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The Musical Water Fountain

Amy Nielsen
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The Musical Water Fountain

Group 12-22-01

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Disclaimer

This project report was written by students at Western Michigan University to fulfill an engineering curriculum requirement. Western Michigan University makes no representation that the material contained in this report is error-free or complete in all respects. Persons or organizations who choose to use this material do so at their own risk.
Abstract

An affordable musical water fountain was designed over the course of one year. The target consumers for this fountain are middle to upper class homeowners. Based on the design parameters and research found on the topic, the fountain presents an aesthetically pleasing light and water show for residential neighborhoods. The design was sought to be competitive on the market with preexisting fountains. Since it must play music and perform a water and light show all in synchronous, there was confidence in the unique features to sell with today’s consumers. SolidWorks was used extensively to design and model the fountain and the assemblies within it. Alongside the computer aided modeling, Arduino microcontrollers were used to program the various electromechanical devices used to control the water movements and light sequence. A scaled down fountain prototype was assembled in order to run various tests and obtain proof of concepts. This prototype was preprogrammed to synchronize the Western Michigan University fight song with the rest of the display and demonstrate its performance capabilities. Many obstacles were encountered through the process of designing the musical fountain. Some of these obstacles include constructing a prototype without financial aid, the synchronization of systems, and long waiting periods for custom 3D printed parts. Once these obstacles were overcome a successful prototype was assembled and tested. The final design of the musical fountain is far from a perfect design due to time constraints and lack of expertise in fountain design. Given more time and resources, further research and tests would have been completed with professionals in the industry to create a more robust product. The primary goal to design an effective musical water fountain was ultimately achieved despite the challenges and difficulties faced.
The Musical Water Fountain

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Introduction

Most residential homeowners enjoy maintaining an attractive property for the community. Typical decorations include flower beds, seasonal objects, and flags. Water fountains are also among these décor options but are not as commonly seen in residential properties because of their high market prices. They are next level pieces of entertainment that involve intricate electromechanical systems. A water fountain is more than an outdoor display, it is an extravagant way to represent status. However, with changing times and modern art there is alternative interest for the development of a new water fountain design. It must fit the modern aesthetic in more affordable terms.

A new and unique water fountain was designed. Many fountains do not have a musical element to them which is why this design does. The musical water fountain has water, music, and light components working separately and together to display a pleasant show in the front yard. The physical design was less of a challenge than the electromechanics. Programming three systems to work individually and together synchronously requires advanced knowledge in computer programming and circuitry. Additionally, proper safety must be advised and maintained when working closely with power sources, electrical components, and water. To prevent electrical hazards, professional electricians are required to install all electrical parts of the fountain, and safeguards and protection of devices is enforced.

With multiple software programs, the fountain was formed. SolidWorks 3D modeling software was an advantageous resource to utilize. Not only was it used to create 3D parts, assemblies, and drawings, it was able to perform finite element analysis (FEA). For electrical diagrams, LT Spice was used to clearly and concisely replicate the approved and tested circuits used to power the LED light strip and servomotors (or servos). To program these circuit components, Arduino programming was learned. Microcontrollers were the key devices in this development. Lastly, to verify flows, stresses, and safety factors MathCAD coding was ran through a numerous amount of trials for a product numerical analysis.

Background Research

Water Fountains

Water fountains are not as simple as they seem. There are advanced systems working behind the scenes to ensure a beautiful display. Many large fountains that are seen in parks and business fronts are typically powered through hardwiring (Fountains 2022). A hardwired power supply means the fountain would draw electricity from the electrical grid on that property. It raises a lot of risk which is why only a licensed electrician may install the hardwired fountain. Once approved, a ground fault circuit interrupter (GFCI) outlet will be installed, and this new outlet will line the circuit breaker box for extra protection against electrocution (Liquid Features 2021). A common and fairly easy way to route necessary extension cords is to hide them within a PVC pipe and bury the pipe in a deep trench.

Additionally, the water systems are connected to the property water line in order to control the volume of water. However, it is better to have a recirculating water system. It uses much less energy, water waste, and improves overall economically.

Materials

Concrete is a commonly used material for outdoor décor and sells for a low price. The appeal for concrete is its safe regard for the environment because it does not release harmful toxins from its material make up (Hardrock 2021). It is made of cement, water, and aggregates or rocks and sand. The mixture of these ingredients creates a strong and durable material. Additionally, concrete is suitable for many types of weather which is why it is a favored material for outdoor use. It holds together for long periods of time,
stretching years of intact material strength with little to no fatigue. Unlike metals, concrete may be easily shaped to any mold. For cleanliness, concrete requires low maintenance and is easy to repair in the case of cracks. For long-term preservation, it may be sealed with a specific type of sealant that overall contributes to a better-looking piece over time. While using concrete, it can be finished as a smooth surface, stamped, brushed, or scored (Hardrock 2021).

Nylon was also explored for material use in the product design. It is a synthetic fiber, a thermoplastic engineered material, also known as polyamide (PA). There are a variety of applications for nylon. The advantage of using it is its high tensile strength and elasticity, fatigue and heat resistance, and resistivity to high voltage (WayKen 2022). Also, nylon is adaptive to weather and outdoor conditions because of its non-biodegradable property. It is well known to be non-toxic and counters mold and bacterial growth. However, it may oxidize in the air. Nylon has several versions of itself and can be chosen based on product needs and requirements (WayKen 2022). As for its machinability, it does well and is just as easy as metals. It could also be used for injection molding or 3D printing.

3D printing is often used to produce prototype items. Polylactic Acid, or better known as PLA, is the most used, cost-effective choice of material. This other type of thermoplastic is rigid, stiff, and holds moderate strength. The melting point of PLA is low compared to nylon, so it does not work well in largely exposed heat applications (SMLease Design 2022). It is also not suitable for long-term use with water or high moisture content as it degrades easily. Thus, it is safe to conclude that intermittent product development and hobby-intent items are the best ways to utilize PLA material.

Aluminum Alloy 1000 series is a low strength material that is very close to being pure aluminum. It has notable welding characteristics and excellent atmospheric and water corrosion resistance. This aluminum metal series is used for low impact and applied load applications. A disadvantage of 1000 series aluminum alloy is its poor machinability. A better alloy series to use is a 2000 or 3000 series aluminum. These have greater machinability and strength. While 3000 aluminum alloys also maintain excellent corrosion resistance and provide a higher strength than the 1000 series alloy, it costs more. On the other hand, the 2000 series does not uphold a great amount of corrosion resistance like the 1000 series (Aluminum Alloy Products). There are multiple series of aluminum alloy, such as 5000, 6000, and 7000. These are used for high strength applications and thus not applicable for the fountain. Depending on the necessary strength and machinability, the fountain could use a corrosion resistant aluminum alloy such as the 1000 or 3000 series.

Programming with Microcontrollers

Microcontrollers have the capability to receive and process input information to control the output of various electromechanical devices. Thus, microcontrollers will be the centralized information processing unit or the “brain” of the fountain’s performance. In order to achieve an effective fountain show, the precise control and synchronization of LED lights, servo motors, valves, and input devices are essential.

Since the team is made up of students with a mechanical and aerospace engineering background, much research and hands on learning was required to obtain the electrical and computer skills necessary for this project. The Arduino microcontrollers paired with the Arduino programming language was selected for controlling the various electromechanical systems. Raspberry pi and some other microcontrollers were considered; however, Arduino was selected because of the large amount of educational material found online for assisting Arduino beginners. An Arduino starter kit was purchased over the summer and an in-depth, hands-on learning was done. To eventually learn complex Arduino functions and complimentary coding, it was necessary to start with the absolute basics. Paul McWhorter
from toptechboy.com has recorded a series of 68 video tutorials where he teaches users about all the basic Arduino functions and how to incorporate various input/output devices. A video tutorial was watched and performed each day throughout the summer. Arduino coding notes, circuit sketches and problem-solving techniques were documented in a notebook to use as a reference for future musical fountain coding applications.

**Arduino Code Structure**

The Arduino programming language is similar to the c or c++ programming languages. However, the Arduino programming language is a bit more simplified due to the wide variety of Arduino beginners with no prior programming knowledge. The structure of a typical Arduino script contains three main parts, the preliminary section, the void setup, and the void loop (Alexaki and Dalmaris 2020). It is necessary to understand how each section works, and what functions to include in each section for the program to run properly.

The preliminary section of the Arduino code is located at the very top of the script. This is where additional libraries can be included so that the Arduino can call upon the library's functions. When including an Arduino library, be sure to use the "#" symbol followed by “include” then type the name of the library inside two horizontal carrot brackets. Note that a semicolon does not need to be added to the end of the statement. An example of this for including the servo library is: #include <Servo.h>. Variables can also be defined in the preliminary section to be used later in the code. It is always a great idea to use variables when coding so that data can be stored and manipulated. It also helps to keep the code clean so that it is easier to debug. There are a few different variable options that can be used to store different data types. An “int” stores integer values, thus, any whole number. Floats can be used to store decimal numbers. It is beneficial to define some variables as floats, especially if the variables are part of any mathematical equations. This will allow for sensitive variables to remain accurate to about six decimal places. Another data type frequently used in Arduino programming is the float. A float is able to store a sequence of characters such as a word or a sentence. These are good to use if it is desired to display a message or gain external input from a user. Finally, binary and hexadecimal numbers may also be stored into Arduino variables. Declaring a data type as a “bin” stores the number in binary and declaring data type “hex” stores the number as a hexadecimal number. Anything from a pin number to a loop counting integer can be declared as a variable (Alexaki and Dalmaris 2020).

The void setup section of the Arduino script is an extremely important part of the Arduino code and should not be overlooked. This is where it is communicated to the microcontroller which pins are inputs and outputs. It is also where various electromechanical devices, as well as the serial monitor, are set up. Without defining each pin in the void setup section, the microcontroller is blind; it will not know which pins to use for each application. To define an Arduino pin, simply use the “pinMode()” command. Inside the parenthesis specify what number pin you are defining and then either “INPUT” or “OUTPUT” depending on if it is being used as an input or output pin (Alexaki and Dalmaris 2020). The void setup has a few other functionalities, however, the most important thing to remember is defining the pins utilized in the code/circuit.

The last but certainly not least section of the Arduino script is known as the void loop. This is where the main body of code goes. The code in the void loop will be continuously looped for an infinite amount of time or until it is told to stop. Within the void loop, the Arduino will execute each command sequentially at an extremely fast rate. To slow down the execution between lines of code, the delay command can be used. This will tell the Arduino to stop and wait for a specified amount of time before going on to the next line of code. Although the void loop section is a loop function in and of itself, other
loop functions can be placed inside the `void loop`. Much of the code developed for the musical fountain utilizes many loop functions to allow for smooth transitions and repeatable movements.

*Arduino Board Basics*

The Arduino Uno microcontrollers are available online for about ten dollars which make it a perfect cost-effective device for controlling lights, water movements, and valves within the fountain. This Arduino contains a series of pins defined as follows. Pins 1-13 are the Arduino output pins which can be connected to various output devices. These pins will then send a signal with instructions on how to function. These instructions can be as simple as telling a valve to open or close or as complex as controlling the flashing speed, and color of LEDs by connecting it to an input device. Some of these pins are digital outputs, meaning they send either a “HIGH” or “LOW” signal telling a device to be on or off. The pins with a squiggle mark next to their number offer a more complex operation. These pins are able to use pulse width modulation to send an analog signal to an output device ranging between 0 and 5 volts. One thing to keep in mind when using these analog output pins is that the variable storage within the Arduino code corresponds to an 8-bit number. Thus, the Arduino recognizes an input of a number ranging from 0 to 255 to send to the analog output device. For example, if it is desired to send a 2.5-volt signal to an output device, the correct corresponding number to incorporate into the Arduino code for the output device is solved for with the ratio shown below.

\[
\frac{2.5}{5} = \frac{x}{255} \rightarrow x = 128
\]

The Arduino also contains a set of input pins labeled A0-A5 which have the ability to read a variable voltage from an input device. Using the Arduino analog read command allows for the input voltage to be read and stored into an 8-bit variable ranging again from 0 to 255. This is extremely important for creating electromechanical circuits to function without constant input from the user. Since the musical fountain will need to function autonomously, the use of these input pins to gather data from various input devices will be critical. This will give the fountain a mind of its own to function within the user defined parameters. These user defined parameters could include a series of conditional “if” statements and for/while loops, or a combination of the two. By understanding the language of Arduino and how the coding mechanics work, analog functions can be used to obtain information from input devices and control a variable output such as the brightness or color of an LED (Alexaki and Dalmaris 2020).

*Controlling LEDs*

One of the key skills that was acquired from these video tutorials by McWhorter is the extensive knowledge associated with constructing circuits, and code for LED lights. LEDs are the most common output device and are a fantastic way to begin because of the immediate feedback that is received. If the circuit and code are both correct, the light will turn on letting you know that the supplied code worked. Although LEDs are a basic electrical device, they can be manipulated to have a wide variety of functions such as dimming, blinking, and color changes. The use of RGB LEDs allows for the creation of any color within the visible light spectrum. Each RGB LED has three analog signal input wires: one for the intensity of red light, another for the intensity of green light and a third for the intensity of blue light. Each input wire must be connected to its own analog output pin on the Arduino board. By manipulating the analog input of the intensity of each color, any color imaginable can be created. Since our fountain prototype will play the WMU fight song, gold will be a crucial color to incorporate. Gold is created by sending an analog input of 255 to the red wire, 210 to the green wire, and 0 to the blue wire. Note that much trial and error can be conducted to fine tune the color scheme.
Since a single or even a few LEDs will not be enough to create a light show, more research was done to explore the possibilities of controlling multiple LEDs. In Arduino tutorials 41-47, McWhorter explains how to use a 74HC595 serial to parallel shift register. To control 8 LEDs at once while only connecting to three of the Arduino output pins. The first pin is known as the latch pin, this pin must be turned on before sending data and turned off after sending data. The second pin is the data pin and will send the signal to the serial to parallel shift register to communicate the information to the LED array. The final pin connected to the Arduino is the clock pin which is necessary for determining the rate of data transfer. A sample code showing how to operate the 74HC595 with an 8-bit LED array is shown below (McWhorter 2019).

```c
digitalWrite(latchPin, LOW);
shiftOut(dataPin, clockPin, LSBFIRST, 11110000);
digitalWrite(latchPin, HIGH);
```

With this method, the 8 LEDs correspond to an 8-bit binary number. Thus, the 8 lights can be controlled simply by altering an 8-bit variable. For example, the number 11110000 will turn the first four LEDs on while keeping the other four LEDs off. Binary mathematics and other Arduino functions can be used to generate different patterns. Many different lighting patterns were tested and verified as possible light displays. However, since the use of a serial to parallel shift register requires a complex circuit setup and can only use 8 constant color LEDs per register, this lighting concept was abandoned and the search for a better method was continued.

It was discovered that RGB LED strip lights are compatible with Arduino microcontrollers. With the use of an externally downloaded Arduino library named <FastLED.h>, complex lighting patterns can be generated for an entire LED strip using just a single Arduino output pin! This is extremely powerful considering just a single Arduino can be used to theoretically control an infinite number of LEDs at once. The raw potential this light control method offers makes it the clear favorite for generating an eye-catching light show for the musical fountain. A factor to consider is the Arduino itself does not supply enough power for an LED strip to function, thus, an external power supply will need to be connected to the LED strip to achieve maximum brightness. The circuit setup for this electrical system is displayed in appendix B.

A WS2812B LED strip was selected due to its Arduino compatibility and positive customer reviews. In order to get the LED strip to work the Arduino output pin and total number of LEDs must first be defined in the code. The WS2812B LED strip must also be named and set up properly. A sample code showing how to set up the LED strip with the FastLED.h library is shown below.

```c
#include <FastLED.h>
#define LED_PIN 7
#define NUM_LEDS 150
CRGB leds[NUM_LEDS];

void setup() {
  FastLED.addLeds< WS2812, LED_PIN, GRB >(leds, NUM_LEDS);
}
```
In this setup the control pin is defined as LED_PIN7, the total number of LEDs is 150 and the WS2812B is named “leds.” Within the void loop section of the code, a function that will set all the LEDs to a single solid color is employed with the fill_solid command. Within this command, the WS2812B name must be specified as well as the total number of LEDs. The third variable within the fill_solid command tells the Arduino what color is desired. The first number is an analog input for the intensity of red light, the second number specifies the intensity of green light, and the third number is the intensity of blue light. The FastLED.show command executed the code and turns the LED strip on and the FastLED.clear command clears the previous LED data sent to the LED strip. Many other functions within the FastLED.h library are available for use and were incorporated into the light show of the musical fountain. GetHub.com is an educational platform where others can share their code for others to use and learn from. These codes were analyzed to learn about the functionality and manipulated to suit the application for the musical fountain light show. These codes containing the various FastLED.h functions used for the project are specified in appendix D.

Controlling Servo Motors
Servo motors are the king of controlling angular outputs to a high degree of accuracy. Code can be used to specify an angle for the servo output shaft. By connecting the servo to a nozzle, the angle at which the nozzle shoots water can be managed with Arduino code. There are many ways to connect the servo output shaft to the nozzle which are explored in the dynamic water movement section of the product design.

Tutorials 30-33 in Paul McWhorter's Arduino tutorial series provide baseline knowledge on how to use servos for various projects. Like the LED strip, servos require an external library to be downloaded. This library is named <Servo.h> and it contains a set of commands that allow for the Arduino to write various angles to the servo shaft. Writing code to set up the servo is not as complicated as the WS2812B LED strip. The Servo.h library must be included at the top of the code, and the servo must be named, and a servo control pin must be declared. Note that the servo pin should be an analog control pin, or one with a squiggle mark on the number. In addition to this, in the void setup section of the code, the servo must be
attached to its control pin so that the Arduino knows which pin is associated with the desired servo. A sample code for how to set up a servo in Arduino is included below.

```cpp
#include <Servo.h>
Servo servo1;
int servoPin = 11;

void setup() {
    servo1.attach(servoPin);
}
```

After the servo is properly set up, functions within the Servo.h library can be used to control the output angle and speed of rotation of the servo shaft. The main command that was learned from Paul McWhorter’s Arduino tutorial series is the servo.write() command. This command is used in the void loop section of the Arduino code and allows for the servo angle to be controlled. Entering an angle into this command will cause the servo shaft to snap to the specified angle. By incorporating “for” loops into the code, it is possible to achieve a constant speed rotation of the servo shaft. A combination of for and while loops can allow the servo to follow and repeat a particular pattern (McWhorter 2019). This concept is used within the musical fountain to allow for the water streams to move in synchronous to the music. The Arduino codes used for the control of the servos are included in appendix D.

### Hydraulic Lifts

Hydraulic lifts are powerful and efficient tools used for the raising and lowering of various platforms, displays, or whatever needs to be raised and lowered. This utility was used in the final design of the fountain for the centerpiece of the fountain. After extensive research it was concluded that it would be the easiest and most effective way to consistently and reliably raise the centerpiece to the desired height.

A hydraulic lift uses a working fluid, typically oil of some kind, to fill a piston apparatus. This piston then rises due to the increase in pressure forcing it to the desired height. O-rings are used to keep all the fluid from leaking, maintaining the pressure created by the pump. To release the pressure a release valve is opened allowing for the fluid to escape the cylinder and flow back into the tank where the fluid is stored. This will then lower the lift to the desired height or until the valve is closed again and the pump is turned back on. Keeping the chamber watertight is incredibly important to the operation of the lift. If the lift is not sealed, then the fluid will escape to the outside leading to pressure loss which makes the lift not function. Leaking would cause the lift to either not rise in the first place, rise slowly, or cause the lift to lower before the release valve is opened and the pump is shut off (Yell 2019).

The small parts within a hydraulic lift are very important. The O-rings and the valves are crucial to the successful operation of the system. A spreadsheet of standard O-ring sizes from Parker Aerospace was used to determine the ideal groove proportions to fit the specific application. This was important to research in order to make fabrication of the parts easier and cheaper. Using the standards meant that custom parts would not have to be ordered and manufactured, greatly reducing cost as well as saving time as the parts would not have to be manufactured for the unique sizing. The valve feeding water into the lift needs to open and close at the correct times. These valves are typically electronically controlled through
the operator. The operator will tell the device whether it needs to be lifted or lowered and the valves will open or close to allow the flow in or out accordingly.

**Design Requirements**

The musical water fountain was required to be an affordable outdoor fashion piece. It must incorporate lights, dynamic water movement, and music. Many requirements were left largely open-ended. This allowed for much freedom in the design process as multiple ideas were explored for each requirement. To narrow down the appeals and determine which features were most important, a survey was created. This survey was sent out to family, friends, and peers and asked people to rank different aspects of the musical fountain from most important to least important. As a result, price and water movement were deemed to be the most crucial factors. Music is a nice touch, but not as necessary as the other two features. The most important aspects were explored and developed in detail, however, due to time constraints, not every aspect was able to be perfected.

**Product Design**

The musical water fountain went through various design changes throughout the year. It was split into four divisions: the basin, hydraulic lift and centerpiece, nozzles, and lighting. Each division came with its own unique challenge and solution. The basin had to be large enough to comfortably fit three pumps, hoses, and electrical components. A wide and deep basin is ideal for this design parameter. The challenge of the center piece was the design of the hydraulic lift and release system. This enables the centerpiece to rise and lower as needed. For the water movement, the design challenge was the incorporation of servos to control the movement of the nozzle. Programming the system was an obstacle because Arduino microcontrollers are only applicable for 5V devices. The beat of the music drove the movement of the lights and water, meaning a preprogrammed song was the best method of synchronization for this design.

