrity.

7.2 Use Case Diagram

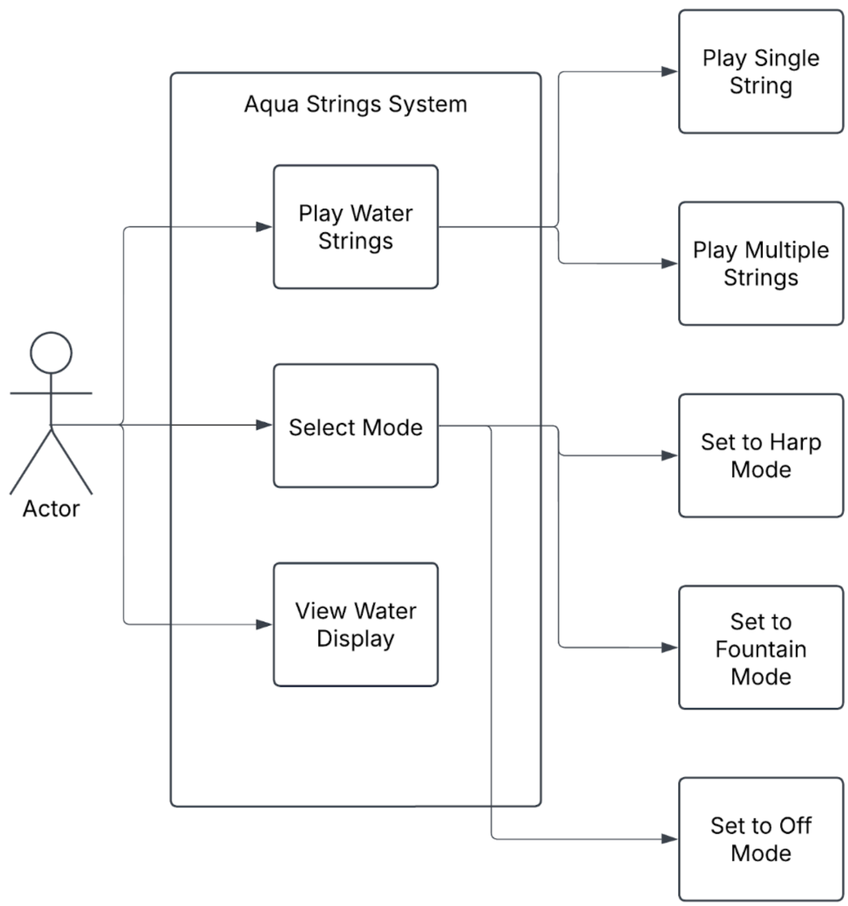


Figure 7.2.1: Use Case Diagram

The Use Case Diagram shows the various user interactions with the Aqua Strings system, which is the principal way an individual can interact with the interactive waterfall screen. The essence of the user experience is contained in five principal interactions: turning the system on and off, selecting between three various operating modes (OFF, FOUNTAIN, and HARP), playing the water strings by interrupting water streams, and watching the visual water display. The diagram also breaks up these interactions into more specific actions—users interrupt individual strings for solo notes or break a group of strings at once for chordal effects for their optimal visual and interactive experience. This systems-level visualization of user interactions highlights the functional aspect from an outside-in perspective, with a focus on the ease of use and intuitiveness of the system over its internal technical processes. By mapping these interactions, the diagram is then used as a blueprint for user instruction and system creation for the Aqua Strings experience to meet expectations of interactive participation.

