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Design and Build of a Paintbrush Washer

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Abstract

Cleaning a paintbrush is a time-consuming and wasteful process. This project aims to design and build a paintbrush washer that cleans a paintbrush in under three minutes while retaining the cleaning medium for future use. The prototype will clean 1 to 3-inch-wide paintbrushes saturated with either water-based or oil-based paints. The design will feature nozzles that spray the cleaning medium through the bristles while the linkage moves the nozzles across the width of the paintbrush. The prototype accomplishes this with the use of a pump, motor-driven linkage, and pipe/nozzle system. The required nozzle exit velocity was found experimentally, and a pump was selected based on the loss in the piping system and the desired flow rate. Experiments were conducted to verify these design choices. These experiments demonstrated that the paintbrush washer cleans a paintbrush in under three minutes.

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Symbol	Description
t_p	Time for one pass across the paintbrush (seconds)
R	Rotational rate (revolutions per minute)
Q	Volumetric flow rate (gallons per minute)
V	Velocity (feet per second)
A	Area (square feet)
$h_{L\ total}$	Total head loss (feet)
h_{L1}	Total head loss from strainer through tee (feet)
h_{L2}	Total head from tee through nozzles (feet)
h_e	Elevation Head Loss (feet)
h_f	Major and minor Losses (feet)
z_f	Final height (inches)
z_i	Initial height (inches)
f	Friction factor (unitless)
L	Length of pipe (inches)
D	Diameter of pipe (inches)
K_L	Loss coefficient (unitless)
g	Gravity (inches per second squared)
ε	Surface roughness (inches)
ρ	Density (pound per cubic inch)
μ	Dynamic viscosity (pound second per square inch)

1.0 Introduction

Cleaning a paintbrush can be a time-consuming and wasteful process. Whether water or paint thinner is used as a cleaning medium, the user must use their hands during the cleaning process. This can be dangerous to the user due to harmful chemicals in some paints as well as cleaning mediums such as paint thinner **[6]**. There also is significant waste during the cleaning process from leaving a faucet running or pouring too much paint thinner from its container. The objective of this project is to design and build a paintbrush washer that cleans paintbrushes saturated with oil-based or water-based paints. The paintbrush washer will mitigate the dangers of cleaning a paintbrush by containing the cleaning medium within the device and not exposing the user to harmful chemicals. It will also reduce the time it takes to clean a paintbrush. With these goals in mind a list of requirements was developed. The paintbrush washer shall wash a paintbrush in under 3 minutes, wash chisel style paintbrushes sized 1 inch to 3 inch, use paint thinner or water, recover and reuse the cleaning medium, be able to drain the cleaning medium, be leak free, have a footprint smaller than 1.5 square feet, and operate from a household 110-volt outlet.

2.0 Background

A paintbrush is considered clean when all of the paint is washed from the bristles. Once the paintbrush dries, the bristles will be soft and nimble, and no dried paint will be in between the bristles. Devices have been designed to try and make the cleaning process of a dirty paintbrush easier. These devices have tried to either decrease the time needed to clean a paintbrush or reduce the waste associated with the cleaning process. Below is a discussion of three devices that aim to do this.

2.1 University of Illinois Team 65

One device designed to aid in the cleaning process is the 2020 University of Illinois Team 65's Electric Paintbrush Cleaner shown in Figure 1 below **[1].** This design allowed the user to place a paintbrush in a cleaning receptacle. Once the device was turned on, the cleaning receptacle would fill with a cleaning medium and drained into a filtration tank once it was dirtied. An LCD screen was used to show the current pH of the cleaning medium in the tank. The cleaning medium would be returned to a desired pH via treatment chemicals, and the receptacle would be refilled via a pump and solenoid valve. This design was never built and tested so its effectiveness is unknown. However, knowing the pH of the cleaning medium may be necessary to ensure adequate cleaning.