During the design process, there were many iterations, some designs drastically different than others. As the requirements and constraints of the fountain became prevalent, the design was simplified to account for cost effectiveness, efficiency, and feasibility as well. A decision matrix ultimately decided which design would be best to carry out. The weights of each design requirement were established through a survey. The survey was a technical questionnaire that addressed which features were more desirable than others amongst the music, light show, and water movements. Each individual was asked to rank the fountain characteristics one to five with one being the least desirable trait and five being the most desirable. Looking at figure 1, the purple bars represent the amount of people who thought the characteristic was most important. Ultimately the survey provided feedback for which elements of synchronization were most desirable. From the results of the survey, water movement was most important to establish in the fountain design with lights as a close runner up. It was also concluded that the synchronization of all three systems would be best based on survey results. Although the survey revealed which technical requirements were most desired, the cost was the largest factor to consider and emphasized greatly by the customer. The fountain must be different and able to compete in the economic market.
Below in Table 1 are the results of the decision matrix. While alternative 4 scored a much lower total, it had the best musical abilities. It was not efficient or cost effective for its purpose. Meanwhile, alternative 0 and the final product design were in close range for highest total score. The final product design was able to perform a wider range of flexible water movements, present music in a more entertaining fashion, and put on a fitting modern look. This won the overall score in the decision matrix.

### Table 1: Decision Matrix

<table>
<thead>
<tr>
<th>Design Alternatives</th>
<th>Music</th>
<th>Lights</th>
<th>Water Movement</th>
<th>Cost Effective</th>
<th>Visually Appealing</th>
<th>Efficiency</th>
<th>Total Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Product Design</td>
<td>8</td>
<td>6</td>
<td>9</td>
<td>8</td>
<td>9</td>
<td>7</td>
<td>7.92</td>
</tr>
<tr>
<td>Alternative 0</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>7.57</td>
</tr>
<tr>
<td>Alternative 1</td>
<td>7</td>
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<td>8</td>
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<td>5</td>
<td>6</td>
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<tr>
<td>Alternative 2</td>
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<td>1</td>
<td>4</td>
<td>7</td>
<td>8</td>
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</tr>
<tr>
<td>Alternative 3</td>
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<td>9</td>
<td>6</td>
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<tr>
<td>Alternative 4</td>
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<td>9</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>5.1</td>
</tr>
</tbody>
</table>

*where 1 is rated low for worst design and 10 is high for best design

Design Alternatives

The following section presents each iteration pictorially and describes them briefly, leading up to the decision of the final design. Each design idea was strictly preliminary and thus were not explored in great depth. If one of these preliminary ideas happened to be chosen, many design changes would need to be made to increase effectiveness and efficiency.
Beginning with alternative 4, as shown in Figure 1, it scored a 10 in the music category and led strong in the categories of light and water movements. Yet, it lacked an effective cost, visual appeal, and overall efficiency. The main attraction of this design was the shower heads raining water down and rotating about the center. Heavy duty power pumps would need to be incorporated to pump the water to the water tank located on top. The idea is that the gravitational potential energy and static pressure energy within the tank would allow the water to exit the showerhead nozzles at a high velocity. As seen in the sketch, a turbine could also be incorporated into the bottom of the basin to harvest the flow energy from the water. The water will be traveling at a high speed; thus, a turbine could redistribute this energy to another component of the fountain such as the lights.

Although this design would be advantageous for a great light display and music projection, it also has a few downsides. This design would be top heavy, and a strong structural support system would need to be incorporated to support the weight of the shower head and water tank. This support system, if designed well could give an aesthetic look to the fountain, however it could also obstruct the view of the water movement. Another challenge with this design is the complexity of spinning shower heads. Many relative velocity, relative acceleration, and moment of inertia calculations would need to be done to figure out the exit velocities from the spinning shower head and torque required from the shower head drive shaft. This design would be better suited for an indoor fountain since wind, snow, hail, and other weather conditions could be harmful to the fountain structure.
The design of alternative 3, shown above in Figure 2, consists of a centralized pillar surrounded by a projector. The pillar would produce a cylindrical waterfall that would ideally experience laminar flow. This cylindrical waterfall would be used as a screen for a projector. It would display moving images into the sheet-like waterfall. The projector would be mounted to a circular track on the outside of the basin and be free to move around the track and project onto the waterfall. Advanced knowledge of motion and control would be needed to control this moving projector.

The top of the pillar on design alternative 3 would have a rotating disc with a few nozzles and a bright RGB LED attached. At dramatic moments, water would be shot out of the top of the pillar with a high velocity. The water stream would be paired with a bright light to illuminate the powerful water surge. This feature would be effective for intense bass drops and dramatic finishes to songs. Design alternative 3 would produce a great light display however the water movements would be limited. The nozzles at the top of the pillar, fixed to the rotating disc, would be the only dynamic water movements for this design. Since eye catching water movement is an important feature to be considered in the design, alternative 3 did not reach a high enough score in the decision matrix.
Design alternative 2 was an original idea that diverted from the scope of the project requirements. The two different views of this idea are shown in Figure 3. This idea was formulated with the intent of creating an innovative feature to be installed in the pool of a typical homeowner or a community pool. Consequently, this design limits the target consumers strictly to pool owners. The concept is similar to design alternative 3 as a laminar flow waterfall will be used as a screen to project onto. Groups of people could gather in the pool area to watch movies projected onto the waterfall screen. In addition to this, individuals could go under the waterfall and hang out in a small area. Jets, music, and lights could be added to this area to make a fun cave for people to spend time in. While this idea has a lot of potential to bring families together to watch projected outdoor movies, it does not follow the scope of the project.
Figure 5: Design alternative 1 displays a head of nozzles in a line format that would create new dynamic movements.

Figure 4 above shows a preliminary sketch of the first musical fountain idea intended for development. The key feature of this fountain is a group of three vertically oriented pipes on the outside edge of the basin. Six nozzles as well as RGB LED’s will be attached to each pipe. Mounting LED lights onto each pillar would allow for the water streams to be illuminated. Creating illuminated streams of water is a concept that would significantly increase the visual appeal of the fountain as it would be easier to see the water movements. The plan was to equip each nozzle with a control mechanism to move each stream of water up and down or left and right. A toy helicopter was purchased to study the servo-motor mechanism used to control the main rotor shaft. Incorporating this mechanism to each nozzle would allow for a wide variety of dynamic water movements. The drawback from this idea is the overall cost to provide all 18 nozzles with this technology. It would also be difficult to engineer an effective and waterproof electrical circuit to reach each servomotor mechanism as well as the LED lights on the three pipes. Another factor that would need to be considered is the flow energy that is lost with the increasing height of the nozzle. The nozzles at the top of the pipes will have less flow energy available since it requires more work to pump water to a greater height. It would be ideal for each nozzle to have identical flows, thus, problem solving, research and testing would need to be done to achieve this.

In addition, a rotating centerpiece with multiple nozzles attached would be incorporated to increase water movement diversity. An effective centerpiece is a key design feature that was added to
nearly all of the design alternatives. It will draw attention to the center of the fountain and help create dramatic effects during the musical fountain performance.

Fountain alternative 1 is an effective fountain design that yielded a high score in the decision matrix. This is due to its all-around ability to produce dynamic water movements and an eye-catching light show while being cost-effective. However, it was agreed that the three pipes attached to the outside of the basin are not necessarily visually appealing. For this reason, along with the feasibility of reaching each light/nozzle with an electrical system, this idea was rejected.

![Figure 6](image)

*Figure 6: Design Alternative 0 displays a disco-like water nozzle ball as the centerpiece of the fountain.*

Pictured above in Figure 5 is the design for alternative 0. It is similar to alternative 1, but without vertical pipes. An attention-grabbing centerpiece will be paired with a circular array of 18 nozzles inside the basin. With this nozzle orientation, radial movement of water toward/away from the centerpiece will be heavily utilized. Limiting the circular array of the nozzles to a single degree of freedom will simplify the design and decrease the overall cost of the product. To pump an even amount of water to each nozzle, the main pump will feed water into a circular PVC pipe with a diameter equal to the diameter of the circular array of nozzles. The PVC pipe will then have 18 exits that feed into each nozzle. By lowering the nozzles to the level of the basin, it will increase the exit velocity of each nozzle as well as draw more attention to the centerpiece.

The centerpiece of design alternative 0, is comprised of a mechanical lifting mechanism with a ball nozzle attached. The ball nozzle is a brass sphere with multiple holes. Thus, when water is pumped up through the lifting mechanism, multiple streams of water will exit through the ball nozzle. This
The centerpiece has much potential to be an eye-catching feature, thus, many ideas were brainstormed to increase the visual effectiveness of the centerpiece. Implementing a tool to rotate the ball nozzle and adding a waterproof RGB LED inside the ball nozzle to illuminate the exiting streams would increase the score of this design alternative.

Design Selection

The final iteration of the fountain design holds a simplistic approach. The design is resembled in Figure 6 by a basic illustration completed using SolidWorks. Not pictured are the lights and tiling around the outside of the basin. This design is within the project scope and delivers an appealing display. Most importantly, it is the most feasible in its field of practice. It was chosen as the product design because of its ability to encompass all of the design requirements while remaining cost effective. The product design includes multiple subassemblies and systems which are discussed in greater detail in the following sections. Each custom part is professionally dimensioned on drawing sheets in Appendix A.

Fountain Basin

To begin with the product design, a large and important feature is the basin of the fountain. While the basin provides much of the visual appeal, it was designed for practicality. The purpose of the basin is to act as a large bowl for water and component storage. The fountain is reusing its water by circulating it through the system and returning it to the basin. It is efficient and cost effective to recycle the water this way. To accommodate the large volume of water and various components to be stored within the fountain, a deep, wide cylinder was chosen for the shape of it. This 2-meter (6 foot) wide outside diameter basin is just shy of standing 1 meter (3 feet) tall. It also has a half meter (6 inch) ledge for children and adults to sit or lean against when they are outside enjoying the scenery and company of one another. The
inside diameter of the fountain is 1.67 meters (5 feet) wide and 0.83 meters (2.5 feet) deep. This was deemed large enough to hold at least 1.13 cubic meters (40 cubic feet) of water and fit the large components including but not limited to the pumps and hydraulic lift for the center piece.

For the fountain, the concrete basin is finished with a smooth surface. Since the look of concrete is not attractive, it was decided to tile the exterior surfaces. Since the tiles are adhered to the outside surface of the fountain, the tile adhesive and grout used to attach the tiles should not affect the material integrity of the concrete (source year). Additionally, on the top and bottom borders of the basin, there will be light LED strips to illuminate the basin. These two components are not represented in the CAD model due to shape and detail complexity. The lights are reviewed in further sections.

While the shape is standard, it is customized to hold a conical plate. To ensure this plate is stable and withstands the pressure of water coming down on it and any additional weather effects, the plate will be mounted to the basin. The basin has a designed inside ledge which the plate will bolt to. This is shown in Figure 7. Since the chosen screw size is relatively small to the overall size of the basin, the ledge has four evenly spaced ¼-20 tapped holes in it. This ensures a secure mount of the plate to the basin.

![Figure 8: Inside ledge of Basin](image)

The design and material choice of the basin make it a well-built structure to support all internal systems. In the Product Analysis section, force evaluations and safety factors are discussed in further detail to reinforce the validity of this design.

Two more parts of the basin are the conical plate and the inside component ledge. The conical plate is a multifunctional part and is shown below in Figure 8. Its first purpose is to serve as a cover to hide all the components within the basin. Secondly, the conical plate is used to funnel a majority of the water back into the fountain. In the plate, there are 18 slotted cuts. These allow the water to shoot up from the individual nozzles.
To hold the individual nozzles and their respective servo assembly, an inside component ledge was made. The ledge will act as a floating shelf for the components and necessary wiring without immersing these parts in water. For correct placement, through holes are made in the ledge for the tubing connected to each nozzle head and pilot holes for the servo assembly placements. There will also be small holes drilled in this ledge for the servo control wires to feed to the electrical box. The ledge is made of aluminum alloy 1060 and is shown below in Figure 9. To hold the ledge up, four steel corner brackets are mounted to the inside wall of the basin. The inside wall of the basin is stamped with these bracket placements for ease of installation and is resembled in Figure 10.
Figure 10: Inside component ledge for individual nozzle parts

Figure 11: Ledge mounted to inside wall of the basin
Underneath the component ledge, a PVC pipe structure is bolted to the bottom face. The structure was built for fluid system one and is detailed in the Fluid Systems section. The entire structure uses PVC piping and requires little fabrication. The large diameter of the top ring is a special feature since standard rings of PVC do not come in diameters that large. It is also drilled with 18 holes and has custom barbed hose connections for the latex tubing. The parts holding up the ring require no special services as those are standard pieces. The Figure below is a simplified representation of the PVC pipe structure.

![Figure 12: PVC Pipe Structure](image)

**Centerpiece**

The centerpiece includes a spinning nozzle head with a waterproof speaker placed on top. This speaker has a bass drum that will bounce water with the beat of the song. The centerpiece is mounted to a hydraulic lift which will raise and lower the apparatus. Due to its many parts, each aspect of the centerpiece is described separately.

**Centralized Water Display**

The centerpiece water nozzle is a 4-arm nozzle head. It has a large body with four 90-degree arms branching off it, as shown in Figure (11). The arms are designed to be set at an angle which creates a helix. The helix is formed by the rotation of the arms. By angling the arms in the same direction, a centripetal force is created and generates an angular rotation about its center point. The speed of the rotation is dependent on the set angle of the arms. Since the fountain is a display item, the arms were not desired to spin very fast, thus they are angled at 85° from horizontal. Likewise, the angle was set high to prevent the nozzles from aiming outside of the basin.

The 4-arm nozzle was provided from an outside source and is available by multiple suppliers. It is made of brass material which has a beautiful finish and is commonly used for water designs. As a supplied part, it is easy to assemble with the entire fountain.
Music is a crucial part of the fountain and one of the main forms of attraction. A loud bass boosted speaker is placed in the center of the fountain. The speaker has a vibrating subwoofer on the top of it which will fill with water and ideally make the water jump to the beat of the music. This innovative approach captures the crowd immediately because it brings more to life than just sound. When there is any bass in the song the subwoofer will move or vibrate. Bass is typically measured in frequency. A high frequency bass greater than or equal to 200 Hertz makes the subwoofer vibrate fast and causes the water to ripple with the amplitude. Similarly, a low frequency bass will vibrate the subwoofer slowly and not move the water significantly. To capture the perfect water-jump scene, the song should have a bass frequency in the middle of the two extremes. Concluded from speaker bass tests, between 50 Hertz and 100 Hertz is the amount of bass frequency a song should have to create a sporadic show.

A challenge with the speaker in the center of the fountain was its ability to move with the centralized water piece. The speaker was designed to sit in the center, which forces the placement on top of the rotating nozzles. To prevent the speaker from rotating with the nozzles, a shaft is threaded into the top of the nozzle body. From outsourced parts, a square head shaft was selected to thread into the top of the nozzle body. Then a small custom shaft was designed to press-fit onto the square bit and hold the ball bearing press-fit to it. The ball bearing is used to hold the speaker as stationary as possible while it sits on the speaker plate. Due to friction and other resistances within the system, the speaker is going to rotate to a small degree. An in-depth numerical analysis for the shaft is detailed in the Product Analysis section for its design stress and safety factor.
The speaker will be held on a custom designed plate. The bottom of the plate will attach to the outside diameter of the ball bearing. To ensure the speaker spins as minimally as possible, the shaft was designed to not contact the plate, only the ball bearing. The speaker plate design has a small wall on it with four evenly spaced slots on it. These slots act as a drain for any buildup of water on the plate. Although the speaker is completely waterproof, there is no need to water load the plate. It will be machined from aluminum alloy 1060 to ensure it is strong and durable. Since the plate will be visible to the consumer, aluminum was chosen for its appealing look and resistance to corrosion.

**Figure 14: Half section view for speaker Assembly**

*Hydraulic Lift*

The original design of the lift shown below in figure 14, involved a siphon to allow the water to escape once the lift had reached its maximum height. However, concerns about this siphon letting water escape too early began to erode confidence in it. The design was changed to remove the siphon and incorporate a shut off valve. When the fountain is on and performing, the valve will remain closed so that the pressurizing water cannot escape, and the lift remains in the extended position. When the fountain is off, the valve will open, thus allowing water to exit the cylinder and the piston to lower to the compressed position.

Looking at figure 14 showing the original lift design, the protrusion within the cylinder is the straw siphon. The siphon was in place to remove difficulties of electrical components to control the raising and lowering of the lift. The ability of the siphon to accomplish this in the desired manner was brought into question shortly before the part was set to be made. Unfortunately, Western Michigan's large
format 3D printer was not operatable during the design and testing phase of the project. The inability to prove the concept works led to a growing lack of confidence in the design and a decision to revise the part.

![Image of a 3D printed object]

Figure 15: Half section view for the original cylinder design. Not pictured: piston, mechanical stop, or stilts

The final design is shown in Figure 15. This design removes the siphon in favor of buoyancy force and a shutoff valve. The piston is hollowed out to create a lightweight object in which the system could use buoyancy force to lift the centerpiece. A shutoff valve will control when the water is being sent to the cylinder to raise the lift and when the water is being sent to the nozzle centerpiece. Once the power to the pump is shut off, the water in the cylinder will escape back into the basin as the lift lowers back into its resting position. Ultimately, the lift has four custom parts to its assembly. These parts are the cylinder, piston, mechanical stop, and stilts. The cylinder and piston are the essential parts, but the system would fail if there were not a mechanical stop on it. Theoretically, the piston could rise as high as the water pressure would allow it. To prevent the piston from rising too high and escaping the cylinder, a bumper was added to the top inside edge of the cylinder to keep the piston from exceeding the maximum height. Four stilts will be used to support the lifting mechanism. These stilts will be press fit into the bottom of the cylinder on one end and press fit into support chucks. The support chucks will be bolted to the bottom of the basin to stabilize the lift and ensure a completely vertical lifting motion. Adding stilts beneath the lifting mechanism provides room for the tubes from fluid systems 2 and 3 to attach to their corresponding pumps. Each part is made of Aluminum 1060 which provided enough strength, durability, and lifetime. More details of the part integrities are mentioned in the Product Analysis.
Ultimately, the lift has five custom parts to its assembly. These parts are the cylinder, piston, mechanical stop, stilts, and support chucks. The cylinder and piston are the essential parts, but the system would fail if there were not a mechanical stop on it. Theoretically, the piston could rise as high as the water pressure would allow it. To restrict the height it rises to, the mechanical stop acts as a stopper. Holding the lift is the stilts which are crucial for the assembly and tube connections to the lift. The stilts allow piping to extend out the bottom of the base and connect to the pump below it without compressing any tubes. To ensure the stilts are secure and do not tip over, the support chucks were designed. Each one is bolted to the basin floor. Each part is made of Aluminum 1060 which provided enough strength, durability, and lifetime. More details of the part integrities are mentioned in the Product Analysis.

Dynamic Water Display
To achieve dynamic and controllable water movement it was necessary to incorporate an electromechanical system that would allow for each nozzle within the fountain to rotate with either one or two degrees of freedom. Due to time and resources, a decision was made about the direction of movement for the nozzles. Ideally, nozzle motions could move in both the x-plane and y-plane, however, in this case two servos would be required for each nozzle. This would generate a variety of water movements, while increasing its complexity and cost. For the final design, nozzles were chosen to move with a single degree of freedom. This will be more beneficial since it will lower the final cost of the fountain. After much
research and discussion, it was determined that a high torque servo paired with an Arduino microcontroller would be the most effective way to control the nozzle movement.

The first iteration of the nozzle/servo mechanism design was comprised of two guide plates with long skinny slots that would restrict the nozzle rotational movement to one direction. The first plate would be fixed to the fountain structure with the slot pointing toward the centerpiece. The nozzle would fit inside the slot of the first plate to only allow rotational motion in the radial direction. Plate number two would be perpendicular to plate number one with the nozzle fitting inside its slot as well. The other side of the second plate would be fixed to the servo output shaft. This will allow for the servo to rotate the second plate clockwise or counterclockwise. The nozzle would be pushed to rotate by plate two and guided radially by plate one. After some time, the flaws of this design began to reveal themselves. This design would require a fair amount of servo torque to rotate the plate, nozzle and overcome friction. Also, since a flexible rubber tube is being used to feed water to the nozzle, the system would not be structurally supported as this mechanism does not provide any support to the nozzle to fix it in place. Because of these issues, the group decided to redesign and improve the nozzle/servo mechanism.