7.3 System State Diagram

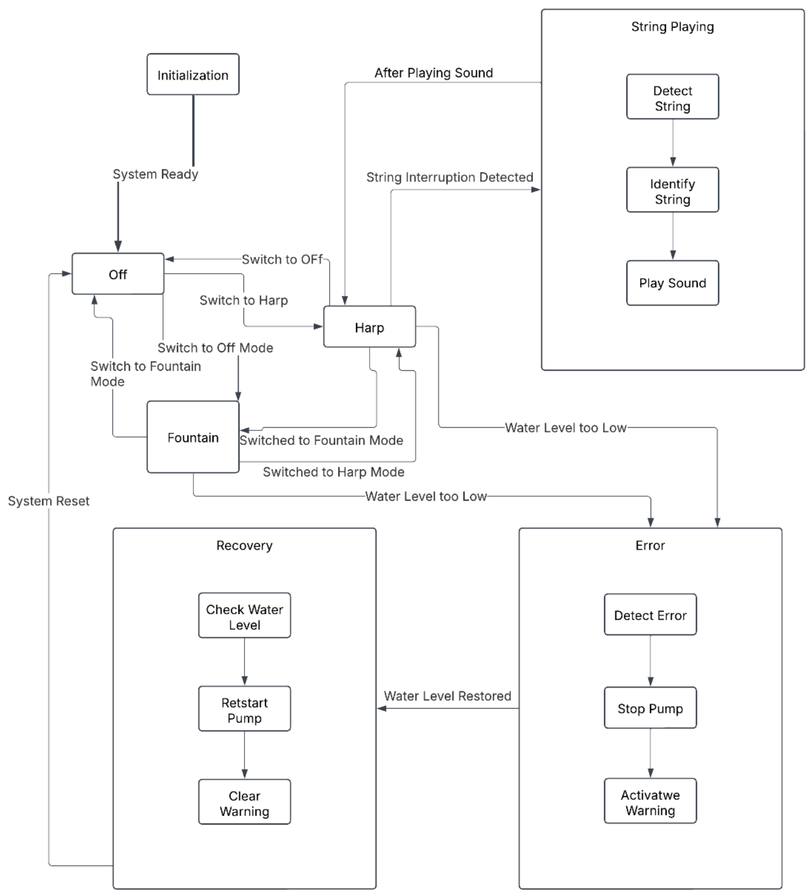


Figure 7.3.1: System State Diagram

The System State Diagram displays the states of operation and transitions among them of the Aqua Strings system, presenting an overall picture of the operation of the system in various states. From an Initialization state where all the systems are initialized, the diagram displays transitions to three principal operational states: Off (powered but not running), Fountain (flow of water without interaction with sound), and Harp (complete interactive mode with production of sound). The figure illustrates how users can switch between these states at will by the mode selector, and how the system responds to some events like string interruptions and error conditions. In Harp mode and the presence of string interruption, the system enters the transient String Playing state where it figures out the specific string, plays the respective note, and resumes the Harp state afterward. The diagram also defines error management in its Error state (triggered by low levels of water) and Recovery state (when water levels are refilled). Each high-level state contains nested substates representing the sequential processes involved in that mode of operation—for example, the String Playing state represents the sequence of detecting an interruption to sounding, and the Error state represents the sequence of detecting a fault, shutting down the pump, and warning. This hierarchical abstraction provides both a summary overview of system behavior and detailed information on individual operating processes.

Chapter 10: Administrative Content

This chapter discusses the administrative considerations for Aqua Strings which involve determining a budget for the project and the schedule for the project to be developed in an organized and timely manner. The costs associated with distinct aspects of the project, e.g., water systems, detecting sensors, electronics, and structural materials, are estimated with alternatives to lower costs taken into consideration. In addition, the project timeline of events is established throughout the two semesters of Senior Design 1 (SD1) and Senior Design 2 (SD2) to include the research phase, purchasing components, prototyping, system integration, and final testing. Overall, by developing a budget and timeline, the Aqua String team has established financial and scheduling considerations that take the project from an initial concept to completion and through final demonstration.

10.1 Budget and Financing

Table 10.1.1 Budget and Financing

Component	Subsystem	Quantity	Unit Estimated Cost	Total Estimated Cost
Water Pumps	Water System	2	$11.00	$22.00
Water Reservoir (Top and Bottom)	Water System	2	$4.00	$8.00
Flow Control Valves	Water System	8	$5.00	$40.00
Tubing (PVC Pipes)	Water System	10 ft	$3.50 for 10 ft	$3.50
Laser Modules	Detection	8	$8.00 for 10	$8.00
Photodiodes	Detection	8	$6.00 for 10	$6.00
Custom PCB	Electronics	1	$50.00	$50.00
Speaker System	Audio	1	$4.00	$4.00
Solenoid Valves	Water system	8	$13.00	$104.00
Power Supply	Electronics	1	$30.00	$30.00
Water Flow Sensors	Water System	2	$9.00	$18.00
Wooden Frame	Structure	1	$60.00	$60.00
Control Panel	User Control	1	$10.00	$10.00
Miscellaneous Cost	All	1	$50.00	$50.00
Total				$413