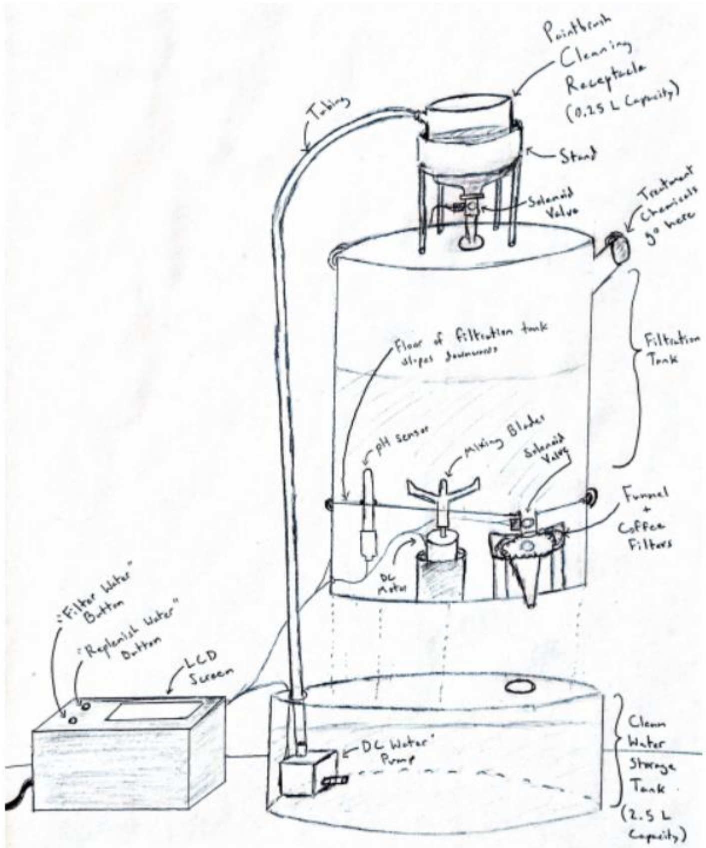

Figure 1. Electric paintbrush cleaner ***[1]***

2.2 Ryobi

Another way of cleaning a paintbrush is by using Ryobi's Bc400 Paint Brush Cleaner shown in Figure 2 below **[7].** This device cleaned a paintbrush by inserting the paintbrush between a set of rollers. The rollers squeezed and brushed the paint out of the paintbrush with the help of a cleaning medium such as water or paint thinner. Physical contact with the bristles of the paintbrush poses a risk of damaging them during the cleaning process. Because of this issue, physical contact with the paintbrush, other than a cleaning medium, should be avoided to mitigate damage to a paintbrush.

Figure 2. Ryobi paint brush cleaner ***[7]***

2.3 Paint Brush Cleaning Device Patent

The next way to clean a paintbrush is by the "Paint brush cleaning device" shown in Figure 3 below **[2]**. This patented device used spiral-shaped brushes to wipe the paint out of the stationary paintbrush. A cleaning medium was sprayed on the spiral-shaped brushes as well as the user's paintbrush. This device allows the user to attach a hose to the device and have a continuous supply of fresh cleaning medium. This device also had a physical contact with the user's paintbrush which could damage the bristles. However, the spraying of the cleaning medium does not damage the bristles. This method of cleaning via spraying is more effective and safer for the paintbrush.

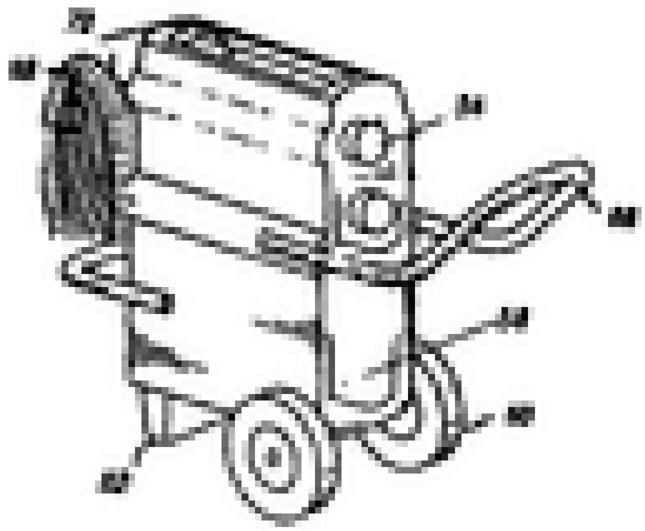

*Figure 3. Paint brush cleaning device patent **[2]***

3.0 Design Concepts

These previous designs did not meet the requirements set for the prototype. Some features will be utilized such as spraying a cleaning medium onto the paintbrush. Others, such as a physical interface with the paintbrush, will be avoided to prevent damage. The next few sections include a discussion of several concepts that helped drive the design process.