Design two would allow for the same desired rotational movement while decreasing the necessary servo torque and increasing the structural support to the nozzle itself. Since the nozzle will have a reaction force due to the mass flow rate of water exiting the nozzle, it is important that the nozzle/servo mechanism is sturdy enough to resist this force and hold the nozzle in place. The improved design, shown in Figure 16 uses a rotating shaft which is composed of smaller parts to be bolted together. One side of the shaft will be fixed to the servo output shaft and the other side to a ball bearing allowing rotational motion. The nozzle will be fixed to this shaft with one attachment point near the top of the nozzle and the other attachment point near the bottom. This will fix the nozzle to the mechanism allowing the nozzle and water stream to rotate when the servo drives the shaft. Each part of the design was modeled in solid works and 3D printed with polylactic acid (PLA) filament for the prototype assembly. The actual fountain model will use aluminum 1060 because of its low weight, low cost and machinability. A stress calculation was done to determine the minimum required shaft diameter, shown in more detail in Appendix C.
Fluid Systems

The musical fountain contains three different fluid systems that function independently of each other. It was first intended that a larger pump be used to power all fluid systems. However, due to limited resources to run proper testing, it was deemed impossible to estimate the proportion of the initial flow rate that was being split to each of the fluid systems. Because of this, pressure losses, stagnation pressures, exit velocities, and maximum water height were not able to be calculated. Thus, it was decided that each fluid system will be powered by its own pump; making it much simpler to estimate flow rates and pressures at various points within the pipes and tubes. It also allows for each system to be controlled individually and eliminate interference effects.

The first fluid system supplies water to the outside nozzles to be controlled by the servo motors. It is powered by a pump that consumes 220 watts of power, supplies a flow rate of 4500 gallons per hour and an initial gage pressure of 55,000 pascals. PVC pipe will be attached to this pump exit and a T-joint is used to split the flow in half. Each supply pipe containing half the initial flow rate will stretch outwards to the basin's edge and up to a circular PVC pipe. This circular PVC pipe will be attached beneath the ledge of which the servo assemblies are mounted on. The water flow will enter the bottom of this circular PVC pipe from opposite ends. The top of the circular PVC pipe contains 18 different exits which will feed to each of the 18 nozzles. Note that the circular pipe is capped on both ends which will eliminate interference between the two supply pipes and drive the fluid out of the nozzles. Thus, each supply pipe will deliver flow to 9 nozzles. Since the nozzles will be experiencing rotational motion, flexible latex tubes will be used to connect each exit of the circular PVC pipe to the individual nozzles. For illustration purposes, the fluid system that powers the 18 outside nozzles is shown in the sketch below.
The second fluid system of the musical fountain supplies water to the centerpiece nozzles. Since the centerpiece only contains four nozzles, a smaller pump is used to obtain exit velocities similar to that of the outside nozzles from the first fluid system. The centerpiece is attached to the piston of the lifting mechanism; which is hollow, thus, allowing water to pass through the piston and to the centerpiece nozzles. A solid pipe/tube cannot be used to deliver water from the pump to the hollow piston since it will restrict the lifting motion. To combat this issue, a flexible latex tube will be incorporated into the design. This tube will have enough slack to provide the centerpiece with flow regardless of the mechanical lift being fully extended or fully compressed. When the lift is compressed, the latex tube will coil up and when the lift is extended, the latex tube will straighten. Water will travel from the pump, through a clear vinyl tube which attaches to a flow adapter on the bottom of the lifting mechanism cylinder. The flow will then transition to the latex tube where it contains enough slack to attach to the flow adapter on base of the piston whether it is raised or lowered. The water then passes through the hollow aluminum piston and into the centerpiece where it branches off to the four nozzles. This fluid system is illustrated in the sketch shown below.
The third fluid system is the hydraulic lift that raises and lowers the centerpiece display. This system houses the tubing for the centerpiece nozzles and is displayed in Figure 19. The hydraulic lift will be powered by a third pump separate from the other two so that interference effects from fluid system 2 will be eliminated. This will allow the lifting mechanism to function independently from the centerpiece nozzles. While the pump is operating, water will flow into the chamber forcing the piston carrying the centerpiece to raise a total of 10 inches. Once the centerpiece has reached its maximum height, its motion is halted by the mechanical stop. O-rings were applied to the outside of the piston head to prevent
pressure losses due to leaking fluid within the cylinder chamber. When the lift needs to go back down the pump will be shut off and a release valve will be opened letting the water escape back into the basin.

![Image: Fluid System 3 for the Hydraulic Lift](image)

*Figure 20: Fluid System 3 for the Hydraulic Lift*

Material selection is very important to this system as it needs to be able to withstand the elevated pressures needed to raise the piston to the desired height. A lightweight material would also be beneficial to decrease the overall weight of the centerpiece. The heavier the centerpiece, the more power output is needed from the pump to raise the centerpiece to the desired height. This material also needs to be able to withstand weather conditions in a multitude of climates. Corrosion resistance is very important to this system as the material is directly exposed to the water unlike most of the other systems that are protected.
by tubing. Considering all of these factors, aluminum 1060 is the selected material. It is cheap, lightweight, corrosion resistant and smooth, making it a good fit for the application.

Light Display

The purpose of the product is to capture people's attention and draw them in to watch the musical water fountain as it is operating. A vibrant and colorful light display is the cherry on top for an eye-catching water fountain show. The lights will be programmed to display a light show that is synchronized with the music as well as the water movement. There were two ideas considered on how to use LEDs to create a light show: Individual LEDs or an LED light strip.

Individual LEDs offer a larger range of applications since each light can be controlled separately. With the use of a parallel shift register, 8 LED lights can be controlled with just 3 pins. The 8 LEDs act like a binary 8-bit number and can be manipulated with binary mathematics. A variation of flashing, shifting or color pattern can be accomplished with appropriate coding. The main drawback of using individual LEDs is that an Arduino microcontroller has a set number of pins that can be used to control lights. The Arduino Uno has 13 pins that can be used at once. Assuming all the pins are used with parallel shift registers, a total of 32 lights could be controlled with a single Arduino. This is not a sufficient number of lights to captivate an audience, thus other options were explored.

Research was done for LED strips, and it was found that the WS2812B LED strip is Arduino compatible. An Arduino library called FastLED.h can be used with the WS2812B light strip. This library offers a wide variety of applications including flashing, brightness control, color control and even individual LED control. With this software, hundreds of LEDs can be managed with only a single Arduino pin. This is a huge advancement as a single Arduino can be used to control an entire light show with hundreds of lights. Additionally, the light strip is waterproof and could theoretically be placed anywhere in the fountain. It could go on the centerpiece, around the outside, or inside the basin. Even though the light strip is waterproof, the connecting wires and associated electrical circuit are not. It will be ensured that no wires are exposed that could potentially come into contact with the water, or an individual. Electrical safety will be prioritized to avoid shock and harm to any person. Another advantage is the LED strip can be cut at any length to fit any application. Thus, an LED strip with maximum length identical to the nominal lengths found within the fountains different components can be cut and mounted to different spots of interest. Due to these multiple advantages and fewer disadvantages, the WS2812B light strip was chosen to generate the light show for the musical fountain.

For ease, the light strip is applied to any surface using the adhesive on the back. The WS2812B light strip with light spacing, 9.15 lights/foot will be mounted on the top of the basin ledge. One on the inside of the basin and one on the outside of the basin. These LED strips will form two circles which will be separate from each other but used together to create contrasting effects. One of the LED circles can be blue while the other is green, or one can be shifting counterclockwise while the other is shifting clockwise. Producing different light effects at the same time will be important for drawing attention. An additional LED strip will also be added to the outside of the basin near the ground. This will illuminate the ground around the basin to diversify the light display. Different LED strips can be controlled with the same Arduino by defining each LED strip with a unique name and wiring them to different output pins. The code used to control the lights in this project is included in Appendix D.

Electrical Components

An electrical box will be installed to keep all the electronics from getting wet. This electrical box can be accessed from the outside of the basin but should only be used by those who have electrical experience and knowledge of safe electrical protocols. Some of the circuits associated with the musical
fountain can be dangerous without proper safety equipment and training. There are two main electrical circuits that need to be constructed for the musical fountain to work properly. The first being the circuit controlling and giving power to the servo. The second circuit will be responsible for providing each LED strip with a control signal and a total of 98 watts of power. Each output device contains three main wires that need to be properly addressed. The hot wire, which supplies the voltage and current to the device, the ground wire which completes the circuit and allows excess electrons a place to go, and the control wire which is hooked up to the Arduino output pins. Circuits for each of the output devices were constructed to support the dynamic water movements and vibrant light show displayed by the fountain.

To power the servo circuit, a 7.4-volt, 2500 mA-h lithium battery was selected. This battery has a hot wire and ground wire which will be hooked up to a voltage node and ground node. The Arduino microcontroller has a 5-volt pin and a ground pin which also need to be connected to these nodes for the Arduino to function. Without connecting these Arduino pins to the hot and ground node, the circuit for the Arduino will be an open circuit and the control signal will not be supplied to the servo. The hot wire and ground wire of the servo will be connected to the corresponding nodes as well. In total there will be three wires connected to the voltage node and three wires connected to the ground node. One from the lithium battery, one from the Arduino and one from the servo. Connecting the hot wires and ground wires from each device to a common node will result in maximum circuit efficiency and ensure that the Arduino microcontroller does not overheat due to high internal currents. A 1000 microfarad capacitor will be placed between the voltage and ground node to ensure smooth voltage and current outputs. In addition to this, pin 7 of the Arduino connects to the control wire of the servo with a 330-ohm current limiting resistor wired in series. This resistor limits the output current of the Arduino which serves as protection, preventing the microcontroller from outputting more current than it is able to handle. Perhaps the most important part of the electrical design is ensuring that the circuit is waterproof. Water meeting the electronics would damage the circuit and pose a fire hazard. Thus, a waterproof box located on the outside of the fountain's basin will be used to encapsulate the electronics. In addition, a custom designed part will be placed over top the servo, ensuring the input wires to the servo do not come into contact with any water. A schematic of the circuit designed to control and power the servo/nozzle mechanism is shown in Figure 20 below.
The circuit setup for the LED light strip is very similar to that of the servo. However, since the lights require significantly more power for operation, a voltage step down, current step-up AC to DC transformer will be used as a power source. This transformer will provide 5 volts and a total of 19.5 amps to successfully power all three of the LED light strips on the fountain. The current required to ensure maximum LED output was calculated in the electrical calculation section of this paper. Two nodes will be incorporated into the circuit design. A voltage node which will attach the hot wire from the power source, the 5-volt pin of the Arduino and the hot wire of each LED strip. The ground node will attach the ground wire from the power source, the ground pin of the Arduino and the ground wire of the LED strip. Again a 1000 microfarad capacitor will be placed between the nodes to smooth the DC voltage signal. Pin 9, 10, and 11 of the Arduino will serve as the control pins for the LED strips. Thus, each pin must be wired to its corresponding LED strip input control wire. Note that each control wire must pass through a 330-ohm current limiting resistor in order to protect the Arduino from outputting more than its allowable current. The circuit schematic for the LED strip is shown in Figure 21 below.
Fabrication & Assembly

The basin of the fountain is an out of house service. It is manufactured by a certified company which has the capabilities to replicate the desired output. During this process, a mold must be created of the basin's overall shape. Then, concrete is poured into the mold. While it cures, it is best practice to vibrate the mold filled with concrete on a vibration table. This eliminates air bubbles from being trapped inside the concrete. Once the concrete basin is finished, the necessary holes are tapped or cut out. The sourced part will be finished with a rough surface for tiling.

Likewise, all custom parts for the speaker, servomotor, and hydraulic lift assemblies will be sent out for machining. Once the parts are machined, they are ready for installation. The step-by-step procedure listed below is not a complete assembly plan with intricately detailed instructions, but rather a guided assembly format that should be followed for a consistent final product.

Preliminary Assemblies:

A certified electrician is required for the safety of persons during build. A landscaper is advised for the placement in the yard.

1. Choose a location for the fountain. This space must be large enough and located in range of the power grid. The electrical box will draw power from extension cords that will be put underground and connected to the power grid of the residential home.
2. Dig out a trench from the edge of the fountain perimeter spot to the power grid connection by the outside of the home. Allow at least a 1.25 in diameter PVC pipe to fit inside this trench. The PVC pipe encases all power extension cords.

3. Create a concrete platform just large enough to fit the entire diameter of the basin (about 6 feet wide). It should be completely level with respect to the ground. A landscaper is advised for this step.

4. Place the concrete basin onto the platform.

**Electrical Box**

5. Set the waterproof electrical box on the ground next to the outside of the basin. This box is equipped with a high voltage node and ground node to be placed in a terminal block mounted to a din rail. This box also encompasses a transformer, two Arduino microcontrollers, and the corresponding control circuit elements.

**Servomotor, Nozzles, and Ledge Assembly**

6. Install the component ledge to the inside wall of the basin with 6 steel L-brackets and 4 bolts per bracket.

7. Attach all latex tubes to the circular PVC pipe structure for fluid system 1.

8. Align the 18 holes in the PVC pipe structure to the 18 holes of the component ledge and feed all 18 latex tubes through the holes before fixing the circular PVC to the servo ledge.

9. Attach the PVC pipe structure with 6 U-bolts to the ledge.

10. Line up the two longer vertical PVC pipes parallel and about 55” apart. Then layout the two shorter straight PVC pipes perpendicular to the bottom end of the vertical pipes. A 90 elbow is used to connect these parts on both sides of the frame. There will be a gap between the horizontal pieces.

11. Use the T joint to connect the horizontal pieces in the middle of the frame to resemble one long horizontal pipe. The unconnected end is pointed to the ground. This end will be connected to the pump. Set aside until further direction.

12. Find all 18 servo assemblies. Connect the latex tube (from the circular PVC pipe structure that is pulled up through the component ledge) to the barbed end of the nozzle assembly within the servo assembly.

13. Now bolt down the servo assemblies to the component ledge. Each assembly uses 5 bolts.

14. Note only a certified electrician may install electrical connections. A battery is encased with the servo in the servo holder, but the power wires of the battery and servo are not connected to its circuit. Connect the wire adapters to the servo circuit board in the electrical box where labeled.

15. Add a custom waterproof cover to each servo holder.

**Centerpiece Assembly**

16. The 4-arm nozzle is preassembled to ensure the angles are at about 85°. Screw the square plug into the top of the 4-arm nozzle body and tighten.

17. On the side, start assembling the speaker plate, ball bearing, and speaker-bearing shaft. Start by press fitting the ball bearing onto the bottom of the speaker plate.

18. Of the inside diameter of the ball bearing, press fit the speaker-bearing shaft on the flat end of the shaft so that the square cut end is facing outward.

19. Now, press these assembled parts onto the square plug in the 4-arm nozzle body. The center piece is ready to assemble with the rest of the fountain.
Hydraulic Assembly

20. Begin constructing the hydraulic lift by press fitting all four of the support stilts into the support chuck.
21. Bolt the stilt support chuck to the bottom of the basin with 4 bolts.
22. Screw in the flow adapters for the cylinder and piston.
23. Press fit the cylinder onto the stilts.
24. Attach fluid systems 2 and 3 to the cylinder. The latex tube, in fluid system 2, will attach to the flow adapter on the inside of the cylinder.
25. Put the O-rings on to the machined grooves of the piston.
26. Attach the free end of the latex tubing to the piston.
27. Slide the piston into the cylinder.
28. Weld the mechanical stop to the cylinder.
29. Thread in the 4-arm nozzle to the top of the piston.
30. Press fit the speaker plate to the 4-arm nozzle.
31. Once secured, place the speaker onto the speaker plate. The speaker should be tight fit in the plate, but able to remove if desired.

Tiling and Lights for Visual Appeal

32. Add tiles to the outside of the basin by applying grout and then the tile. Smooth any grout between tiles for a clean look.
33. Add an LED strip around the outside of the basin in two spots: the top edge and bottom.
34. Add the third LED strip to the inside of the basin on the top edge.
35. Construct LED light strip circuit in the waterproof electrical box for powering and controlling the LED light show. (A hole will be made in concrete basin for LED wires to reach the electrical box).
36. All codes will be pre-uploaded with the correct sequences.

Power source

37. Construct an underground path for wiring the electronics to the electrical grid of the property. A long trench will need to be dug up. Combine all power cables into one insulated sleeve.

Cost Analysis

The fountain is designed for middle-upper class residents. Currently, the manufacturer’s suggested retail price (MSRP) for large 6-foot diameter fountains ranges from about $6,000 to $10,000. To counter these market prices, the musical water fountain is projected to cost $3,000 at most. It was a challenge to reduce costs while creating an original fountain design that had more intricate parts to it than the standard water fountains found on the market. Based on cost approximations from industrial suppliers like McMaster-Carr and Grainger, the supplies for the musical water fountain is estimated to cost a maximum value of $3,000. Refer to the bill of materials below for the estimated prices of each component.
## Bill of Materials

### Custom Parts

<table>
<thead>
<tr>
<th>Part</th>
<th>Qty</th>
<th>Cost per Unit</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin</td>
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<tr>
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<tr>
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<tr>
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<tr>
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<tr>
<td>Support Chuck</td>
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<td>Circular PVC Pipe</td>
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**Sub Total** $3,127.40

### Plumbing

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<td>Vinyl Tube 1&quot; ID, 3 ft</td>
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<td>1/4&quot; T-Joint PVC</td>
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<td>90° Elbow PVC</td>
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<td>1/4&quot; Barbed Fitting Threaded</td>
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<tr>
<td>Barbed Pipe Reducer, 1&quot; to 1/4&quot;</td>
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<tr>
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**Sub Total** $445.00

### Electronics

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<td>Arduino Uno</td>
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<td>Capacitor, 1000 microFarad</td>
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<tr>
<td>Transformer, AC to DC</td>
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<td>Electrical Box, 9&quot; x 6&quot; x 2&quot;</td>
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<tr>
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<td>Din Rail</td>
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**Sub Total** $953.40

### Hardware

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<td>SHCS 6-32, Lg. 3/8&quot;, 100 pc</td>
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<td>6-32 Std. Hex Nut, 100 pc</td>
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<tr>
<td>2&quot; L-Brackets</td>
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<td>U-Bolt</td>
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<td>Ball Bearing, 1/2&quot; Shaft</td>
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<tr>
<td>Ball Bearing, 3/8&quot; Shaft</td>
<td>18</td>
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**Sub Total** $216.00

**Final Cost** $3,127.40
In order to estimate the cost of all the custom machined parts there are a few variables that are important to consider. The first of which being the cost of the material used. The second thing to consider is the cost of labor for machining the specific material. Nearly all custom machined parts for the fountain will be fabricated from an aluminum 1060 alloy. This material is cheap and light making it a great material selection for the low stress applications of the fountain. Al 1060 is also very ductile, making it an easy material to machine into various shapes. Keeping the same material for most of the customized parts makes manufacturing easier and allows for the purchase of this material in bulk. The first step that was taken to estimate the cost of each custom machined part was calculating the mass of each part. This was done by multiplying the total volume of the part by the density of Al 1060. It was found that the average cost of this aluminum alloy is roughly $2000 per metric ton, which converts to $1 per kilogram. Thus, the calculated mass of each Aluminum part in kilograms is equivalent to the price in dollars. Next, the cost of labor to machine each custom part needed to be estimated. It was found that on average Aluminum has a machining labor cost of about $2 per minute. Thus, the total time required to fabricate each part needs to be estimated according to the complexity of the part. Some factors that were considered are the total number of cuts required, the number of drill bit changes, and the total number of identical parts to be machined. Modern metal fabrication is very efficient meaning basic shaped parts can be machined quickly from stock material. However, it is important to consider an appropriate setup time to calibrate the cutting machine and fix the aluminum stock in place. If several identical parts will all be machined in a row, this calibration time will only need to be considered once for the initial setup. This concept is applicable to the servo assembly parts as 18 identical parts are required. The equation used to estimate the cost of the custom aluminum parts is shown below in Equation (0).

\[
\text{Cost} = (V \cdot \rho) + \left( t_{\text{setup}} \right) \cdot \left( \frac{2 \text{ dollars}}{\text{min}} \right) + \left( \frac{t_{\text{machining}}}{\text{part}} \right) \cdot \left( \frac{2 \text{ dollars}}{\text{min}} \right) \cdot \left( \# \text{ of parts} \right) \quad \text{(0)}
\]

Aside from the custom machined parts, the rest of the components were split into categories of plumbing, electronics, and hardware to better understand the cost and weight on the final cost. Of the final cost, the plumbing only makes up 14.23% of the expenses. Standard pipes and sizes were chosen for ease of purchase and mass production prices. It was also cost effective to use the same plumbing components in each fluid system. In comparison, electronics contributed 30.50% of the cost, about twice as expensive as the plumbing. This was expected because electronics are more complex parts. However, the hardware was ultimately the cheapest parts to purchase for the fountain. Hardware is 6.90% of the final cost. There is always a demand for hardware in the industrial world, thus parts are inexpensive to buy, especially in bulk quantities.

The purchase of items in large quantities tends to lower the overall price of the parts. It is a concept used to increase consumer rates. For instance, the custom parts which require a high quantity of 18 pieces is ultimately going to lower the machining price per unit compared to the production of a single part. Another component which this concept economically benefits from is the purchase of 100 flat head screws instead of ordering a specific quantity. While 100 pieces is more than needed, it is best practice to have extra hardware parts in case a few are misplaced or damaged. This cost analysis was performed under the assumption of purchasing all the materials necessary to produce a single fountain. However, if this product is proved to have a large demand, the necessary parts for assembly can be purchased in bulk. This will significantly reduce the cost of the fountain.