Our budget for Aqua Strings will be completely self-funded by the group. The estimated cost is subject to change and will be further adjusted later throughout the actual ordering process due to available suppliers. The total estimated cost for this project is $413, however some components may be able to be sourced from the senior design lab or from cheaper options, reducing our overall expenses.

A key requirement of our project is the Custom PCB, which will integrate the microcontroller, laser sensor system, power distribution, audio output and water flow control logic. This PCB will handle the signal processing for detecting when the water strings are played, playing the correct note audio output. The estimated cost of designing and the fabrication of the PCB is $50, but this could change based on design, complexity, manufacturer, and component selection.

Our project will require a 12V/5V power supply, capable of powering the electronic sensors, our custom PCB, and the water pumps. To retain the portability of the harp we will be using a LiPo battery system, this will allow for our harp to run on battery power or be directly plugged into the wall. The estimated cost for the power supply and battery system is $30.

The frame of our harp will be constructed out of wood, we chose this material for its affordability, ease of modifying and to fit the theme as wood is what many traditional harps are made of. The wooden frame for the harp along with any fasteners or adhesive to keep the frame together is estimated to be $60. Additional miscellaneous costs such as any wiring, connectors or tools are estimated at $50.

Many of the components were estimated based on current market research, the final prices may vary when we go to purchase our components. Certain components may also be found from alternative sources such as 3D printing or preowned materials, also possibly lowering our costs.

10.2 Project Milestones for SD1 and SD2

Our Aqua Strings project is structured over two semesters Senior design 1 in the Spring and Senior Design 2 in the Summer. Senior Design 1 focuses on research, documentation, and planning, while Senior Design 2 spends its semester prototyping, testing, finalizing the design and assembly. Some of the key milestones of Senior Design 1 include the completion of major documentation, initial component selection and dry prototyping to ensure the systems' functionality. Senior Design 2 is dedicated to system integration including reservoir construction, PCB fabrication, and wet testing the laser dedication system. The final stage will include system optimization, repeated testing, and a final live demonstration.

Table 10.2.1: Senior Design 1 Milestones

Milestone	Week #	Due Date	Description
Complete Divide and Conquer Document	Week 4	January 24, 2024	First 10 pages of our Divide and Conquer Report
Order Electronics	Week 6	N/A	Ordering our essential electronic components for testing compatibility and initial prototyping
Complete 60-Page Mid-Report	Week 10	March 24, 2024	First half of our final 120-page report
Build Single Laser, Dry Prototype	Week 11	N/A	Constructing and testing a single laser-based detection system without introducing water
Determine Components for Custom PCB	Week 12	N/A	Finalize needed components and designing the layout of our custom PCB
Complete 120-Page Final Report	Week 16	April 22, 2024	final documentation detailing our research, system design and initial testing

Table 10.2.2: Senior Design 2 Milestones

Milestone	Week #	Due Date	Description
Build Test Reservoir Enclosure	Week 1	TBD	Construct the enclosure for the water reservoir and pump system
Complete PCB Design for Print	Week 3	TBD	Finalize and prepare the custom PCB layout for manufacturing
Test Single Laser, Wet Prototype	Week 4	TBD	Evaluate our laser-based detection system with water in the system
Test Multiple Laser, Wet Prototype	Week 6	TBD	Expand our testing to multiple laser water strings simultaneously
Finalize Reservoir and Pump System	Week 8	TBD	Ensure optimal water flow for consistent operation
Perform Final System Tests	Week 10	TBD	Conduct full-scale testing and debugging of the whole water harp system
Final Live Demo Presentation	Week 12	TBD	Showcase our completed project to faculty for final review and grade

Week #	Major Deadline	Milestone	Date Range

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