3.1 Vertically Translating Nozzle Concept

The first conceptual design considered was the vertically translating nozzle concept. This concept can be seen below in Figure 4. This concept required the user to turn a crank which would move the nozzles vertically via two pulleys, a belt, and a lead screw. A guide rod was used to keep the nozzle pointed at the paintbrush.

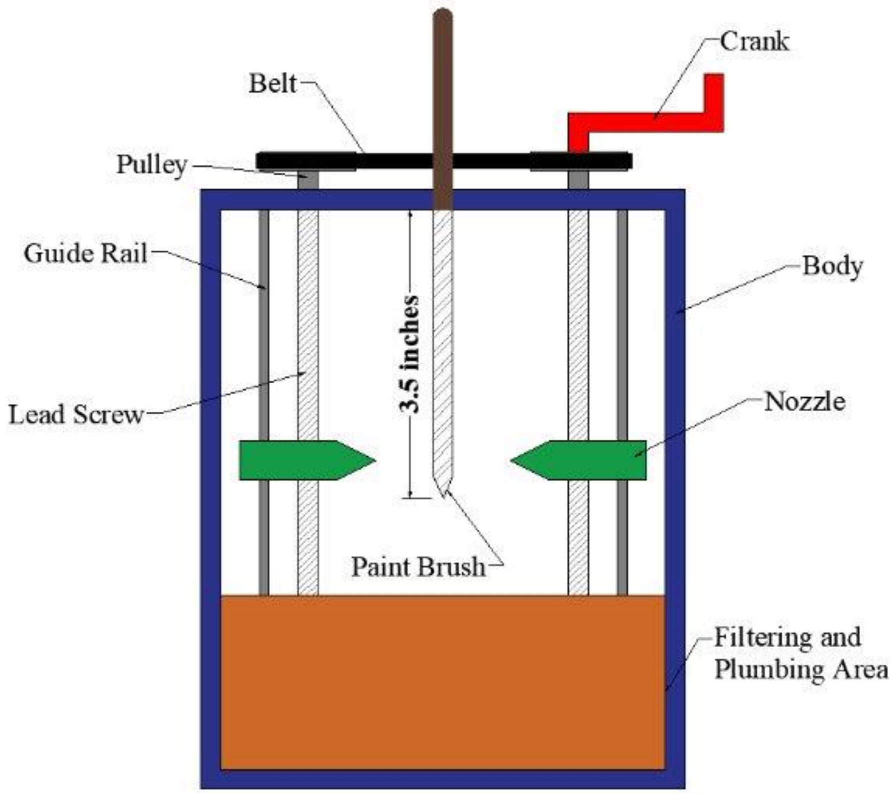

Figure 4. Vertically translating nozzle concept (side view)

There are a couple advantages for this concept. The movement of the nozzles will help to wash the paint of the bristles. This allows for a more effective cleaning process. The other advantage of this concept is that the nozzle spray pattern will cover the entire area of the bristles due to the vertical movement. This means the whole paintbrush will be cleaned.

The biggest disadvantage with this concept is the user must physically interact with the device during the entire cleaning process. Another disadvantage for this concept is that the spray pattern did not penetrate the bristles of the brush. The spray pattern of the nozzle would be horizontal while the bristles would be vertical. This means the cleaning medium would not penetrate the bristles fully resulting in inadequate cleaning. For these reasons, this concept was abandoned in favor of other concepts.

3.2 Stationary Nozzle Array Concept

The next concept considered was the stationary nozzle array concept seen below in Figure 5. This concept includes six stationary nozzles with three on either side of the paintbrush. This design requires six different pipes to supply the cleaning medium to the nozzles. No movement is required in this design.