Finally, the last factor that will influence the overall cost of this product is the installation cost. A landscaper, an electrician and a plumber will need to be employed to ensure accurate and safe installation of the musical fountain. Typically, landscapers and electricians charge between $50-$100 per hour.
whereas plumbers are usually at the higher end at $100 per hour. The total time required to completely assemble the musical fountain will vary depending on the location and the skill level of the workers.

Reflecting on the total cost of the musical fountain, it is more than what was initially expected. The goal was to keep the retail price below $3000, however, the total cost of materials, parts and labor exceeds this goal. In order to ensure a profit, the retail price of this fountain will need to be greater than $3,000. Thus, assuming a reasonable profit margin of 25% the retail price of this fountain design would be $4,000 plus the cost of installation. Considering the many capabilities of this fountain and its uniqueness compared to other fountains on the market, this is an excellent price. Nonetheless, if a cheaper price is desired, there are a few changes that could be made to reduce the overall cost. Since the servo assemblies contain many custom parts, reducing the number of assemblies would significantly reduce the overall cost of the fountain. It is estimated that each servo assembly removed would decrease the overall cost of the musical fountain by about $60. Thus, removing six servo assemblies so that there would be a total of twelve would reduce the cost by about $360. Another option for cutting back on the cost would be to change each servos power source from a lithium battery to a transformer. This would increase the complexity of the assembly process since a power and ground wire would need to be wired from the electrical box to each servo. Nonetheless, this change would result in a cost reduction of about $250.

**Product Analysis and Results**

**Factors of Safety**

A factor of safety (FOS) is calculated for engineered product designs. It is a method used to account for uncertainties and to assure the product functions through wear and tear. The following Equation (1) is used to calculate the FOS.

\[
FOS = \frac{Yield\ Stress}{Design\ Stress}
\]  

(1)

The important parts to analyze are the components carrying significant loads. This includes the component ledge, all shafts in the speaker and servomotor assembly, and the hydraulic lift parts. Dependent on the part, there is normal and shear stress to account for during the design stress analysis. Normal stress is represented by sigma, \( \sigma \), and shear stress is represented by tau, \( \tau \), and are shown in Equations (2) and (3) respectively.

\[
\sigma = \frac{F}{A} = \frac{Mr}{I}
\]  

(2)

\[
\tau = \frac{T\tau}{J}
\]  

(3)

Where \( F \) is the applied force, \( A \) is the area, \( M \) is the moment, \( r \) is the radius, \( I \) is the moment of inertia, \( T \) is torque, and \( J \) is polar moment of inertia. The normal stress has two general methods of solution depending on the load. For applied axial forces, the normal stress is found by dividing the force, \( F \), by the area, \( A \). For applied loads which cause bending, the normal stress is found by dividing the product of the moment, \( M \), and radius, \( r \), by its moment of inertia, \( I \). The servo assembly is a situation where bending stress occurs because of the downward force on the long axis of the shaft.
For the more complex scenarios of applied loads, the principal stress ($\sigma_1$ and $\sigma_2$) calculations were found to better approximate the design stress and is shown below in Equation (4). For instance, the servo shaft has an applied torque and vertical downward force acting on the shaft. To account for the different loads, the normal and shear stresses in the x- and y-direction were used to find the principal stress. Once the principal stress was found, a Von Mises stress ($\sigma_{vm}$) was calculated. Von Mises stress is a common way to use the design stress for further analysis. For special case cylindrical shapes, like the base of the hydraulic lift, the principal stresses 1 and 2 may be replaced by the hoop ($\sigma_H$) and longitudinal ($\sigma_l$) stress to apply the Von Mises stress.

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$  \hspace{1cm} (4)

$$\sigma_{vm} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$  \hspace{1cm} (5)

$$\sigma_H = \frac{P d}{2t}$$  \hspace{1cm} (6)

$$\sigma_l = \frac{P d}{4t}$$  \hspace{1cm} (7)

Where P is fluid pressure and t is part thickness. Below in Table 2 are the results of the design stresses for the critical parts of the fountain. For a thorough analysis of the design stresses, refer to Appendix C for the MathCAD analysis.

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<thead>
<tr>
<th>Assembly</th>
<th>Part</th>
<th>Diameter (m)</th>
<th>Area (m²)</th>
<th>Torque (Nm)</th>
<th>Force (N) or Pressure (Pa)</th>
<th>Normal Stress (Pa)</th>
<th>Shear Stress (Pa)</th>
<th>Principal Stress (Pa)</th>
<th>Design Stress (Pa)</th>
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<td>7.08E+06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-4083000</td>
</tr>
<tr>
<td>Hydraulic Lift Assembly</td>
<td>Base</td>
<td>0.1016</td>
<td>0.0081</td>
<td>NA</td>
<td>46670</td>
<td>NA</td>
<td>NA</td>
<td>187100</td>
<td>1.62E+05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>93540</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piston</td>
<td>0.0191</td>
<td>0.0002</td>
<td>NA</td>
<td>10.0900</td>
<td>47627</td>
<td>NA</td>
<td>47627</td>
<td>4.76E+04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0097</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stilts</td>
<td>0.0254</td>
<td>0.0005</td>
<td>NA</td>
<td>14.5203</td>
<td>28056</td>
<td>NA</td>
<td>28056</td>
<td>2.87E+04</td>
</tr>
</tbody>
</table>

Another method of analysis is finite element analysis (FEA). This type of analysis is useful to predict how a part or assembly reacts to realistic loads, pressures, vibrations, and more. The parameters to assess are dependent on the part and its intended use and exposure. FEA is applicable to all assemblies of the fountain, however due to restricted time the most stressed assembly was taken into consideration. Since the servomotor assembly resulted in higher design stresses, especially for the servo shaft, FEA analysis was performed on this assembly.
For analysis, the servo shaft, bearing shaft, and nozzle guides were analyzed and is shown in Figure 22. The bearing holder and servo holder were excluded from analysis for simplicity.

![Simplified Servomotor Assembly for FEA Analysis](image)

*Figure 23: Simplified servomotor assembly for FEA analysis*

For simulation, it was assumed the bearing shaft had a bearing support on its end and the servo shaft was fixed to the servo plate. The applied load on the nozzle guide is 0.35 N and a torque of 0.196 N-m is applied to the servo shaft. The result of this simulation is shown below in Figure 23. From the simulation, the servo shaft saw the highest amount of stress in the light orange region which is 7.03 MPa. The numerical analysis resulted in a stress of 7.08 MPa. In comparison to the numerical stress calculations, the simulation resulted in a similar stress value, just 0.05 MPa higher than the numerical analysis. This shows confidence between theoretical analysis versus simulated reality.

![Static Stress Results](image)

*Figure 24: FEA result of Von Mises stress*
Many of the product designs for the fountain have a low design stress compared to the material yield stress. The fountain is a décor piece which experiences minimal amounts of load on several of its parts. The servomotor assembly sees the largest amount of stress compared to the other system parts. Although high, the material is able to carry such stress. Below is a table describing the part, material yield stress and corresponding FOS. The FOS for most parts is drastically high, suggesting the product designs will not fail under their intended loads and more. However, such high factors of safety suggest the part is over designed. To lower the factor of safety to an appropriate value, such as a factor between 2 and 5, the design should remove any unnecessary material. The prevention of overdesigned parts lowers the part and machining costs.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Part</th>
<th>Material</th>
<th>Yield Stress (Pa)</th>
<th>Design Stress (Pa)</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speaker Assembly</td>
<td>Speaker-Bearing Shaft</td>
<td>PLA</td>
<td>3.59E+07</td>
<td>1.13E+04</td>
<td>3177.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al 1060</td>
<td>1.70E+07</td>
<td></td>
<td>1504.4</td>
</tr>
<tr>
<td>Servomotor Assembly</td>
<td>Bearing Shaft</td>
<td>PLA</td>
<td>3.59E+07</td>
<td>5.07E+03</td>
<td>7080.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al 1060</td>
<td>1.70E+07</td>
<td></td>
<td>3352.8</td>
</tr>
<tr>
<td></td>
<td>Servo Shaft</td>
<td>PLA</td>
<td>3.59E+07</td>
<td>7.08E+06</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al 1060</td>
<td>1.70E+07</td>
<td></td>
<td>2.4</td>
</tr>
<tr>
<td>Hydraulic Lift Assembly</td>
<td>Base</td>
<td>PLA</td>
<td>3.59E+07</td>
<td>1.62E+05</td>
<td>221.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al 1060</td>
<td>1.70E+07</td>
<td></td>
<td>104.9</td>
</tr>
<tr>
<td></td>
<td>Piston</td>
<td>PLA</td>
<td>3.59E+07</td>
<td>4.76E+04</td>
<td>753.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al 1060</td>
<td>1.70E+07</td>
<td></td>
<td>356.9</td>
</tr>
<tr>
<td></td>
<td>Stilts</td>
<td>PLA</td>
<td>3.59E+07</td>
<td>2.87E+04</td>
<td>1252.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al 1060</td>
<td>1.70E+07</td>
<td></td>
<td>593.2</td>
</tr>
</tbody>
</table>

Fluid Analysis

As mentioned, the fountain has three distinct fluid systems. The 18 nozzles use a parallel flow design which directs the water flow into two equidistant pathways. For the 4-arm nozzle, a single flow path is used to direct water from the pump to the body of the 4-arm nozzle piece. Lastly, the hydraulic lift is designed on the basis of fluid mechanics, so it is thoroughly analyzed to confirm there is a sufficient lift of the centerpiece.

To obtain the results, important fluid concepts were used. Bernoulli’s equation, shown in Equation (8), is fundamental to fluid mechanics. The concept is to relate the pressure, velocity, and elevation at a certain point in the control volume. By conservation of energy, two separate points along a streamline within a system may be analyzed to solve for unknown variables about those points. In a perfect world the energy will remain constant at all points within the fluid system. However, in real engineering scenarios there will be losses within the system. There are two main types of losses that were considered in the flow analysis: major loss which is due to friction effects within the pipes and tubes, and minor loss which is caused by bends, joints and couplings. This was the basis of solution for the calculations in the fluid systems. Similarly, by conservation of mass, the system must satisfy the continuity of mass flow rates, such as a division in the flow path. It is assumed that within all fluid systems, the flow of water is incompressible; meaning the density of water will be a constant 1000 kg/m$^3$. Thus, the flow rate coming in must be equal to the flow rate coming out. In other words, the fluid
velocity multiplied by the cross-sectional area of the tube/pipe will be constant at each point within each system. The only flow being supplied to each system is the flow output of the water pump. This will be equal to the flow out of the system, through the multiple nozzles. This is better described in mathematical terms by Equation (9).

\[
\left( \frac{P}{\rho g} + \frac{V^2}{2g} + z \right)_1 = \left( \frac{P}{\rho g} + \frac{V^2}{2g} + z + h_{\text{minor}} + h_{\text{major}} \right)_2
\]

\[
Q_{1,\text{in}} = Q_{2,\text{out}} + Q_{3,\text{out}} + \ldots + Q_{n,\text{out}}
\]  

To determine the landing position of the water shot from each nozzle, the kinematic motion equations are used to approximate its projectile displacement. The derived displacement, \( \Delta s \), is described below in Equation (10). This motion equation is a well-known physics equation which characterizes the motion of an object that holds a constant acceleration. Note that in the horizontal or \( \Delta x \) direction, the acceleration term is dropped. Once the water leaves the nozzle there are no forces acting on the water in the horizontal direction. Each of the nozzles will have some angle \( \theta \) to them, thus, the horizontal and vertical components of the exit velocity can be calculated to use in their respective \( \Delta x \) and \( \Delta y \) displacement Equations (11) and (12).

\[
\Delta s = V_0 t + \frac{1}{2} a t^2
\]

\[
\Delta x = V_0 \cos(\theta) t + \frac{1}{2} a t^2
\]

\[
\Delta y = V_0 \sin(\theta) t + \frac{1}{2} a t^2
\]

The variable of interest is \( \Delta x \) as this will determine whether the water stays within the perimeter of the basin. To solve for \( \Delta x \), we need to first solve for time in Equation (12). The time it takes for the water to fall from the maximum height to its original exit height was calculated by assuming \( \Delta y \) is zero. Since this is a quadratic equation, solving will yield two different time values; the positive one will be used. Once the time in the air is found, this value can be substituted into equation 11 to solve for the horizontal displacement. To ensure no spillage occurs, the horizontal displacement for the nozzles attached to the servo assembly shall not exceed 4.8 feet or 1.46 meters. For the centerpiece nozzles, the horizontal displacement cannot exceed 2.5 feet or .762 meters.

The result of this analysis is presented in Table 4 for the 18-nozzle parallel system flow and Table 5 for the 4-arm nozzle. Certain points were evaluated in each system and are illustrated below in figures 24 & 25 respectively.
Theoretically, the systems were projected to work as intended. The head, or maximum height the water will shoot in the air, is considerably high for the system. However, it is difficult to predict the head losses associated with the circular PVC. Testing will need to be done to measure the actual height. With an ideal system, the 18 nozzles aim about 2 meters higher than the 4-arm nozzle. From the ground, the highest water projectile is about 4.67 meters (14 feet) at full pump capacity. Throughout the water show, the angle of the nozzle will be constantly changing but never fall below a minimum angle of 60 degrees from horizontal. Since the water's exit angle and velocity is known, the kinematic equations of motion can be used to calculate the horizontal displacement of the water. It is critical to know the horizontal displacement at the maximum servo angle to ensure no water escapes the basin perimeter. At full capacity
and an angle of 30 degrees, the horizontal displacement of the water is about 2.2 meters which will land outside of the basin. To keep this from happening, a flow diffuser or solenoid valve can be used to restrict the water flow and obtain a desired exit velocity to ensure no spillage. It was decided that the fountain should have the capability to shoot water at least 2 m (6 feet) in the air, especially at dramatic moments within a song. Thus, a solenoid valve will be incorporated into the design to restrict the water flow when the servo is operating. Implementing a maximum horizontal displacement condition of 1.46 meters into Equation (11) returns the maximum exit velocity of 4 meters per second for no spillage to occur when the servo angle is at 60° from horizontal. Thus, when the servo is operating, the exit velocity shall not exceed this value in order to reuse about the same volume of water.

Table 4: Parallel Pipe Fluid System for 18 Nozzles

<table>
<thead>
<tr>
<th>Point</th>
<th>Stagnation Pressure (Pa)</th>
<th>Pressure (Pa)</th>
<th>Flow Rate (m³/s)</th>
<th>Velocity (m/s)</th>
<th>Head Losses (m)</th>
<th>Head (m)</th>
<th>Landing Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Pump</td>
<td>62210</td>
<td>55000</td>
<td>0.004330</td>
<td>3.7980</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2: PVC</td>
<td>56400</td>
<td>54590</td>
<td>0.002000</td>
<td>1.8990</td>
<td>0.5930</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3: Latex</td>
<td>38540</td>
<td>9695</td>
<td>0.000241</td>
<td>7.5960</td>
<td>1.6740</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4: Nozle</td>
<td>8.7800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Series Pipe Fluid System for 4-Arm Nozzle

<table>
<thead>
<tr>
<th>Point</th>
<th>Stagnation Pressure (Pa)</th>
<th>Pressure (Pa)</th>
<th>Flow Rate (m³/s)</th>
<th>Velocity (m/s)</th>
<th>Head Losses (m)</th>
<th>Head (m)</th>
<th>Landing Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Pump</td>
<td>47510</td>
<td>42000</td>
<td>0.001682</td>
<td>3.3190</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2: PVC</td>
<td>39090</td>
<td>21680</td>
<td>0.001682</td>
<td>5.9010</td>
<td>0.6310</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3: Latex</td>
<td>24300</td>
<td>6889</td>
<td>0.001682</td>
<td>5.9010</td>
<td>1.0510</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4: Nozle</td>
<td>6.6020</td>
<td>2.2120</td>
<td>0.2560</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The 4-arm nozzle fluid calculations were found for the lift in a fully compressive state and fully expanded state. The lift is intended to rise to its full expanded state during the use of the fountain but may be left in its lowered state as well. This is due to the independent fluid system used to raise the piston.

The lift is raised and lowered by the principals of fluid mechanics. The primary force which drives the piston up is buoyancy force. Fundamentals of buoyancy force are based on the force balance and the lightweight mass object. There must be more force pushing upward on the piston than there is downward. Buoyancy force is mathematically described in Equation (13). Since the buoyancy force is used to push the piston up, work done is calculated using Equation (14) and pressure P is described in Equation (15).
From theoretical calculations, the buoyancy force was found to be 20.14 N. This is larger than the weight force on the piston, thus the lift will raise until it hits the mechanical stop. From knowledge of the pump and the work required, the time it takes to raise is 3.25 seconds, which is quick enough for its intention of use. These results are shown in Table 6 below.

Table 6: Series Pipe Fluid System for Hydraulic Lift

<table>
<thead>
<tr>
<th>Pump Pressure (Pa)</th>
<th>Bouyancy Force (N)</th>
<th>Work (kJ)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4465</td>
<td>20.14</td>
<td>6.65</td>
<td>3.25</td>
</tr>
</tbody>
</table>

Electrical Circuit Analysis

Many factors had to be considered for the electronic systems to function smoothly.

Supplying electromechanical devices with the proper voltage, current and power rating will ensure optimal performance for various electromechanical devices. Servos with 20 kg-cm of torque will be used to control the angle that the nozzles point. This corresponds to roughly 2 newton meters of torque which is plenty for its application. The small servo assembly is composed of parts made of aluminum 1060 and thus will be extremely lightweight, making the moment of inertia small. The mechanism also employs a low friction ball bearing to allow for smooth rotation. Two newton meters of torque was tested and proven to be sufficient for precise and quick rotations.

Since this servo has a working voltage of 7.4 volts and minimum working current of 1 amp, a power supply that matches these values needs to be provided to the system for optimal performance. One option that was explored is the use of a transformer to step down the voltage and current of the 120 VAC signal. However, since the servos do not require a heavy amount of power, it was decided that lithium batteries could provide an effective amount of power to the servo. A battery with maximum voltage of 7.4 volts and a current output of 2500 mA hours was selected to power the servos electrical circuit. A switch will be employed to ensure that the battery is only operating when the fountain is on; when the fountain is off, the switch will disconnect the battery from the circuit allowing it to rest and recharge.

Powering the LED strip is a bit more complex than the servo due to the fact that it requires significantly more current for operation. The WS2812B LED strip purchased for the fountain prototype requires a voltage of 5 volts and 30 watts of power. Using Equation (16) shown below the total required current to power the LED was found to be 6 Amps.

\[
P = V \cdot I \rightarrow I = \frac{P}{V}
\] (16)
The LED strip for the prototype has a total of 150 lights in series meaning each LED requires a power of: \( \frac{30}{150} = 0.2 \) watts. To achieve maximum brightness in each of the LEDs in series, each light needs to be supplied with 0.2 watts of power. An AC to DC, voltage step down transformer was selected to power the prototype LED circuit. This transformer will take the 120-volt AC signal from the power grid of the property, step the voltage down to 5 volts, increase the current to 6 amps and smooth the AC signal into a DC signal through the use of a diode, bridge rectifier, and capacitor. Supplying a smooth DC current to the LED strip will ensure constant LED brightness, and smooth color transitions which will be important factors for the light display. An electrical circuit was constructed containing this transformer as a power source, the Arduino, the WS2812B LED strip, a resistor, and a capacitor. It was concluded that the selected voltage step down transformer was a great power source for the LED strip as all the lights shined bright and were consistent for all the different colors and patterns.

This same concept can be applied to the light strips employed by the full-scale model fountain. There will be a total of 3 LED strips to be powered, one ring around the inside diameter and two around the outside diameter. It is known that the spacing between lights is 9.15 LEDs per foot. With this information the total number of LEDs in the fountain can be calculated by finding the total distance of LED light strip and multiplying by the LED spacing. The total distance of LED strip will be the perimeter of the inside of the basin plus two times the perimeter of the outside of the basin. This distance was calculated using the Equation (17) below.

\[
\text{Length} = 2 \cdot \pi \cdot d_o + \pi \cdot d_i = 17\pi
\] (17)

Thus, it can be calculated that the total number of LED lights on the musical fountain is 489. Since the actual fountain design contains significantly more LEDs than the prototype, a transformer supplying a much larger current will need to be used. It was previously calculated that each LED requires 0.2 watts of power to operate at full brightness, thus the total power to be supplied by the transformer will be 0.2 watts multiplied by the total number of LEDs. This power was found to be about 98 watts. The WS2812B strips are rated for a voltage of 5 volts, therefore the total current to be supplied to the three LED strips will be about 19.5 amps. This was calculated by dividing the total power by the voltage.

Within the waterproof electrical box, the transformer output wires will be connected to two nodes, one ground node and one power node. All of the power wires for the LED strips will then be connected to the power node and all the ground wires for the LED strips will be connected to the ground node. Each LED strip will be connected in parallel with one another, and the individual LEDs of each strip will be connected in series. This will allow for a proportional current to flow to each LED strip and supply each LED with 0.2 watts of power.

By employing a DC power source with 5 volts and 6 amps, each light will be supplied with efficient power to create a bright and vibrant light display. An AC to DC, voltage step down transformer was selected to power the LED circuit. This transformer will take the 120-volt AC signal from the power grid of the property, step the voltage down to 5 volts, increase the current to 6 amps and smooth the AC signal into a DC signal through the use of a diode, bridge rectifier, and capacitor. Supplying a smooth DC current to the LED strip will ensure constant LED brightness, and smooth color transitions which will be important factors for the light display. An electrical circuit was constructed containing this transformer as a power source, the Arduino, the WS2812B LED strip, a resistor, and a capacitor. This circuit, shown in
appendix B was tested to observe LED performance. It was concluded that the selected voltage step down transformer was a great power source for the LED strip as all the lights shined bright and were consistent for all the different colors and patterns.

**Prototype Model & Results**

**Model**

The fountain was prototyped using an industrial grade waste can and 3D printed parts. Important concepts to prove included the servo and speaker assemblies, hydraulic lift, and lights. The prototype modeled the system interactions but did not resemble the product design in its entirety. It focused on the electrical and fluid systems of the fountain. It was most important to test the Arduino microcontrollers with the music, servomotors, and lights. For simplicity, the fountain was preprogrammed to the Western Michigan University fight song. The assembly of the prototype and its various systems revealed some challenges. These challenges include the selection and incorporation of external power supplies to match the voltage and current rating of the electronic components. Another obstacle was obtaining various pipe couplings for connecting the pump and nozzle to their respected tubes as well as switching the tube material from plastic vinyl to latex for more flexibility. The prototype is shown in Figure 26 for reference.
The servo assembly is bolted to the top wood shelf. Due to a small prototype basin, the nozzle and servo assembly were placed on the outside of the basin. Below the servo assembly are the electronic circuits which control the servomotor and LED light strip. The prototype contains two microcontrollers. On the left shelf a microcontroller is connected to the servomotor which controls the angle at which the nozzle points. The other microcontroller is placed on the right shelf and controls the LED light strip. This strip is wrapped around the entire can for an exaggerated effect and to observe its potential. To protect the
electrical circuits from water, a durable, water-resistant plastic cover was stapled to the wood shelves. For extra protection, the cover was lined with waterproof tape.

The prototype basin is primarily used to show that there will be a large water supply for the pumps to access. Inside the basin are two pumps, a hydraulic lift, and centerpiece apparatus. The centerpiece and hydraulic lift also identified as fluid systems 2 and 3 share the same pump because of limited resources. To direct flow to either the lift or the 4-arm nozzle, a ball valve is used. When the ball valve is closed, the pump only supplies water to the 4-arm nozzle. While open it permits flow to the lift. The model is best shown with the ball valve first in its open position to raise the lift, and then switch closed to hold that lifted position and redirect flow to the 4-arm nozzle. The second pump was used for the single nozzle on the outside of the prototype basin. It was plumbed through the wall of the prototype basin for a direct connection and did not interrupt validation tests.

Results

Overall, the fountain worked as expected with the systems working together in synchronous. The lights and servo were timed with the music with a push of a button. Timing the push of the button was tricky and leaves room for improvement with a remote controller. However, the sequence and dynamic movements were successful in action and increased confidence levels for repeatability. The external power sources were sufficient during testing and proved capable of withstanding prolonged use. Similarly, the servomotor, speaker, and lights were repeatedly used for performance testing and showed no sign of exhaustion. In the hydraulic lift, the piston was able to rise with the buoyancy force created by the volume and pressure of water inside the cylinder. It was important to test its functionality and validate the design. It did not rise in a timely manner due to friction between the two PLA surfaces of the piston and cylinder. However, the surface finish on the machined parts is designed to be much smoother to reduce friction.

Leakage tests were carried out on all connection points and through holes. The large holes drilled out for the pump power wires leaked a small amount, but to prevent leakages a proper wire port is designed to be installed. Fittings and threaded joints showed little to no leakages. When the tubing was tested with the rotating nozzle it was found to be too stiff and restricted the nozzle motion. Instead, latex tubing was used for its greater amount of flexibility.

Conclusion

Impact

Most residential fountains on the market are extremely basic since they serve for one singular function to pump water. These fountains are not very impressive and thus do not draw significant attention. The goal of this project was to design a unique water fountain that would display a multitude of different functions working in synchronous with each other. Most people only expect to see these types of fountains at fancy hotels or along the Vegas strip, thus, seeing a musical water fountain in a residential neighborhood would be quite out of the ordinary. This product will revolutionize the fountain industry by providing a modern and exciting water show that will attract people passing by.

Recommendations

Arduino Frequency Sampling

The initial plan for synchronizing the fountain involved using continuous sampling from an Arduino microcontroller to constantly detect the frequency of the music being played. To achieve this, the audio signal of the music would connect to an analog input pin of the Arduino. Since the Arduino can
only read small voltages between 0 and 5 volts, the audio signal would be scaled to fit within the range with 2.5 volts being the mean voltage of the audio signal. The developed code would need to detect when the audio signal has a positive slope and when the audio signal crossed the 2.5 volt mean voltage. Using the Arduinos internal timer, the time would be measured between consecutive instances in which the input signal crosses the 2.5-volt value with a positive slope. The Arduino timer value will give the period of the input signal which can be used to calculate a real time frequency using the equation:

\[ f = \frac{1}{T} \]

The frequency value obtained by the Arduino through continuous sampling would then be incorporated into the code for the light display, and water movements. Multiple “if” statements can be created for a range of frequencies such that a distinct color would be portrayed depending on the frequency of the music playing. For example, if an “A note” is being played, the fountain will glow red and if a “G note” is being played, the fountain will glow blue.

Successfully sampling the frequency of an input signal while still running code for lights and water movements is very difficult. As the code for the lights and water movements is running, the Arduino needs to periodically take a break to quickly execute a separate set of commands which will sample the signal frequency. This is done using Arduino interrupts. Another thing to consider is how long each interruption will take. Pausing the light/water show to sample the frequency momentarily is not ideal, even if it takes less than a second. Thus, bit manipulation with the use of the Arduino registers would need to be incorporated. This allows for faster communication between the Arduino and its pins, thus increasing the sampling speed. It is apparent that the more research that is done on this topic, the more complex it becomes. Much time and energy was put into researching continuous Arduino sampling, however, due to extreme complexity of the topic, limited time, and lack of expertise in the computer engineering field, this idea had to be abandoned. If given more time and resources, this topic would be the driving force behind the synchronization of the musical fountain.

Temperature, Humidity, and Time Display
Arduino microcontrollers are compatible with many electromechanical devices and sensors which lead to a large range of potential applications for the musical fountain. One of these sensors is a temperature and humidity module. By setting up an additional circuit the Arduino is able to receive input data from this sensor and calculate the temperature and humidity of the environment. This information would not be handy without a way to display it. Thus, an LCD display module would be used in unison with the sensor to display the temperature, humidity and even the time. Although the addition of this feature would increase the final cost of the product, the fountain would serve as a thermometer, humidity gauge and a clock.

Solar Energy
The fountain is powered from an electrical grid. While it is an efficient and reliable source of energy, the power could be sourced from solar energy. This renewable source of energy would lower electric bills for the residents and be efficient enough to power the fountain. Also, it would increase the environmental safety and waste less energy for the fountain, making it more appealing for residential purchase. This solar energy could be used for many applications such as charging servo batteries, as well as powering pumps, and lights. Through product research and a deeper understanding about solar energy and how it is generated into useable energy, the fountain could switch its source of energy completely, or use it in dual mode with the electrical grid.
Solenoid Valves

A fluid system is well controlled with the use of solenoid valves. Solenoid valves are powered by a current which strokes a spool in the valve. The spool movement either allows or restricts fluid from passing through an orifice. Each nozzle could be equipped with a valve and easily create a larger variety of fluid patterns to display. Allowing more flow to pass through would allow the water to shoot faster and higher out of the nozzles. Decreasing the flow rate would produce the opposite effect. Additionally, a valve on the hydraulic lift system would allow commanded lift sequences. Overall, valves could make transitions smoother and more controllable in the fountain.

Lights on Centerpiece

Due to the location and connections of the centerpiece lights that would be incorporated there would have to operate independently of the other light systems. In order for the lights to have power from the same source the wires need to navigate through the basin to get to the electrical box. This creates a water proofing nightmare because the only way to get the electricity to the lights is by going through the basin and the basin is holding all the water for the fountain. The only other way to get the power to these lights would be to house the circuits within the lift and have it run through the material of the basin and not through where the water is but that makes the basin and the lift much more difficult to manufacture and build. A separate power source and controller would most likely be the best option to have lights on the centerpiece.
Appendix A: Parts and Assemblies
Appendix B: Numerical Analysis

KNOWN PARAMETERS:

SYSTEM PROPERTIES:

\[ P_1 = 6889 \text{ Pa} \quad \text{MAX PRESSURE FROM SYSTEM ON SHAFT} \]
\[ V_1 = 5.901 \frac{\text{m}}{\text{s}} \quad \text{MAX VELOCITY FROM SYSTEM ON SHAFT} \]
\[ h = 0.00725 \text{ m} \quad \text{HEIGHT OF SQUARE CUT IN} \]
\[ d_1 = 0.0125 \text{ m} \quad \text{OUTSIDE DIAMETER OF SPEAKER SHAFT} \]
\[ d_2 = 0.008181 \text{ m} \quad \text{EQUIVALENT DIAMETER OF SQUARE CUT IN} \]
\[ t = \frac{d_1 - d_2}{2} = 0.002 \text{ m} \quad \text{THICKNESS OF SHAFT} \]

MATERIAL YIELD STRESS:

\[ \sigma_{AL} = 17 \cdot 10^6 \text{ Pa} \quad \text{ALUMINUM 1060 YIELD STRESS} \]
\[ \sigma_{PLA} = 35.9 \cdot 10^6 \text{ Pa} \quad \text{PLA YIELD STRESS} \]

SPEAKER-SHAFT:

\[ \sigma_{\text{hoop}} = \frac{P_1 \cdot d_2}{2 t} \quad \text{HOOP STRESS} \quad \sigma_{\text{hoop}} = (1.305 \cdot 10^4) \text{ Pa} \]
\[ \sigma_{\text{long}} = \frac{P_1 \cdot d_2}{4 t} \quad \text{LONGITUDINAL STRESS} \quad \sigma_{\text{long}} = (6.525 \cdot 10^3) \text{ Pa} \]
\[ \sigma_{vm} = \frac{1}{\sqrt{2}} \cdot \left( (\sigma_{\text{hoop}} - \sigma_{\text{long}})^2 + (\sigma_{\text{hoop}})^2 + (\sigma_{\text{long}})^2 \right)^{\frac{1}{2}} \quad \sigma_{vm} = (1.13 \cdot 10^4) \text{ Pa} \]
\[ SF_1 = \frac{\sigma_{PLA}}{\sigma_{vm}} \quad \text{SAFETY FACTOR OF SHAFT USING PLA} \quad SF_1 = 3.177 \cdot 10^3 \]
\[ SF_2 = \frac{\sigma_{AL}}{\sigma_{vm}} \quad \text{SAFETY FACTOR OF SHAFT USING AL} \quad SF_2 = 1.504 \cdot 10^3 \]
KNOWN PARAMETERS:

SYSTEM PROPERTIES:

\[
\rho := 1000 \frac{kg}{m^3} \quad \text{DENSITY OF WATER}
\]

\[
g := 9.81 \frac{m}{s^2} \quad \text{GRAVITY}
\]

\[
d1 := 0.00625 \ m \quad \text{SERVO SHAFT ARM DIAMETER}
\]

\[
d2 := 0.009375 \ m \quad \text{BEARING SHAFT ARM DIAMETER}
\]

\[
d3 := 0.0055 \ m \quad \text{FLOW PIPE DIAMETER}
\]

\[
l1 := 0.06069 \ m \quad \text{LENGTH FROM SERVO TO CENTER OF NOZZLE}
\]

\[
l2 := 0.05893 \ m \quad \text{LENGTH FROM BEARING FACE TO CENTER OF NOZZLE}
\]

\[
T1 := 0.196 \ N \cdot m \quad \text{TORQUE APPLIED}
\]

\[
V_{\text{exit}} := 3.835 \frac{m}{s} \quad \text{EXIT VELOCITY OF CENTERPIECE}
\]

MATERIAL YIELD STRESS:

\[
\sigma_{AL} := 17 \cdot 10^6 \ Pa \quad \text{ALUMINUM 1060 YIELD STRESS}
\]

\[
\sigma_{PLA} := 35.9 \cdot 10^6 \ Pa \quad \text{PLA YIELD STRESS}
\]
SERVO SHAFT:

\[
A_{\text{flow}} := \frac{\pi}{4} \cdot d^2
\]

FLOW AREA

\[
A_{\text{flow}} = (2.376 \cdot 10^{-3}) \, m^2
\]

\[
F_f := \rho \cdot (V_{\text{exit}})^2 \cdot A_{\text{flow}}
\]

REYNOLDS TRANSPORT THEOREM

\[
F_f = 0.349 \cdot \frac{s^4 \cdot A^2}{k_g^2 \cdot m^2} \cdot \frac{k_g^3 \cdot m^3}{s^6 \cdot A^2}
\]

\[
M := \frac{3 \cdot F_f \cdot (l_1 + l_2)}{16}
\]

MOMENT

\[
M = 0.008 \, J \quad \text{NOTE A JOULE IS N-m}
\]

\[
I := \frac{\pi}{64} \cdot d_1^4
\]

MOMENT OF INERTA

\[
I = (7.49 \cdot 10^{-11}) \, m^4
\]

\[
\sigma_{xs} := \frac{M \cdot \left(\frac{d_1}{2}\right)}{I}
\]

NORMAL STRESS IN THE X-DIRECTION

\[
\sigma_{xs} = (3.27 \cdot 10^5) \, Pa
\]

\[
\tau_{xy} := \frac{16 \cdot T_1}{\pi \cdot d_1^3}
\]

SHEAR STRESS

\[
\tau_{xy} = (4.089 \cdot 10^6) \, Pa
\]

\[
\sigma_1 := \frac{\sigma_{xs}}{2} + \sqrt{\left(\frac{\sigma_{xs}}{2}\right)^2 + \tau_{xy}^2}
\]

PRINCIPAL STRESS 1

\[
\sigma_1 = (4.255 \cdot 10^6) \, Pa
\]
\[ \sigma_{-2} := \sigma \frac{x s}{2} - 2 \sqrt{\left( \frac{\sigma_{-1}}{2} \right)^2 + \tau_{xy}^2} \quad \text{PRINCIPAL STRESS 2} \]

\[ \sigma_{vm} := \frac{1}{\sqrt{2}} \left( (\sigma_{-1} - \sigma_{-2})^2 + (\sigma_{-2})^2 + (\sigma_{-1})^2 \right)^{\frac{1}{2}} \quad \text{VON MISES STRESS} \]

\[ \sigma_{vm} = (7.089 \cdot 10^6) \quad \text{Pa} \]

\[ SF_{s1} := \frac{\sigma_{PLA}}{\sigma_{vm}} \quad \text{SAFETY FACTOR FOR SERVO SHAFT USING PLA} \]

\[ SF_{s1} = 5.064 \]

\[ SF_{s2} := \frac{\sigma_{AL}}{\sigma_{vm}} \quad \text{SAFETY FACTOR FOR SERVO SHAFT USING AL} \]

\[ SF_{s2} = 2.398 \]

**FATIGUE ANALYSIS FOR SERVO SHAFT:**

**CYCLE:** WHEN THE SERVO SHAFT CHANGES ROTATION DIRECTION

\[ \tau_{ult} := 48300000 \quad \text{Pa} \quad \text{ULTIMATE SHEAR STRESS} \]

\[ \sigma_{ult} := 68900000 \quad \text{Pa} \quad \text{ULTIMATE NORMAL STRESS} \]

**ASSUME Kf=1, SMOOTH SPECIMEN, NO NOTCHES, SMOOTH RADII**

\[ Sn' := \frac{1}{2} \cdot \sigma_{ult} \quad \text{ENDURANCE LIMIT} \]

\[ Cl := \frac{1}{\sqrt{3}} \quad \text{LOADING EFFECTS FOR TORSION} \]

\[ Cg := 1.189 \cdot d_1^{-0.097} \quad \text{SIZE EFFECTS FOR SHAFT DIAMETER} \]

\[ Cs := 0.95 \quad \text{ASSUMED SURFACE EFFECT IS MACHINED, LOW STRESS} \]

\[ Ct := 1 \quad \text{ASSUMED TEMPERATURE EFFECTS FOR MILD TEMPERATURES} \]

\[ Cr := 0.84 \quad \text{RELIABILITY CORRECTION FACTOR, ASSUME 98% LEVEL OF CONFIDENCE} \]

\[ Sn := Sn' \cdot Cl \cdot Cs \cdot Ct \cdot Cr \quad \text{STRESS AT 10,000,000 CYCLES} \]

\[ Sn = (1.587 \cdot 10^7) \quad \text{Pa} \]
\[ S_f := 0.9 \cdot \frac{\sigma_{ult}}{\sqrt{3}} \]  
STRESS AT 10,000 CYCLES:

\[ S_f = (3.58 \cdot 10^7) \text{ Pa} \]

A STRESS AMPLITUDE OF 4.09 MPa IS WELL BELOW THE FATIGUE FAILURE CURVE, THUS THE DESIGN WILL ENSURE "INFINITE LIFE".

\[ SF := \frac{S_n}{4.09 \text{ MPa}} \]  
FATIGUE SAFETY FACTOR \( SF = 3.881 \)

**BEARING-SHAFT:**

\[ A_{bshaft} := \frac{\pi}{4} \cdot (d2^2) \]  
CROSS SECTION AREA OF BEARING SHAFT

\[ A_{bshaft} = (6.903 \cdot 10^{-5}) \text{ m}^2 \]

\[ M_b := M \]  
MOMENT

\[ I_b := \frac{\pi}{64} \cdot (d2)^4 \]  
MOMENT OF INERTIA

\[ I_b = (3.792 \cdot 10^{-10}) \text{ m}^4 \]

\[ \sigma_{xb} := \frac{M_b \cdot (d2)}{2 \cdot I_b} \]  
NORMAL STRESS IN THE X-DIRECTION

\[ \sigma_{xb} = (9.688 \cdot 10^4) \text{ Pa} \]

\[ SF_{b1} := \frac{\sigma_{PLA}}{\sigma_{xb}} \]  
SAFETY FACTOR FOR BEARING SHAFT USING PLA

\[ SF_{b1} = 370.559 \]

\[ SF_{b2} := \frac{\sigma_{AL}}{\sigma_{xb}} \]  
SAFETY FACTOR FOR BEARING SHAFT USING AL

\[ SF_{b2} = 175.474 \]
THE MUSICAL WATER FOUNTAIN

NUMERICAL ANALYSIS: FACTOR OF SAFETY HYDRAULIC LIFT

KNOWN PARAMETERS:

SYSTEM PROPERTIES:

\[ \rho = 1000 \ \frac{kg}{m^3} \]  
DENSITY OF WATER

\[ g = 9.81 \ \frac{m}{s^2} \]  
GRAVITY

\[ t = 0.0127 \ m \]  
THICKNESS OF STILTS

\[ d_1 = 0.0254 \ m \]  
DIAMETER OF STILTS

\[ d_2 = 0.01905 \ m \]  
OUTSIDE DIAMETER OF PISTON TOP

\[ d_3 = 0.009652 \ m \]  
INSIDE DIAMETER OF PISTON TOP

\[ d_4 = 0.1016 \ m \]  
OUTSIDE DIAMETER OF PISTON BOTTOM

\[ V_{exit} = 6.586 \ \frac{m}{s} \]  
EXIT VELOCITY OF CENTERPIECE

\[ A_{exit} = 1.59 \cdot 10^{-5} \ m^2 \]  
EXIT NOZZLE AREA

WEIGHTS:

\[ W_c = 3.56 \ N \]  
WEIGHT OF CENTERPIECE

\[ W_s = 3.771 \ N \]  
WEIGHT OF SPEAKER

\[ W_w = 20.195 \ N \]  
WEIGHT OF WATER

\[ W_p = 5.4268 \ N \]  
WEIGHT OF PISTON

\[ W_b = 22.37 \ N \]  
WEIGHT OF BASE

\[ F_{water} = 4 \cdot \rho \cdot V_{exit}^2 \cdot A_{exit} \]  
FORCE OF EXITING WATER

\[ F_{water} = 2.759 \ N \]
MATERIAL YIELD STRESS:

\[ \sigma_{AL} := 17 \cdot 10^6 \text{ Pa} \quad \text{ALUMINUM 1060 YIELD STRESS} \]

\[ \sigma_{PLA} := 35.9 \cdot 10^6 \text{ Pa} \quad \text{PLA YIELD STRESS} \]

STILTS:

\[ F_{\text{weight}} := W_c + W_s + W_w + W_p + W_b + F_{\text{water}} \quad \text{TOTAL WEIGHT FORCE} \]

\[ F_{\text{weight}} = 58.081 \text{ N} \]

\[ \frac{F_{\text{weight}}}{4} \quad \text{NORMAL STRESS FOR STILTS} \]

\[ \sigma_{stilts} = \frac{\pi}{4} (d1^2) \]

\[ \sigma_{stilts} = (2.866 \cdot 10^4) \text{ Pa} \]

\[ SF_{stilts1} := \frac{\sigma_{AL}}{\sigma_{stilts}} \quad \text{FACTOR OF SAFETY FOR STILTS USING AL} \]

\[ SF_{stilts1} = 593.237 \]

\[ SF_{stilts2} := \frac{\sigma_{AL}}{\sigma_{stilts}} \quad \text{FACTOR OF SAFETY FOR STILTS USING AL} \]

\[ SF_{stilts2} = 593.237 \]