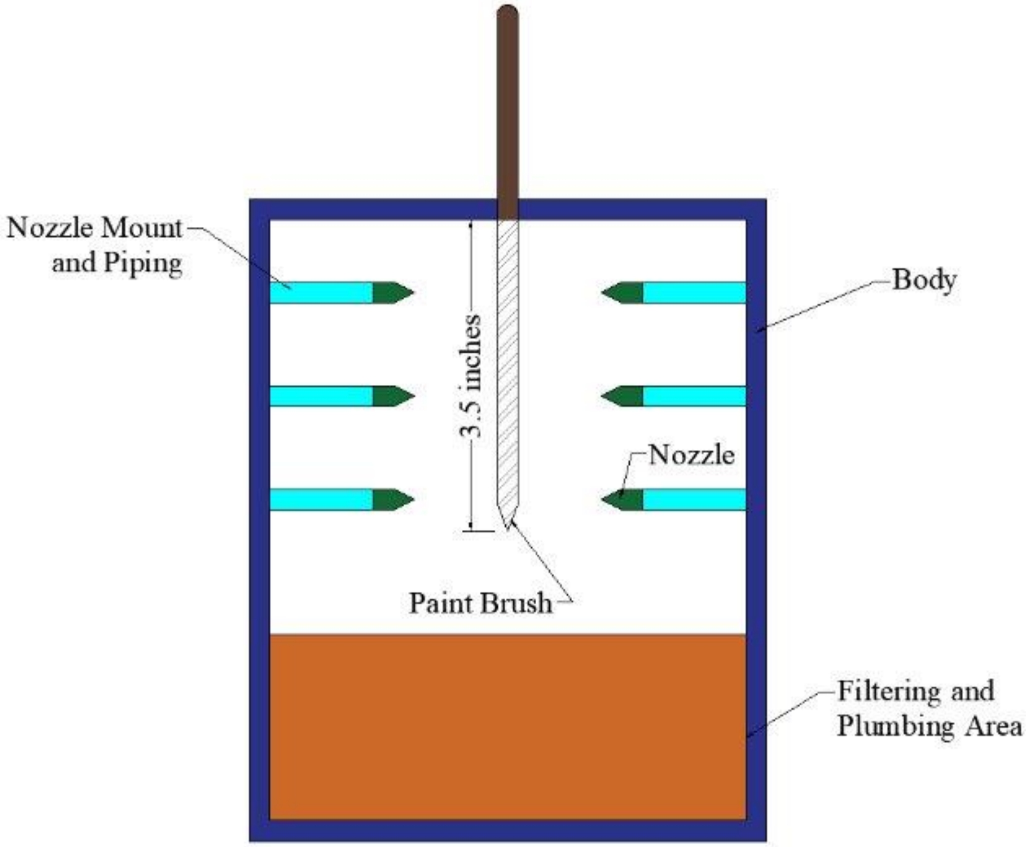

Figure 5. Stationary nozzle array concept (side view)

The advantages of this concept includes no movement and no user input required. No movement in the nozzles means no complex mechanism is required. This saves space as well decreases the chance of a system malfunction. No user input required means the user can insert the brush into the device and walk away. This allows the user to perform other tasks while the paintbrush washer is operating which saves the user time.

One of the disadvantages for this concept is the requirement of a larger capacity pump. With more nozzles, more flow is required to achieve an equal spray pattern from each nozzle. With more nozzles, more piping is also required. This takes up more space and adds more weight to the system. Another disadvantage of this system is the cleaning medium will not be sprayed on the entire surface area of the brush. With the nozzles stacked on top of each other and no movement involved, areas between the spray patterns will not receive adequate cleaning medium resulting in poor cleaning of the brush. This concept also uses horizontal nozzles which is another disadvantage.

3.3 Oscillating Nozzle Concept

The next concept considered was the oscillating nozzle concept shown below in Figure 6. This concept includes two oscillating nozzles with a vertical spray pattern. The nozzles will oscillate via a link that is driven by a motor in the plumbing area.