PISTON:

\[ F_{\text{weight2}} := W_c + W_s + F_{\text{water}} \quad \text{WEIGHT ON PISTON TOP} \]

\[ F_{\text{weight2}} = 10.09 \text{ N} \]

\[ A1 := \frac{\pi}{4} (d2^2 - d3^2) \quad \text{AREA OF PISTON TOP} \]

\[ A1 = (2.119 \cdot 10^{-4}) \text{ m}^2 \]

\[ \sigma_{piston} := \frac{F_{\text{weight2}}}{A1} \quad \text{NORMAL STRESS FOR PISTON} \]

\[ \sigma_{piston} = (4.763 \cdot 10^4) \text{ Pa} \]
The Musical Water Fountain

\[ SF_{\text{piston1}} := \frac{\sigma_{\text{PLA}}}{\sigma_{\text{piston}}} \quad \text{SAFETY FACTOR FOR PISTON USING PLA} \]

\[ SF_{\text{piston1}} = 753.798 \]

\[ SF_{\text{piston2}} := \frac{\sigma_{\text{AL}}}{\sigma_{\text{piston}}} \quad \text{SAFETY FACTOR FOR PISTON USING AL} \]

\[ SF_{\text{piston2}} = 356.952 \]

**BASE:**

\[ P_1 := 42000 \, \text{Pa} \quad \text{PUMP PRESSURE} \]

\[ V_1 := 3.319 \, \frac{\text{m}}{\text{s}} \quad \text{PUMP VELOCITY} \]

\[ h := 0.075 \, \text{m} \quad \text{HEIGHT OF STILTS} \]

\[ P := P_1 + \frac{1}{2} \cdot \rho \cdot V_1^2 - \rho \cdot g \cdot h \quad \text{PRESSURE AT ENTRANCE OF LIFT} \]

\[ P = (4.677 \cdot 10^4) \, \text{Pa} \]

\[ \sigma_{\text{hoop}} := \frac{P \cdot d^4}{2 \cdot t} \quad \text{HOOP STRESS} \]

\[ \sigma_{\text{hoop}} = (1.871 \cdot 10^5) \, \text{Pa} \]

\[ \sigma_{\text{long}} := \frac{P \cdot d^4}{4 \cdot t} \quad \text{LONGITUDINAL STRESS} \]

\[ \sigma_{\text{long}} = (9.354 \cdot 10^4) \, \text{Pa} \]

\[ \sigma_{\text{vm}} := \frac{1}{\sqrt{2}} \cdot \left( (\sigma_{\text{hoop}} - \sigma_{\text{long}})^2 + (\sigma_{\text{hoop}})^2 + (\sigma_{\text{long}})^2 \right)^{\frac{1}{2}} \quad \text{VON MISES STRESS} \]

\[ \sigma_{\text{vm}} = (1.62 \cdot 10^5) \, \text{Pa} \]

\[ SF_{\text{base1}} := \frac{\sigma_{\text{PLA}}}{\sigma_{\text{vm}}} \quad \text{SAFETY FACTOR OF BASE USING PLA} \]

\[ SF_{\text{base1}} = 221.573 \]

\[ SF_{\text{base2}} := \frac{\sigma_{\text{AL}}}{\sigma_{\text{vm}}} \quad \text{SAFETY FACTOR OF BASE USING AL} \]

\[ SF_{\text{base2}} = 104.923 \]
The Musical Water Fountain

**SAFETY FACTOR FOR SERVO SHAFT USING PLA**

\[ SF_{s1} := \frac{\sigma_{PLA}}{\sigma_{vm}} \]

\[ SF_{s1} = 5.069 \]

**SAFETY FACTOR FOR SERVO SHAFT USING AL**

\[ SF_{s2} := \frac{\sigma_{AL}}{\sigma_{vm}} \]

\[ SF_{s2} = 2.4 \]

**BEARING-SHAFT:**

\[ A_{bshaft} := \frac{\pi}{4} \cdot (d^2) \]

**CROSS SECTION AREA OF BEARING SHAFT**

\[ A_{bshaft} = (6.903 \cdot 10^{-5}) \text{ m}^2 \]

\[ \sigma_{xb} := \frac{F_f}{A_{bshaft}} \]

**NORMAL STRESS IN THE X-DIRECTION**

\[ \sigma_{xb} = (5.062 \cdot 10^3) \text{ Pa} \]

**SAFETY FACTOR FOR BEARING SHAFT USING PLA**

\[ SF_{b1} := \frac{\sigma_{PLA}}{\sigma_{xb}} \]

\[ SF_{b1} = 7.092 \cdot 10^3 \]

**SAFETY FACTOR FOR BEARING SHAFT USING AL**

\[ SF_{b2} := \frac{\sigma_{AL}}{\sigma_{xb}} \]

\[ SF_{b2} = 3.358 \cdot 10^3 \]
The Musical Water Fountain

Numerical Analysis: 18 Nozzle Heads

Known Parameters:

System Properties:

- \( \rho = 1000 \text{ kg/m}^3 \) Density of Water
- \( \mu = 0.001 \text{ Pa s} \) Dynamic Viscosity
- \( g = 9.807 \text{ m/s}^2 \) Gravity

Pump Properties:

- \( Q_1 = 0.00433 \text{ m}^3/\text{s} \) Pump Flow Rate
- \( P_1 = 55000 \text{ Pa} \) Pump Pressure

Pipe System Properties:

- \( d_1 = 0.0381 \text{ m} \) PVC Pipe Inner Diameter
- \( d_2 = d_1 \) PVC Pipe Inner Diameter
- \( d_3 = 0.00635 \text{ m} \) Latex Pipe Inner Diameter
- \( d_{exit} = 0.0055 \text{ m} \) Exit Diameter
- \( \theta = 65^\circ \) Maximum Nozzle Angle
- \( z_1 = 0 \text{ m} \) System Datum at Point 1
- \( z_2 = 0.454 \text{ m} \) Height of PVC Pipe
- \( z_3 = 0.6 \text{ m} \) Height of Latex Pipe
- \( L_1 = 0.7 \text{ m} \) Length of Tube (Horizontal)
- \( L_2 = 0.454 \text{ m} \) Length of Tube (Vertical)
- \( K_T = 0.9 \) Threaded T Joint K-Factor
- \( K_90 = 0.75 \) 90 Degree Elbow Joint, Long Radius K-Factor
- \( K_{exit} = 1 \) Exit K-Factor
- \( K_{bushing} = 0.05 \) Reduced Bushing K-Factor
- \( K_{nozzle} = 0.1 \) Nozzle K-Factor

Assumptions:

- PVC is completely smooth \( \rightarrow \frac{c}{d} \sim 0 \)
- Water is incompressible fluid
SOLUTION:

FLOW AREAS:

\[ A_1 := \frac{\pi \cdot (d_1)^2}{4} \text{ PVC PIPE FLOW AREA} \quad A_1 = 0.001 \ m^2 \]

\[ A_2 := A_1 \text{ PVC PIPE FLOW AREA} \quad A_2 = 0.001 \ m^2 \]

\[ A_3 := \frac{\pi \cdot (d_3)^2}{4} \text{ LATEX PIPE FLOW AREA} \quad A_3 = (3.167 \cdot 10^{-5}) \ m^2 \]

VELOCITIES AND FLOW RATES:

\[ V_1 := \frac{Q_1}{A_1} \text{ PUMP EXIT VELOCITY} \quad V_1 = 3.798 \ \frac{m}{s} \]

\[ Q_2 := \frac{Q_1}{2} \text{ FLOW RATE OUT OF PVC PIPE} \quad Q_2 = 0.002 \ \frac{m^3}{s} \]

\[ Q_3 := \frac{Q_2}{9} \text{ FLOW RATE OUT OF LATEX PIPE} \quad Q_3 = (2.406 \cdot 10^{-4}) \ \frac{m^3}{s} \]

\[ V_2 := \frac{Q_2}{A_2} \text{ PVC PIPE EXIT VELOCITY} \quad V_2 = 1.899 \ \frac{m}{s} \]

\[ V_3 := \frac{Q_3}{A_3} \text{ LATEX PIPE EXIT VELOCITY} \quad V_3 = 7.596 \ \frac{m}{s} \]

REYNOLDS NUMBERS:

\[ \text{Re}_{y2} := \frac{\rho \cdot V_2 \cdot d_2}{\mu} \text{ REYNOLDS NUMBER AT EXIT OF PVC PIPE} \quad \text{Re}_{y2} = 7.235 \cdot 10^4 \]

TURBULENT FLOW

\[ \text{Re}_{y3} := \frac{\rho \cdot V_3 \cdot d_3}{\mu} \text{ REYNOLDS NUMBER AT EXIT OF PVC PIPE} \quad \text{Re}_{y3} = 4.823 \cdot 10^4 \]

TURBULENT FLOW

FRICTION FACTORS:

\[ f_2 := 0.019 \text{ FRICTION FACTOR} \]

\[ f_3 := 0.022 \text{ FRICTOR FACTOR} \]

MAJOR AND MINOR HEAD LOSSES FROM PIPE AND NOZZLES:

\[ h_{\text{major}2} := f_2 \cdot \frac{(L_1 + L_2)}{d_1} \cdot \left( \frac{V_2^2}{2 \cdot g} \right) \text{ MAJOR HEAD LOSS FROM 1 TO 2} \]

\[ h_{\text{major}2} = 0.106 \ m \]

\[ h_{\text{major}3} := f_3 \cdot \frac{(z_3 - z_2)}{d_3} \cdot \left( \frac{V_3^2}{2 \cdot g} \right) \text{ MAJOR HEAD LOSS FROM 1 TO 3} \]

\[ h_{\text{major}3} = 1.488 \ m \]
\[ K_2 = K_T + K_{90} + K_{exit} \quad \text{K FACTOR} \quad K_2 = 2.65 \]

\[ K_3 = K_{bushing} + K_{nozzle} \left( 1 - \frac{d_{exit}}{d_3} \right) \quad \text{K FACTOR} \quad K_3 = 0.063 \]

\[ h_{\text{minor}2} = K_2 \cdot \frac{V_2^2}{2 \cdot g} \quad \text{MINOR LOSSES} \quad h_{\text{minor}2} = 0.487 \text{ m} \]

\[ h_{\text{minor}3} = K_3 \cdot \frac{V_3^2}{2 \cdot g} \quad \text{MINOR LOSSES} \quad h_{\text{minor}3} = 0.186 \text{ m} \]

**SYSTEM PRESSURES:**

\[ P_{o1} = P_1 + \frac{1}{2} \cdot \rho \cdot V_1^2 \quad \text{STAG. PRESSURE AT PUMP} \quad P_{o1} = (6.221 \cdot 10^4) \frac{kg}{m \cdot s^2} \]

\[ P_{o2} = \rho \cdot g \cdot \left( \frac{P_{o1}}{\rho \cdot g} - \frac{V_2^2}{2 \cdot g} - h_{\text{major2}} - h_{\text{minor2}} \right) \quad \text{PRESSURE AT PVC END} \quad P_{o2} = (5.459 \cdot 10^4) \frac{kg}{m \cdot s^2} \]

\[ P_{o3} = P_{o2} + \frac{1}{2} \cdot \rho \cdot V_2^2 \quad \text{STAG. PRESSURE AT PVC END} \quad P_{o3} = (5.64 \cdot 10^4) \frac{kg}{m \cdot s^2} \]

\[ P_3 = \rho \cdot g \cdot \left( \frac{P_{o2}}{\rho \cdot g} + (z_2 - z_3) - \frac{V_3^2}{2 \cdot g} - h_{\text{major3}} - h_{\text{minor3}} \right) \quad \text{PRESSURE AT LATEX END} \quad P_3 = (9.695 \cdot 10^3) \frac{kg}{m \cdot s^2} \]

\[ P_{o3} = \left( \frac{P_3}{\rho} + \frac{1}{2} \cdot \rho \cdot V_3^2 \right) \quad \text{STAG. PRESSURE AT LATEX END} \quad P_{o3} = (3.854 \cdot 10^4) \frac{kg}{m \cdot s^2} \]

**NOZZLE EXIT:**

\[ V_4 = \left( \frac{2 \cdot P_{o3}}{\rho} \right) \quad \text{NOZZLE EXIT VELOCITY} \quad V_4 = 8.78 \frac{m}{s} \]

\[ V_v = V_4 \cdot \sin(\theta) \quad \text{VERTICAL COMPONENT OF EXIT VELOCITY} \quad V_v = 7.957 \frac{m}{s} \]

\[ V_h = V_4 \cdot \cos(\theta) \quad \text{HORIZONTAL COMPONENT OF EXIT VELOCITY} \quad V_h = 3.711 \frac{m}{s} \]

\[ z_5 = \frac{V_4^2}{2 \cdot g} \quad \text{SYSTEM HEAD HEIGHT} \quad z_5 = 3.93 \text{ m} \]
NOZZLE WATER PROJECTILE:

\[ t := 0.718 \text{ s} \quad \text{TIME OF WATER DESCENT} \]

\[ \Delta y = -\frac{1}{2} \cdot g \cdot t^2 + V_4 \cdot \sin(\theta) \cdot t \]

KINEMATIC MOTION EQUATIONS:

\[ \Delta x = -\frac{1}{2} \cdot g \cdot t^2 + V_4 \cdot \cos(\theta) \cdot t \]

CONSTRAINTS:

- \( \Delta X \leq 1.46 \text{ m} \) (4.8 ft)
- \( \theta \leq 60^\circ \) (WORST CASE)

SOLVE THE FOLLOWING SYSTEM OF EQUATIONS:

\[ -\frac{1}{2} \cdot g \cdot t^2 + V_{\text{exit}} \cdot \sin(\theta) \cdot t = 0 \]

\[ -\frac{1}{2} \cdot g \cdot t^2 + V_{\text{exit}} \cdot \cos(\theta) \cdot t = 1.46 \]

OBTAIN THAT EXIT VELOCITY IS:

\[ V_{\text{exit}} = 4.066 \frac{m}{s} \]

\[ \text{deltax} := V_{\text{exit}} \cdot \cos(\theta) \cdot t \quad \text{X-DIRECTION PROJECTILE LANDING} \]

\[ \text{deltax} = 1.46 \text{ m} \]

THUS, WATER WILL NOT SPILL OVER THE BASIN PERIMETER
THE MUSICAL WATER FOUNTAIN
NUMERICAL ANALYSIS: PIPE STRESS ANALYSIS FOR PVC

KNOWN PARAMETERS:

SYSTEM PROPERTIES:

\[ \rho := 1000 \frac{kg}{m^3} \quad \text{DENSITY OF WATER} \]
\[ \mu := .001 \cdot Pa \cdot s \quad \text{DYNAMIC VISCOSITY} \]
\[ g = 9.807 \frac{m}{s^2} \quad \text{GRAVITY} \]

PUMP PROPERTIES:

\[ Q_1 := 0.00433 \frac{m^3}{s} \quad \text{PUMP FLOW RATE} \]
\[ P_1 := 55000 \text{ Pa} \quad \text{PUMP PRESSURE} \]

PIPE SYSTEM PROPERTIES:

\[ d_1 := 0.0381 \text{ m} \quad \text{PVC PIPE INNER DIAMETER} \]

MATERIAL INTEGRITY:

\[ SF := 2 \quad \text{DESIRED MINIMUM SAFETY FACTOR} \]
\[ \sigma_u := 52000000 \text{ Pa} \quad \text{ULTIMATE STRESS FOR PVC} \]

\[ t := \frac{P_1 \cdot d_1 \cdot SF}{4 \cdot \sigma_u} \quad \text{ALLOWABLE THICKNESS OF PVC PIPE} \]

\[ t = (2.015 \cdot 10^{-5}) \text{ m} \quad \text{THIS TELLS US THAT THE PRESSURE INSIDE THE PVC PIPE IS NOT GOING TO CAUSE A SIGNIFICANT AMOUNT OF STRESS ON THE PIPE STRUCTURE. THUS, A STANDARD THICKNESS FOR PVC PIPES FOUND IN HARDWARE STORES IS OK TO USE.} \]

\[ t_{\text{std}} := 0.00381 \text{ m} \quad \text{STANDARD PVC PIPE THICKNESS} \]

\[ \sigma_{\text{hoop}} := \frac{P_1 \cdot d_1}{2 \cdot t_{\text{std}}} \quad \text{HOOP STRESS FOR STANDARD PVC PIPES} \]
\[ \sigma_{\text{hoop}} = (2.75 \cdot 10^5) \text{ Pa} \quad \text{OBSERVE } \sigma_{\text{hoop}} < \sigma_u \quad \text{SO OK TO USE} \]
KNOWN PARAMETERS:

SYSTEM PROPERTIES:

\[ \rho = 1000 \frac{kg}{m^3} \quad \text{DENSITY OF WATER} \]
\[ \mu = 0.001 \cdot Pa \cdot s \quad \text{DYNAMIC VISCOSITY} \]
\[ g = 9.807 \frac{m}{s^2} \quad \text{GRAVITY} \]

PUMP PROPERTIES:

\[ Q_1 = 0.001682 \frac{m^3}{s} \quad \text{PUMP FLOW RATE} \]
\[ P_1 = 42000 \ Pa \quad \text{PUMP PRESSURE} \]

PIPE SYSTEM PROPERTIES:

\[ d_1 = 0.0254 \ m \quad \text{PIPE INNER DIAMETER} \]
\[ d_2 = 0.01905 \ m \quad \text{LATEX PIPE INNER DIAMETER} \]
\[ d_3 = d_2 \quad \text{PISTON INNER DIAMETER} \]
\[ d_4 = 0.007 \ m \quad \text{4 ARM ENTRANCE DIAMETER} \]
\[ d_5 = 0.0045 \ m \quad \text{4 ARM EXIT DIAMETER} \]
\[ d_{exit} = 0.0055 \ m \quad \text{NOZZLE EXIT DIAMETER} \]
\[ \theta = 86^\circ \quad \text{ANGLE OF NOZZLE ARMS} \]

\[ z_1 = 0 \ m \quad \text{SYSTEM DATUM AT POINT 1} \]
\[ z_{2\_comp} = 0.254 \ m \quad \text{HEIGHT OF LATEX TUBE IN LIFT FULL COMPRESSION} \]
\[ z_{2\_exp} = 0.4572 \ m \quad \text{HEIGHT OF LATEX TUBE IN LIFT FULL EXPANSION} \]
\[ z_{3\_comp} = 0.7112 \ m \quad \text{HEIGHT OF NOZZLE HEAD IN LIFT FULL COMPRESSION} \]
\[ z_{3\_exp} = 0.9144 \ m \quad \text{HEIGHT OF NOZZLE HEAD IN LIFT FULL EXPANSION} \]

\[ L_1 = 0.203 \ m \quad \text{LENGTH OF LATEX TUBE (HORIZONTAL)} \]
\[ L_2 = 0.254 \ m \quad \text{LENGTH OF TUBE (VERTICAL)} \]
\[ L_4 = 0.021 \ m \quad \text{LENGTH OF BRASS ARM} \]

\[ K_{1} = 0.5 \quad \text{SQUARE EDGE INLET} \]
\[ K_{2} = 0.167 \quad \text{COEFFICIENT FOR REDUCING BUSHING} \]
\[ K_{3} = 0.125 \quad \text{COEFFICIENT FOR REDUCING BUSHING} \]
\[ K_{4} = 0.208 \quad \text{COEFFICIENT FOR REDUCING BUSHING} \]
\[ K_{5} = 0.08 \]
\[ K_{6} = 0.31 \quad 90 \text{ DEGREE INLET (REGULAR, WELDED)} \]
ASSUMPTIONS:

- PVC IS COMPLETELY SMOOTH $\Rightarrow \frac{\varepsilon}{d} \sim 0$
- WATER IS INCOMPRESSIBLE FLUID

SOLUTION:

FLOW AREAS:

$A_1 := \frac{\pi \cdot (d_1)^2}{4}$ PIPE FLOW AREA $A_1 = (5.067 \cdot 10^{-4}) \ m^2$

$A_2 := \frac{\pi \cdot (d_2)^2}{4}$ LATEX PIPE FLOW AREA $A_2 = (2.85 \cdot 10^{-4}) \ m^2$

$A_3 := A_2$ LATEX PIPE FLOW AREA $A_3 = (2.85 \cdot 10^{-4}) \ m^2$

$A_4 := \frac{\pi \cdot (d_4)^2}{4}$ 4 ARM ENTRANCE FLOW AREA $A_4 = (3.848 \cdot 10^{-5}) \ m^2$

$A_5 := \frac{\pi \cdot (d_5)^2}{4}$ NOZZLE EXIT AREA $A_5 = (1.59 \cdot 10^{-5}) \ m^2$

VELOCITIES:

$V_1 := \frac{Q_1}{A_1}$ PUMP EXIT VELOCITY $V_1 = 3.319 \ m/s$

$V_2 := \frac{Q_1}{A_2}$ LATEX PIPE EXIT VELOCITY $V_2 = 5.901 \ m/s$

$V_3 := \frac{Q_1}{A_3}$ NOZZLE BODY EXIT VELOCITY $V_3 = 5.901 \ m/s$

$V_4 := \frac{Q_1}{4 \cdot A_4}$ 4 ARM VELOCITY $V_4 = 10.926 \ m/s$

REYNOLDS NUMBERS:

$Rey_1 := \frac{\rho \cdot V_1 \cdot d_1}{\mu}$ REYNOLDS NUMBER AT EXIT OF PUMP $Rey_1 = 8.431 \cdot 10^4$

TURBULENT FLOW

$Rey_2 := \frac{\rho \cdot V_2 \cdot d_2}{\mu}$ REYNOLDS NUMBER AT EXIT OF LATEX PIPE $Rey_2 = 1.124 \cdot 10^5$

TURBULENT FLOW

$Rey_3 := \frac{\rho \cdot V_3 \cdot d_3}{\mu}$ REYNOLDS NUMBER AT EXIT OF NOZZLE BODY $Rey_3 = 1.124 \cdot 10^5$

TURBULENT FLOW
FRICTION FACTORS:
\[ f_1 = 0.019 \quad \text{FRICTION FACTOR} \]
\[ f_2 = 0.012 \quad \text{FRICTION FACTOR} \]
\[ f_3 = 0.018 \quad \text{FRICTION FACTOR} \]
\[ f_4 = 0.014 \quad \text{FRICTION FACTOR} \]

MAJOR AND MINOR HEAD LOSSES FOR THE PIPES AND NOZZLE HEAD:
\[ h_{\text{major}2} := f_1 \left( \frac{L_1}{d_1} \right) \left( \frac{V_1^2}{2 \cdot g} \right) + f_2 \left( \frac{L_2}{d_2} \right) \left( \frac{V_2^2}{2 \cdot g} \right) \quad \text{MAJOR HEAD LOSS FROM 1 TO 2} \]
\[ h_{\text{major}2} = 0.369 \text{ m} \]
\[ h_{\text{major}3} := f_3 \left( \frac{z_3 - z_2}{d_3} \right) \left( \frac{V_3^2}{2 \cdot g} \right) \quad \text{MAJOR HEAD LOSS FROM 1 TO 3} \]
\[ h_{\text{major}3} = 0.767 \text{ m} \]
\[ h_{\text{exit}} := f_4 \left( \frac{L_4}{d_4} \right) \left( \frac{V_4^2}{2 \cdot g} \right) \quad \text{MAJOR HEAD LOSS FROM EXIT} \]
\[ h_{\text{exit}} = 0.256 \text{ m} \]

\[ K_2 := K_{\text{1}} - K_{\text{2}} \left( \frac{d_2}{d_1} \right)^2 - K_{\text{3}} \left( \frac{d_2}{d_1} \right)^3 - K_{\text{4}} \left( \frac{d_2}{d_1} \right)^3 \quad \text{K-FACTOR} \]
\[ K_2 = 0.217 \]

\[ K_3 := 2 \cdot K_{\text{5}} \quad \text{K-FACTOR} \]
\[ K_3 = 0.16 \]

\[ h_{\text{minor}2} := K_2 \left( \frac{(V_1 + V_2)^2}{8 \cdot g} \right) \quad \text{MINOR LOSSES} \]
\[ h_{\text{minor}2} = 0.235 \text{ m} \]

\[ h_{\text{minor}3} := K_3 \cdot \frac{V_3^2}{2 \cdot g} \quad \text{MINOR LOSSES} \]
\[ h_{\text{minor}3} = 0.284 \text{ m} \]

SYSTEM PRESSURES:
\[ P_{o1} := P_{1} + \frac{1}{2} \cdot \rho \cdot V_1^2 \quad \text{STAG. PRESSURE AT PUMP} \]
\[ P_{o1} = \left( 4.751 \cdot 10^4 \right) \frac{\text{kg}}{\text{m} \cdot \text{s}^2} \]

PRESSURES @ LIFT IN FULL COMPRESSION:
\[ P_{2_{\text{comp}}} := \rho \cdot g \left( \frac{P_{o1}}{\rho \cdot g} - \frac{V_2^2}{2 \cdot g} - z_{\text{2\_comp}} - h_{\text{major}2} - h_{\text{minor}2} \right) \quad \text{PRESSURE AT LATEX END} \]
\[ P_{2\_comp} = (2.168 \cdot 10^4) \frac{kg}{m \cdot s^2} \]

\[ P_{o2\_comp} := P_{2\_comp} + \frac{1}{2} \rho \cdot V^2 \]

STAG. PRESSURE AT LATEX END

\[ P_{o2\_comp} = (3.909 \cdot 10^4) \frac{kg}{m \cdot s^2} \]

\[ P_{3\_comp} := \rho \cdot g \left( \frac{P_{o2\_comp}}{\rho \cdot g} + (z_{2\_comp} - z_{3\_comp}) - \frac{V^3}{2 \cdot g} - h_{major3} - h_{minor3} \right) \]

PRESSURE AT NOZZLE BODY

\[ P_{3\_comp} = (6.889 \cdot 10^3) \frac{kg}{m \cdot s^2} \]

\[ P_{o3\_comp} := \left( P_{3\_comp} + \frac{1}{2} \rho \cdot V^3 \right) \]

STAG. PRESSURE AT NOZZLE BODY

\[ P_{o3\_comp} = (2.43 \cdot 10^4) \frac{kg}{m \cdot s^2} \]

PRESSURES AT LIFT IN FULL EXPANSION:

\[ P_{2\_exp} := \rho \cdot g \left( \frac{P_{o1}}{\rho \cdot g} - \frac{V^2}{2 \cdot g} - z_{2\_exp} - h_{major2} - h_{minor2} \right) \]

PRESSURE AT LATEX END

\[ P_{2\_exp} = (1.969 \cdot 10^4) \frac{kg}{m \cdot s^2} \]

\[ P_{o2\_exp} := P_{2\_exp} + \frac{1}{2} \rho \cdot V^2 \]

STAG. PRESSURE AT LATEX END

\[ P_{o2\_exp} = (3.71 \cdot 10^4) \frac{kg}{m \cdot s^2} \]

\[ P_{3\_exp} := \rho \cdot g \left( \frac{P_{o2\_exp}}{\rho \cdot g} + (z_{2\_exp} - z_{3\_exp}) - \frac{V^3}{2 \cdot g} - h_{major3} - h_{minor3} \right) \]

PRESSURE AT NOZZLE BODY

\[ P_{3\_exp} = (4.896 \cdot 10^3) \frac{kg}{m \cdot s^2} \]

\[ P_{o3\_exp} := \left( P_{3\_exp} + \frac{1}{2} \rho \cdot V^3 \right) \]

STAG. PRESSURE AT NOZZLE BODY

\[ P_{o3\_exp} = (2.231 \cdot 10^4) \frac{kg}{m \cdot s^2} \]
EXIT CONDITIONS:

PRESSURES @ LIFT IN FULL COMPRESSION:

\[
V_{\text{comp}} = \left( 2g \left( \frac{P_{03\text{comp}}}{\rho \cdot g} - h_{\text{Mexit}} \right) \right)^{\frac{1}{2}} \quad \text{VELOCITY OUT OF NOZZLE}
\]

\[
V_{\text{comp}} = 6.602 \, \frac{m}{s}
\]

\[
V_{v_{\text{comp}}} = V_{\text{comp}} \cdot \sin(\theta) \quad \text{VERTICAL VELOCITY COMPONENT}
\]

\[
V_{v_{\text{comp}}} = 6.586 \, \frac{m}{s}
\]

\[
V_{h_{\text{comp}}} = V_{\text{comp}} \cdot \cos(\theta) \quad \text{HORIZONTAL VELOCITY COMPONENT}
\]

\[
V_{h_{\text{comp}}} = 0.461 \, \frac{m}{s}
\]

\[
z_{6} = \frac{V_{v_{\text{comp}}}^2}{2 \cdot g} \quad \text{NOZZLE HEAD HEIGHT FROM NOZZLE EXIT}
\]

\[
z_{6} = 2.212 \, m
\]

PRESSURES @ LIFT IN FULL EXPANSION:

\[
V_{\text{exp}} = \left( 2g \left( \frac{P_{03\text{exp}}}{\rho \cdot g} - h_{\text{Mexit}} \right) \right)^{\frac{1}{2}} \quad \text{VELOCITY OUT OF NOZZLE}
\]

\[
V_{\text{exp}} = 6.293 \, \frac{m}{s}
\]

\[
V_{v_{\text{exp}}} = V_{\text{exp}} \cdot \sin(\theta) \quad \text{VERTICAL VELOCITY COMPONENT}
\]

\[
V_{v_{\text{exp}}} = 6.278 \, \frac{m}{s}
\]

\[
V_{h_{\text{exp}}} = V_{\text{exp}} \cdot \cos(\theta) \quad \text{HORIZONTAL VELOCITY COMPONENT}
\]

\[
V_{h_{\text{exp}}} = 0.461 \, \frac{m}{s}
\]

\[
z_{6\text{ exp}} = \frac{V_{v_{\text{exp}}}^2}{2 \cdot g} \quad \text{NOZZLE HEAD HEIGHT FROM NOZZLE EXIT}
\]

\[
z_{6\text{ exp}} = 2.009 \, m
\]
NOZZLE WATER PROJECTILE:

\[ f(x) = -\frac{1}{2} \cdot g \cdot x^2 + V_{\text{comp}} \cdot \sin(\theta) \cdot x \]

KINEMATIC MOTION EQUATION

SOLVE QUADRATIC, LET \( x \) REPRESENT TIME \( t \)

\[ t = 1.36 \text{ s} \quad \text{TIME OF WATER DESCENT} \]

\[ \text{deltax}_\text{comp} = V_{\text{comp}} \cdot t \]

\[ \text{deltax}_\text{comp} = 0.626 \text{ m} \quad < 0.762 \text{m RADIUS OF BASIN, THEREFORE THE WATER WON'T SPILL OVER} \]

\[ \text{deltax}_\text{exp} = V_{\text{exp}} \cdot t \]

\[ \text{deltax}_\text{exp} = 0.597 \text{ m} \quad < 0.762 \text{m RADIUS OF BASIN, THEREFORE THE WATER WON'T SPILL OVER} \]
The Musical Water Fountain

THE MUSICAL WATER FOUNTAIN
NUMERICAL ANALYSIS: HYDRAULIC LIFT

NOVEMBER 2022

KNOWN PARAMETERS:

SYSTEM PROPERTIES:

\[ \rho = 1000 \frac{kg}{m^3} \quad \text{DENSITY OF WATER} \]
\[ \mu = 0.001 \cdot \text{Pa \cdot s} \quad \text{DYNAMIC VISCOSITY} \]
\[ g = 9.807 \frac{m}{s^2} \quad \text{GRAVITY} \]

PUMP PROPERTIES:

\[ Q_1 = 0.0008517 \frac{m^3}{s} \quad \text{PUMP FLOW RATE} \]
\[ P_{\text{pump}} = 4464.8 \text{ Pa} \quad \text{PUMP PRESSURE} \]
\[ P_{\text{atm}} = 101 \text{ Pa} \quad \text{ATMOSPHERIC PRESSURE} \]
\[ P = 70 \text{ W} \quad \text{PUMP POWER RATING} \]

SYSTEM PROPERTIES:

\[ h_1 = 0.3566 \text{ m} \quad \text{LIFTED HEIGHT} \]
\[ h_2 = 0.1016 \text{ m} \quad \text{STILT HEIGHT} \]
\[ h_3 = 0.00206 \text{ m} \]
\[ D = 0.1016 \text{ m} \quad \text{DIAMETER OF INSIDE CYLINDER} \]
\[ F_{\text{weight}} = 10.01 \text{ N} \quad \text{WEIGHT LIFTED} \]

SOLUTION:

\[ F_b = \rho \cdot g \cdot \left( \frac{\pi \cdot D^2}{4} \right) \cdot (h_1 - h_2) \quad \text{BOUYANCY FORCE} \]
\[ F_b = 20.274 \frac{kg \cdot m}{s^2} \]

\[ W = \left( P_{\text{pump}} - \left( \frac{F_{\text{weight}}}{\pi \cdot D^2} \right) \right) \cdot (h_3) \quad \text{WORK DONE} \]
\[ W = 6.654 \frac{kg}{s^2} \]

\[ t = \frac{W}{P} \quad \text{LIFT TIME} \]
\[ t_{\text{lift}} = 3.25 \text{ s} \]
Appendix C: FEA Results

Figure 28: FEA Displacement Results

Figure 29: FEA Strain Results
Appendix D: Arduino Code
LED Light Strip Code for Prototype
#include <FastLED.h>

#define LED_PIN 7
#define NUM_LEDS 150

% Defining variables
int buttPin = 12;
int buttVal;
int r;
int g;
int b;
int i;
int j;
int k;
int l;
float beat = 373;
float dt1 = 1.286;
float dt2 = 5.851;

CRGB leds[NUM_LEDS];

void setup() {
  Serial.begin(9600);
  pinMode(buttPin, INPUT);
  digitalWrite(buttPin, HIGH);
  FastLED.addLeds< WS2812, LED_PIN, GRB>(leds, NUM_LEDS);
}

void loop() {

    buttVal = digitalRead(buttPin);
    Serial.print(buttVal);

    while(buttVal == 1){
        buttVal = digitalRead(buttPin);
        Serial.print(buttVal);
    }
    delay(2*beat);

    for(i=0; i<3; i++){
        fill_solid( leds, NUM_LEDS, CRGB(240,80,0));
        FastLED.show();
        delay(beat);
        FastLED.clear();

        fill_solid( leds, NUM_LEDS, CRGB(58,21,2));
        FastLED.show();
        delay(beat);
        FastLED.clear();
    }

    for(k=0; k<2; k++){

        for(j=110; j<=255; j++){
            r = j;
            g = r - 95;
            fill_solid( leds, NUM_LEDS, CRGB(r,g,0));
            FastLED.show();
        }
    }
}

delay(dt1);

}
for(j=255; j>=110; j--){
    r = j;
    g = r - 95;
    fill_solid( leds, NUM_LEDS, CRGB(r,g,0));
    FastLED.show();
    delay(dt1);
}

for(i=0; i<6; i++){
    fill_solid( leds, NUM_LEDS, CRGB(240,80,0));
    FastLED.show();
    delay(beat/4);
    FastLED.clear();
    delay(beat/4);
    fill_solid( leds, NUM_LEDS, CRGB(58,21,2));
    FastLED.show();
    delay(beat/4);
    FastLED.clear();
    delay(beat/4);
}

fill_solid( leds, NUM_LEDS, CRGB(0,0,255));

for(i=0; i<=149; i++){
    leds[i] = CRGB(0,0,255);
    FastLED.show();
delay(5.33);

for(i=149; i>=0; i--){
    
    leds[i] = CRGB(255,0,0);
    FastLED.show();
    delay(5.33);
}

for(i=0; i<=149; i++){
    
    leds[i] = CRGB(0,255,0);
    FastLED.show();
    delay(5.33);
}

for(i=149; i>=0; i--){
    
    leds[i] = CRGB(210,0,100);
    FastLED.show();
    delay(5.33);
}

delay(beat);

for(j=0; j<390; j++){
    static uint8_t hue = 0;
    FastLED.showColor(CHSV(hue++, 255, 255));
    delay(dt2);
}

for(i=0; i<=149; i++){
    
    leds[i] = CRGB(255,255,255);
FastLED.show();
delay(5.33);
FastLED.clear();

for(i=149; i>=0; i--){
    leds[i] = CRGB(255,255,255);
    FastLED.show();
    delay(5.33);
    FastLED.clear();
}

fill_solid(leds, NUM_LEDS, CRGB(255,255,255));
FastLED.show();
delay(beat/2);

fill_solid(leds, NUM_LEDS, CRGB(0,0,0));
FastLED.show();
delay(beat/2);

fill_solid(leds, NUM_LEDS, CRGB(255,255,255));
FastLED.show();
delay(beat/2);

fill_solid(leds, NUM_LEDS, CRGB(0,0,0));
FastLED.show();
delay(beat/2);

fill_solid(leds, NUM_LEDS, CRGB(240,80,0));
FastLED.show();
delay(beat/2);

fill_solid(leds, NUM_LEDS, CRGB(0,0,0));
FastLED.show();
delay(beat/2);

fill_solid(leds, NUM_LEDS, CRGB(240,80,0));
FastLED.show();
delay(beat/2);

fill_solid(leds, NUM_LEDS, CRGB(0,0,0));
FastLED.show();
delay(beat/2);

for(i=0; i<35; i++){
    if(i==0 || i==6 || i==12 || i==18 || i==24 || i==30){
        r = 255;
        g = 0;
        b = 0;
    }
    else if(i==1 || i==7 || i==13 || i==19 || i==25 || i==31){
        r = 200;
        g = 60;
        b = 0;
    }
    else if(i==2 || i==8 || i==14 || i==20 || i==26 || i==32){
        r = 200;
        g = 120;
        b = 0;
    }
}
else if(i==3 || i==9 || i==15 || i==21 || i==27 || i==33){
    r = 0;
    g = 255;
    b = 0;
}
else if(i==4 || i==10 || i==16 || i==22 || i==28 || i==34){
    r = 0;
    g = 0;
    b = 255;
}
else if(i==5 || i==11 || i==17 || i==23 || i==29 || i==35){
    r = 200;
    g = 0;
    b = 100;
}

fill_solid( leds, NUM_LEDS, CRGB(r,g,b));
FastLED.show();
delay(5);

fill_solid( leds, NUM_LEDS, CRGB(0,0,0));
FastLED.show();
delay(5);
}

Servomotor Code for Prototype
#include <Servo.h>
Servo servo1;

int servoPin = 11;
int x = 1;
int y = 1;
int z = 1;
int i;
float angle = 0;
float beat = 400;
float dt2 = 18;

int buttPin = 2;
int buttVal;

void setup() {
    Serial.begin(9600);
    pinMode(buttPin, INPUT);
    digitalWrite(buttPin, HIGH);
    servo1.attach(servoPin);
}

void loop() {
    buttVal = digitalRead(buttPin);

    while(buttVal == 1){
        buttVal = digitalRead(buttPin);
    }
}
Serial.print(buttVal);
}
buttVal = 0;

for (angle = 0 ; angle<=45 ; angle = angle + 7.5){
    servo1.write(angle);
    delay(beat);
}
delay(beat);

while(angle >= 0){
    servo1.write(angle);
    angle = angle - 1;
    delay(dt2);
}

while(angle <= 45){
    servo1.write(angle);
    angle = angle + 1;
    delay(dt2);
}

while(angle >= 0){
    servo1.write(angle);
    angle = angle - 1;
    delay(dt2);
}
delay(2*beat);

for (angle = 0 ; angle<=37.5 ; angle = angle + 7.5){
servo1.write(angle);
    delay(beat);
}
delay(beat);

servo1.write(18.75);
delay(beat/2);

servo1.write(0);
delay(beat/2);

while(angle <= 45){
    servo1.write(angle);
    angle = angle + 1;
    delay(dt2);
}

while(angle >= 0){
    servo1.write(angle);
    angle = angle - 1;
    delay(dt2);
}

while(angle <= 45){
    servo1.write(angle);
    angle = angle + 1;
    delay(dt2);
}

for (angle = 45 ; angle>=0 ; angle = angle - 7.5){
servo1.write(angle);
  delay(beat);
}

while(angle <= 45){
  servo1.write(angle);
  angle = angle + 1;
  delay(dt2);
}

while(angle >= 0){
  servo1.write(angle);
  angle = angle - 1;
  delay(dt2);
}

while(angle <= 45){
  servo1.write(angle);
  angle = angle + 1;
  delay(dt2);
}

delay(2*beat);

servo1.write(22.5);
delay(beat);

servo1.write(45);
delay(beat/2);

servo1.write(22.5);
delay(beat/2);

servo1.write(0);
delay(beat);

servo1.write(9);
delay(beat/2);

servo1.write(18);
delay(beat/2);

servo1.write(27);
delay(beat/2);

servo1.write(36);
delay(beat/2);

servo1.write(45);
delay(beat);

delay(2*beat);

servo1.write(30);
delay(2*beat);

servo1.write(15);
delay(2*beat);

servo1.write(0);
angle = 0;

for(angle = 0; angle <= 45; angle = angle + 1){  

servo1.write(angle);
    delay(10);
}  

for(angle = 45; angle >=0; angle = angle -1){
    servo1.write(angle);
    delay(10);
}

delay(100000);
Appendix E: ABET Questionnaire

ABET Program Evaluation Questionnaire

Mechanical and Aerospace Engineering Project (ME/AE 4800) Program Outcomes’ Indicators Assessment Worksheet

Mechanical and Aerospace Engineering Programs

Semester: Fall 2022 | Project Group Number: 12-22-01

Project Title: The Musical Water Fountain

Student Team Members: Joseph Bonnen, Amy Nielsen, Gavin Peddie

Faculty Team Members: Dr. Bade Shrestha, Dr. Javier Montefort

Please respond to all of the following questionnaires as best you can.

Outcome (2) An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

Performance Indicators:

1. Generates a detailed statement of all the specified engineering needs for the design project.
2. Identifies and lists potential public health, safety and welfare concerns for consideration in the design process.
3. Identifies and lists global, cultural, social, environmental and economic factors that are relevant to the development of the project product.
4. Produces solutions that satisfy the engineering needs, address the public concerns and consider the effects of the relevant design factors.