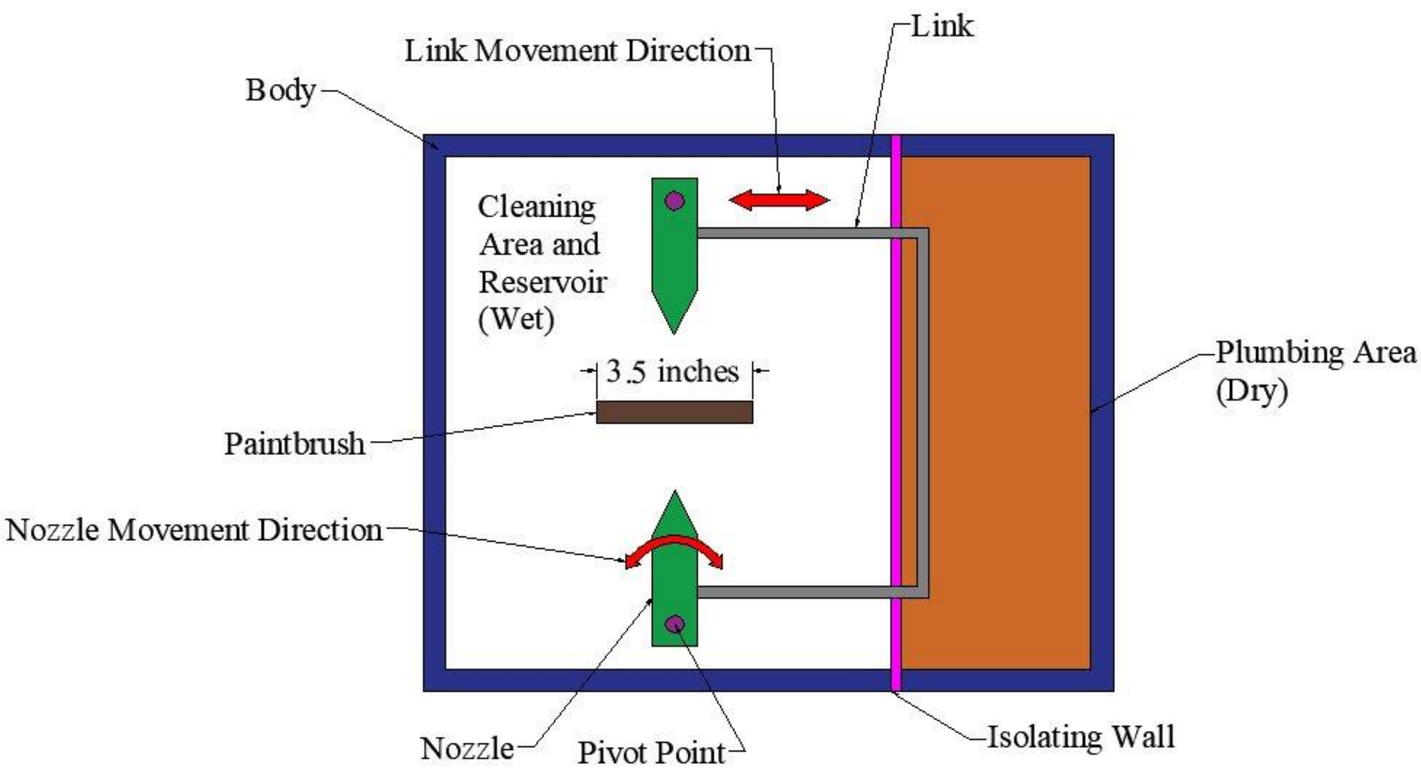

Figure 6. Oscillating nozzle concept (top view)

Two main advantages of this concept are the addition of a motor and the orientation of the spray pattern. With the addition of a motor, the user will not have to interact with the device during the cleaning process. Also, an isolating wall must be included to separate the electrical motor from the liquid cleaning medium. This is necessary to prevent damage to the motor during the cleaning process. Since the spray pattern orientation is now vertical, the cleaning medium can fully penetrate the bristles of the paintbrush ensuring all paint is dislodged and the paintbrush is fully cleaned.

The main disadvantage to this concept is the inconsistent distance between the end of the nozzle and the paintbrush. As the nozzles oscillate and reach the end of their path, the separation between the brush and nozzle will be greater than when the nozzle is in its middle position. Due to this change in distance, inconsistent cleaning could occur.

3.4 Horizontally Translating Nozzles

The final concept is the horizontally translating nozzle concept shown in Figure 7 below. This concept also includes two vertically oriented nozzles connected to a linkage, which moves across the entire width of the paintbrush without rotation. The linkage will be driven via a motor housed in the plumbing area.

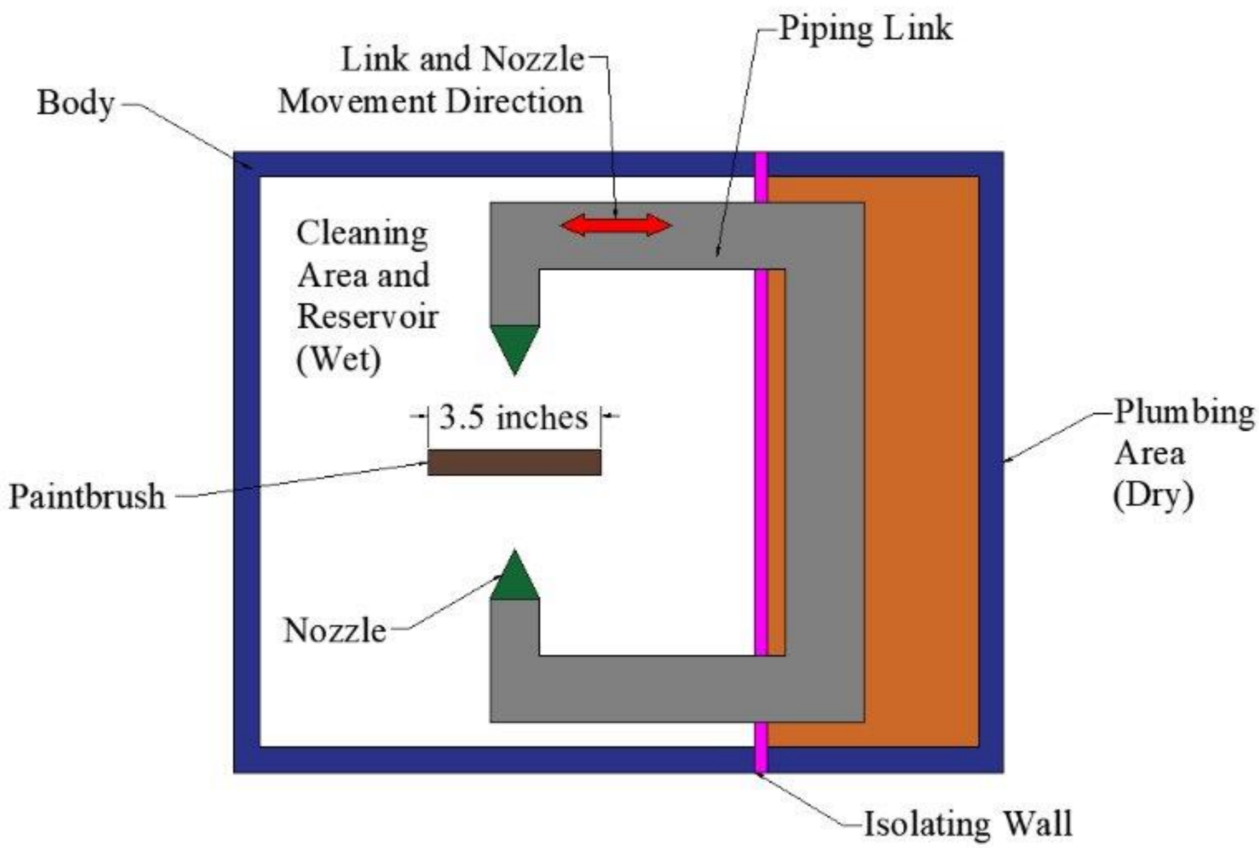

Figure 7. Horizontally translating nozzle concept (side view)

The biggest advantage to this concept is the consistent separation between the nozzles and the paintbrush during the entire cleaning process. Since the nozzles are connected directly to the piping link and no longer oscillate, the distance between the nozzles and paintbrush does not change. This will ensure even and adequate cleaning during the entire process.