(If you copy and paste from the report, mention Section number or page numbers. If any question or item is not relevant to your project, write N/A)
Performance Indicator 1

Describe the engineering needs for this project.

- Programming expertise for coding with microcontrollers
- Machining, design, and manufacturing knowledge with experience preferred
- Safe electrical engineering practices

List the project goals along with performance criteria.

- Incorporate music, lights, and water movement into a synchronized system
- The fountain had to “dance” to the music. This implied that the fountain could not just go through generic movements but rather move along to specific songs
- Make the product affordable. This was interpreted as making the fountain cost $3,000 at most

List the project constraints.

- No project funding for prototype development
- Elementary knowledge of computer programming with microcontrollers
- Wait time on part services (3D prints from CEAS)

List the methods/procedures that were implemented to ensure that the customer expectations were addressed.

- Requirements were discussed and clearly portrayed by the faculty mentor
- Based off requirements, multiple designs were created and put into a decision matrix to define the best approach to the problem
- Frequent meetings with the customer were held to discuss progress and design choice updates
- Project documentation and organization was established early on in the project planning phase
- Prototype planning and expenses were reviewed by the team before beginning its build and testing. Drew multiple illustrations of the different prototype systems
- At least 8 hours a week were dedicated to group meetings to work together on the project, perfecting and testing designs
**Performance Indicator 2**

Describe potential public health, safety, and welfare concerns regarding this project and describe how they were addressed in the final design.

Public health:

- Material which releases toxic waste would be harmful to the residents within the area
- Protect the public health by using non-toxic materials

Public safety:

- Electrical systems are exposed to water and could be damaged without protective measures. Also, the mix of water and electricity is hazardous and could electrocute persons touching the water.
  - Designed the electrical box to be outside of the water fountain
  - Designed to use waterproof insulated wires from the servo, lights and other parts to the electrical box
  - Component ledge is designed to be installed above the water level for minimal interaction between the servo and water
- Improper installation of electrical systems is a hazard
  - Require that only certified electricians may install the electrical systems and assemble those components of the fountain.
- Improper installation of the concrete basin could crush a body considering its large size
  - A certified landscaper is instructed to advise placement and reassure there is a level and sturdy ground
- Improper install of fluid systems could burst a pipe and potentially injure person near the fountain
  - A certified plumber is required to install fluid systems

Public welfare:

- Careful consideration was taken to ensure the affordability and functionality of the fountain so people could be confident in their purchase of the fountain and not be a waste of money.
- It was important not to oversell the capabilities of the fountain so the public would not be purchasing this product with unrealistic expectations

**Performance Indicator 3**

List and explain all possible global, cultural, social, environmental, and economic factors relevant to the product of this project.

Global factors:

- N/A

Cultural factors:

- N/A

Social factors:
To bring communities together with a personal music, water, and light show

Environmental factors:

- Make sure that installation and operation of the fountain does not harm the surrounding environment
- Reuse water

Economic factors:

- To make the fountain competitive within the water fountain market and more affordable for the average middle to upper class homeowner

**Performance Indicator 4**

(To be addressed by the faculty adviser).
Outcome (5) An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks and meet objectives

Performance Indicators:

1. Student’s ability to function effectively
2. Student provides task specific leadership.
3. Student creates a collaborative and inclusive environment.
4. Group establishes goals.
5. Group plans tasks

(If you copy and paste from the report, mention Section number or page numbers.)

**Performance Indicators 2 & 5**

List all tasks required to accomplish the goals of this project, and name the group member responsible for the completion of each task.

<table>
<thead>
<tr>
<th>Task</th>
<th>Responsible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arduino Programming for servo and LED light strips</td>
<td>Gavin Peddie</td>
</tr>
<tr>
<td>Electrical circuit design for various electronic devices, as well as electrical testing.</td>
<td>Gavin Peddie</td>
</tr>
<tr>
<td>Research for all electrical and programming applications</td>
<td>Gavin Peddie</td>
</tr>
<tr>
<td>Synchronization of systems</td>
<td>Gavin Peddie</td>
</tr>
<tr>
<td>Fluid calculations including pressures, exit velocities, heights and horizontal water displacement.</td>
<td>Gavin Peddie</td>
</tr>
<tr>
<td>Design of fluid system 1</td>
<td>Gavin Peddie &amp; Amy Nielsen</td>
</tr>
<tr>
<td>Design of fluid system 2</td>
<td>Gavin Peddie</td>
</tr>
<tr>
<td>Design of servo assembly</td>
<td>Gavin Peddie</td>
</tr>
<tr>
<td>Modeling servo assembly in SolidWorks</td>
<td>Amy Nielsen</td>
</tr>
<tr>
<td>Design and modeling of speaker assembly</td>
<td>Amy Nielsen</td>
</tr>
<tr>
<td>Design and modeling of basin, component ledge, plate, pvc pipe structure</td>
<td>Amy Nielsen</td>
</tr>
<tr>
<td>Selected material and learned how tiling would work</td>
<td>Amy Nielsen</td>
</tr>
<tr>
<td>Material selection of all components except hydraulic lift assembly</td>
<td>Amy Nielsen</td>
</tr>
<tr>
<td>Final assembly of musical fountain in SolidWorks. As well as all assembly schematics incorporated into final paper.</td>
<td>Amy Nielsen</td>
</tr>
<tr>
<td>Dimensioned engineering drawings for all custom machined parts</td>
<td>Amy Nielsen</td>
</tr>
<tr>
<td>Organizing all equations and final values into MathCAD for clear presentation and analysis</td>
<td>Amy Nielsen</td>
</tr>
<tr>
<td>SolidWorks FEA analysis</td>
<td>Amy Nielsen</td>
</tr>
<tr>
<td>Selection of all brackets and bolts used for final assembly</td>
<td>Amy Nielsen</td>
</tr>
<tr>
<td>Materials research to determine the best materials to use for each application.</td>
<td>Amy Nielsen &amp; Joseph Bonnen</td>
</tr>
<tr>
<td>Design of hydraulic lift</td>
<td>Joseph Bonnen</td>
</tr>
</tbody>
</table>
### Performance Indicator 1

(Project’s adviser will determine whether the listed tasks were completed).

### Every student must answer the following question (add Student 3 & 4 if needed):

**Student 1 name: Joseph Bonnen**

For project tasks in which I was **not** the leader, I provided the following inputs towards their completion:

- Offering alternatives that could be pursued
- Assembly assistance
- Testing assistance

**Student 2 name: Amy Nielsen**

For project tasks in which I was **not** the leader, I provided the following inputs towards their completion:

- Used organization skills to make sure various tasks were completed in a timely manner.
- Provided advice for troubleshooting and revision of work
- Asked members to map out the problem from the beginning in order to find root cause issues or flaws in concept
- Quickly responded with research to backup concepts being explored
• Modeled systems for better visual understandings and pulled measurements from the models
• Provided resources like textbook material, Parker o-ring handbook, tables, and graphs
• Made final decisions on debated design choices

Student 3 name: Gavin Peddie

For project tasks in which I was not the leader, I provided the following inputs towards their completion:

• Asking good questions to make sure group members were considering all aspects of the design.
• Detailed conversations with group members about the progress of various tasks.
• Providing suggestions on how to improve.
• Created many hand sketches and diagrams to illustrate parts/assemblies and calculation concepts.
• Double checked the work of my peers (as well as them double checking my work).

Performance Indicator 3

For project tasks in which you were the leader, describe the input other group members provided towards the successful completion of these tasks.

Student 1 name: Joseph Bonnen:

• Offering factors to be addressed that had not been considered yet
• Software help where my own skills were lacking
• Questioning the form and function to make sure that the end product was the best it could be

Student 2 name: Amy Nielsen

• Question why I made a certain decision – helped me and them see if there were any obvious problems
• Revision of conceptual thoughts
• Provide reminders of important due dates
• Assist when needed for quick math, part assemblies, and prototype production
• Brainstorm with me to improve designs

Student 3 name: Gavin Peddie

• Group members provided SolidWork models for my designs and ideas.
• Group members helped to organize and present all equations and values prevalent in my calculations.
• Shared various equations and concepts that were learned from classes and work.
• Provided opinion on various light and servo sequences to be incorporated into the prototype.
• Attended meetings with Dr. Miller to learn about the electronics portion of the project.
Performance Indicator 4

List all goals this project had to satisfy to be considered successfully completed.

- The price of the fountain is to be affordable and competitive on the market.
- The music, water, and lights had to operate synchronously with each other while being separate systems.
- The design must be safe for the customer and comply with all safety standards.

Performance Indicator 6

(To be addressed by the faculty adviser)

Outcome (7) An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Performance Indicators:

1. Student’s ability to find information relevant to problem solution without guidance.
2. Student’s ability to identify the additional knowledge needed to complete project.
3. Student’s ability to acquire and apply the additional knowledge needed to complete project.

Performance Indicator 1

Describe what information you found in order to successfully complete the tasks you were assigned in the project.

Student 1 name: Joseph Bonnen

- Researched hydraulic lift design and operation
- Stress equations in order to perform safety factor analysis on the Lift
- Fluid equations to calculate the pressure from the pump to determine the minimum amount of strength needed to lift the piston
- Discussed with Dr. Fajardo about the piston design to make sure that the idea was sound
Student 2 name: Amy Nielsen

- Material research for all parts of fountain
- Simulation analysis in SolidWorks including FEA
- How to make a concrete basin
- researched various standards for proper fountain installation.
- Speaker bass frequencies and subwoofer vibration levels

Student 3 name: Gavin Peddie

- YouTube tutorial series on the basics of Arduino programming.
- Research on power supplies and conversations with Dr. Miller to learn how to set up effective electronic circuits.
- Equations to approximate losses within fluid systems.
- Compared prices of various parts and components to approximate the total cost of the design.
- I talked to some people at Lowes to get opinions on plumbing and wiring.

What sources did you use to find this information?

Student 1 name: Joseph Bonnen

- Western Michigan University Library
- Google Scholar
- Fundamentals of Fluid Mechanics eighth edition by Philip M. Gerhart, Andrew L. Gerhart, and John I. Hochstein
- How do Hydraulics Work – HP Hydraulics
- Parker O-ring Handbook

Student 2 name: Amy Nielsen

- Fundamentals of Fluid Mechanics eighth edition by Philip M. Gerhart, Andrew L. Gerhart, and John I. Hochstein
- All aluminum and nylon material sources found in the references on the last page
- Liquid Features – How to install outdoor fountain wiring
- Fountains – 10 things to know
- Hardrock – Why concrete
- WMU mechanical engineering class materials – statics, mechanics of materials, design of thermal systems, machine design, fluid mechanics

Student 3 name: Gavin Peddie

- Paul McWhorter YouTube tutorial series.
- Arduino coding sharepoints.
- Notes taken in: Mechanical behavior of materials, machine design, fluid mechanics, circuits and programming in C.
- Fundamentals of Fluid Mechanics eighth edition by Philip M. Gerhart, Andrew L. Gerhart, and John I. Hochstein
- Subtractive manufacturing processes for machining.
- McMaster-Carr, Amazon, Lowes, Home Depot websites for pricing.

**Performance Indicator 2**

Describe what additional knowledge/skills you needed to acquire or improve in order to successfully complete the tasks you were assigned in the project.

**Student 1 name**: Joseph Bonnen

- Needed to improve SolidWorks skills
- Reviewed fluid mechanics
- Improved explanations of systems
- Gain a working knowledge on the function and operation of hydraulic lifts

**Student 2 name**: Amy Nielsen

- Improvement on simulation analysis and modeling in SolidWorks
- Improvement on MathCAD and excel
- Improvement on teamwork skills, communication, and compromise
- Improvement on leadership and presentation skills
- Improvement on research skills
- Knowledge of PLA filament and further improvement with 3D printing
- Knowledge of major and minor losses in pipe systems
- Improve application of Bernoulli fluid calculations and stress FOS

**Student 3 name**: Gavin Peddie

- Improvement in matlab to keep an organized program that keeps track of variables.
- Improvement in Solidworks (I have NX experience, but WMU does not have a license).
- Knowledge and experience with 3D printing.
- An improved understanding of series and parallel fluid system analysis.
- Advanced Arduino programming skills including the use of interrupts, the timer function, and port manipulation.
- Becoming a more confident presenter.
- More expansive knowledge of various materials.
Performance Indicator 3

Describe what approach/process you followed in order to acquire or improve the additional knowledge/skills you needed.

**Student 1 name:** Joseph Bonnen

- I worked with the programs and asked those more experienced than me to show me how to use necessary functions for SolidWorks
- The group tracked down a fluid mechanics textbook from the library which I used to review and study from to incorporate the information into the design
- I performed research on hydraulic lifts using library resources and other external sources to learn how hydraulic lifts function
- I sought out those with more knowledge than myself to help guide me through various problems I was facing

**Student 2 name:** Amy Nielsen

- Ask for help from professors and engineers at FEMA
- Spent time researching online and reviewing previous class work
- Bought parts and messed with them to understand them better (i.e. the pump, tubes, manifolds, ball valves, speaker w subwoofer)
- Spent hours on SolidWorks to learn new ways to mate assemblies
- Mess with different bass levels from YouTube videos on the speaker to find the right frequency to make the water bounce well

**Student 3 name:** Gavin Peddie

- Online research including many informational videos.
  - Kept a notebook where I documented everything, I learned in order to reference it later.
- Asked professors for assistance when I felt stuck on a particular topic.
- Dug through notes and textbooks from previously taken classes to find useful equations.
- Researched how plumbing, electronics, and various mechanical parts are used in engineering applications to obtain a greater understanding.
References


JOSEPH BONNEN
Phone Number: 248-804-7538 (Please leave a message) | E-Mail: jebonnen@gmail.com

Objective  Dedicated individual seeking a career in the engineering field. Detail oriented and creative with a drive to succeed.

EDUCATION
WESTERN MICHIGAN UNIVERSITY
Fall 2018 – Present:
  • Bachelor of Science in Mechanical Engineering. GPA: 3.0
  • Expected Graduation: Fall of 2022

WALLED LAKE CENTRAL HIGH SCHOOL
May 2018:
  • Received diploma and graduated magna cum laude with a GPA of 3.81
  • Graduated from the high school’s chapter of the National Honor Society

EXPERIENCE
Summer of 2022:
  Intent Design (Contracted to Toyota)
  • Ensured hundreds of parts daily were assembled correctly and shipped on time.
  • Reviewed bills of materials for successful assembly of components being shipped
  • Made strategic changes to parts being assembled in order to keep up with demand

Summer of 2021:
  Calhoun County Road Department
  • Quality tested and inspected asphalt being laid.
  • Measured the traffic on the county roads
  • Inspected silt fence installation across the county
  • Inspected construction done to maintain various roads such as slope restoration and skip paves

Summer of 2020:
  Michigan Department of Natural Resources, Pontiac Lake Recreation Area
  • Maintained Pontiac Lake Park grounds and help run park operations
  • Maintained campground and dealt with the public. Learned good communication skills
  • Learned valuable teamwork skills to accomplish tasks in a timely fashion

SKILLS
  • AutoCad Software
  • SolidWorks Software
  • Oracle Software
  • Fast Learner
  • Creative
  • Critical Thinking
  • People Skills

ACTIVITIES
  • Member of the Western Aerospace Launch Initiative’s (WALI) thermal sub-team
Amy Nielsen

+1 231 620 2773 | amynielsen436@gmail.com | https://www.linkedin.in/amynielsen436

Education

BACHELOR OF ENGINEERING | WESTERN MICHIGAN UNIVERSITY (WMU) | SENIOR
- Major: Mechanical Engineering
- GPA: 3.59
- Expected graduation: December 2022
- Related: Lee Honors College, Solar Car Team
- Awards: Dean’s List each term, WMU Achievement Award 1, State of MI Scholarship for 2 consecutive years

ASSOCIATE OF SCIENCE AND ARTS | NORTHWESTERN MICHIGAN COLLEGE (NMC) | MAY 2019
- Major: Engineering
- GPA: 3.59
- Awards: Dean’s List each term, graduated with honors

HIGH SCHOOL DIPLOMA | TRAVERSE CITY WEST SENIOR HIGH | JUNE 2018
- General curriculum with early-middle college classes
- GPA: 3.87
- Awards: National Honor Society, Excellence in the World Languages Department, graduated with honors

Experience

MECHANICAL ENGINEERING INTERNSHIP | FEMA CORPORATION | SEPTEMBER 2020 – PRESENT
- Assemble and test 4 types of hydraulic valves by hands-on production
- Set up and perform more than 5 different hydraulic tests in the Engineering Laboratory
- Purchase over $500 worth of material necessary to the Engineering Laboratory
- Perform internal audits for the company to ensure ISO 17025-2017 standards are met
- Develop organizational skills and time management to properly meet deadlines for over 7 independent projects
- Create model designs and drawings using GD&T, perform tolerance stack-ups, and other engineering calculations

MEMBER | SUNSEEKER SOLAR CAR TEAM AT WMU | SEPTEMBER 2019 – JUNE 2020
- Designed the hub for the 2020 solar car through SolidWorks 3D modeling software
- Designed and constructed the 10 supports needed to hold up the car fiber glass layers
- Built a body layer of the car by performing 3-4 fiber glass and carbon layups on Styrofoam molds
- Established a company sponsorship with Arconic and collected a $10,000 donation worth of aluminum material

PRODUCTION WORKER | SKILLED MANUFACTURING INC. | JUNE 2019 – AUGUST 2019
- Deburred 30 hand-sized aluminum parts per day and ball-sized 50 of those parts per hour using Opti-touch automation machine
- Learned the importance of production safety and optimization

ASSOCIATE | PAESANO’S PIZZA | AUGUST 2017 – AUGUST 2019
- Provided customer service and managed opening lunch shifts
- Made over 8 different types of pizzas, 3 salads, and 4 subs while maintaining the ovens

Skills
- Proficient in NI-MAX, NI-DAQ, and LABVIEW
- Proficient in SolidWorks over its multiple interfaces
- Proficient in Microsoft Word, Excel, OneNote, and Teams
Gavin T. Peddie

Kalamazoo, MI 49009 • Phone: (616) 498-8341 • Email: gavin.t.peddie@wmich.edu

OBJECTIVE
To work for an organization that will challenge me every day to maximize my engineering potential. I want to utilize my diverse set of engineering skills to help the company grow.

EDUCATION
Western Michigan University
I am a senior at Western Michigan University with a current GPA of 3.8. I am double majoring in mechanical and aerospace engineering and plan to graduate fall of 2022. I have also made the dean’s list every semester that I have been at Western.

Grandville High School
Graduated high school with a 4.26 GPA with an extremely rigorous schedule consisting of almost all AP or honors classes.

EXPERIENCE
Williams International, Pontiac MI - Production Support Intern May 2022 – August 2022
- Worked with a team of engineers to aid in the production of fanjet engines, military propulsion systems and other Williams’ products.
- Used GD&T skills, CAD software, and complex geometry to fix and improve various parts and assemblies.

Accomplishments:
- Revised the drawing and remodeled the components of a diffuser assembly for military cruise missile propulsion system.
- Revised a set of bell moutch inlet tools used for testing of commercial fanjet engines.

Wright Coating Technologies, Kalamazoo MI – Part Manufacturer August 2021
- Collaborated with a team to prepare, assemble, and package solar panel technology.

DoorDash Driving, Grandville & Kalamazoo MI – Delivery Driver March 2020 – Present
- Self-employed during the summer of the Covid-19 pandemic and had self-discipline to stick to a consistent work schedule.
- 4.9-star rating and completed all orders on time.

Sinclair Recreation, Holland MI - Playground Contractor May 2018 – August 2020
- Planned the layout to make sure the playground would fit into the space provided and would comply with government safety regulations.
- Used linear mathematics to plot where holes needed to be dug for the playground posts.

GENERAL SKILLS
- Great at analyzing problems and identifying solutions because of my ability to think critically and learn quickly.
- I have a high level of self-confidence which allows me to work well under pressure and adapt to changes.
- A strong work ethic and will persevere through difficult obstacles. This helps me to be an extremely dependable individual as well as a valuable member of any team or group.
- I am very neat with my work which allows others to clearly see my thought process of how I arrived at a solution.
- Effective communicator of complex engineering and physics topics in layman’s terms.

TECHNICAL SKILLS
- Proficient in CAD modeling and drawing software (NX) as well as GD&T.
- Arduino/MATLAB coding and some electronic circuit experience.
- Fluid mechanics and aerodynamics.
- Statics and dynamics.
- Orbital Mechanics, and propulsion systems.

CLASS PROJECTS
- Financial optimization orbital mechanics satelitite orbital mission project. (A)
- Aircraft structural optimization design and finite element analysis of aircraft fuselage section. (B)
- Payload delivery to Mars spacecraft propulsion system design project. (A)
- Mechanics and applications of the turboshaft engine paper and presentation. (A)
- Designing, and building a musical fountain prototype for my senior design project. (In progress)

EXTRA CURRICULAR
Varsity Football – Placekicker August 2018 – January 2022
- Won the starting placekicking job as a true freshman walk on and went on to finish the season with 69 points scored and a 75% field goal percentage. Earned a full scholarship after my first year.

WMU Mascot – Buster Bronco February 2022 – Present
- Used my limitless energy to interact with fans, throw t-shirts, heckle opposing team, and hype up the crowd. I also brainstormed creative ways to get on the jumbotron and entertain the crowd.