The biggest disadvantage to this concept is the amount of room needed to accommodate the piping link and nozzles. The link must move nearly 3.5 inches during the cleaning process. This means the plumbing area as well as the cleaning area must be large enough to fit the piping link as it moves. An increase in size of the plumbing area and cleaning area will make the overall size of the body larger which could make the device larger than 1.5 square feet.

4.0 Design

4.1 Nozzle Movement System

In order to move nozzles during the cleaning process, a nozzle movement system must be designed. Several components were developed including a link, crank, and motor to make the desired movement possible. The next few sections will discuss this movement system.

4.1.1 Linkage

The linkage is one of the most important parts of the paintbrush washer as it is responsible for moving the nozzles across the paintbrush. The linkage used in the prototype can be seen below in Figure 8. A motor, shown in red, drives the linkage. The motor mount, shown in yellow, supports the motor. The first component of the linkage, shown in light grey, is the crank. The second linkage component, shown in orange, is the piping link. The drawer sliders are shown in lime green and purple. The nozzles are threaded into the piping link and are shown in dark green.

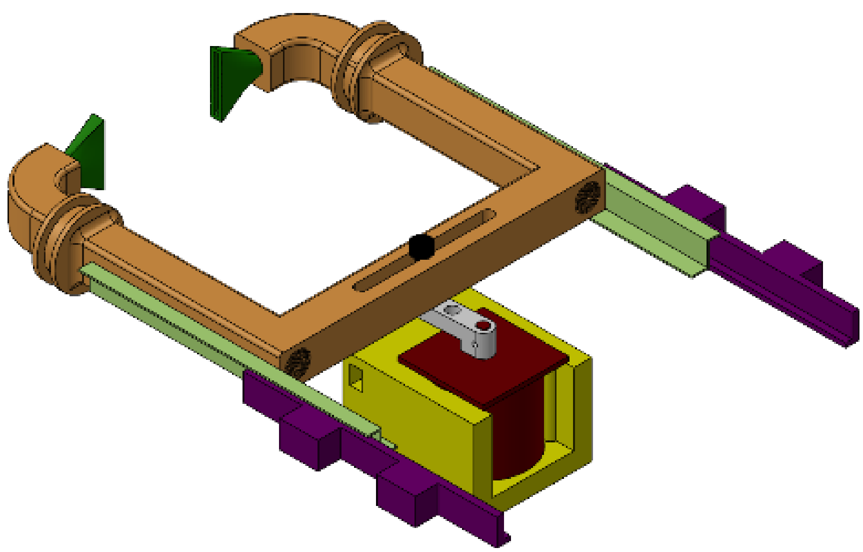

Figure 8. Linkage overview

A bolt shown in black in Figure 8 above connects the piping link to the crank so that as the motor turns the crank, it translates the piping link. The slot in the back of the piping link acts as a slider thus enabling the back-and-forth motion. The crank features three holes through the link. The first hole has a profile that matches the shape of the motor shaft. The other two holes control how far the nozzles move with the outer hole moving the nozzles 3.25 inches and the middle hole moving the nozzles 1.625 inches. This allows the user some adjustability for different sized paintbrushes. The crank can be seen below in Figure 9.

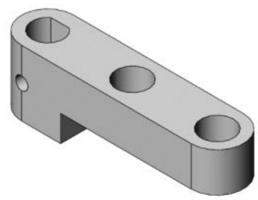

Figure 9. Crank

The initial piping link can be seen below in Figure 10. This link fits inside of the preliminary body which can be seen below in Figure 11. The preliminary body features a cleaning reservoir and a dry pumping reservoir. The link also offers an attachment point for the nozzles with the holes at the end of the link. Problems with this link include requiring four penetrations through the middle wall of the body which is not ideal for keeping the prototype leak free and no way to support the link as it moves.

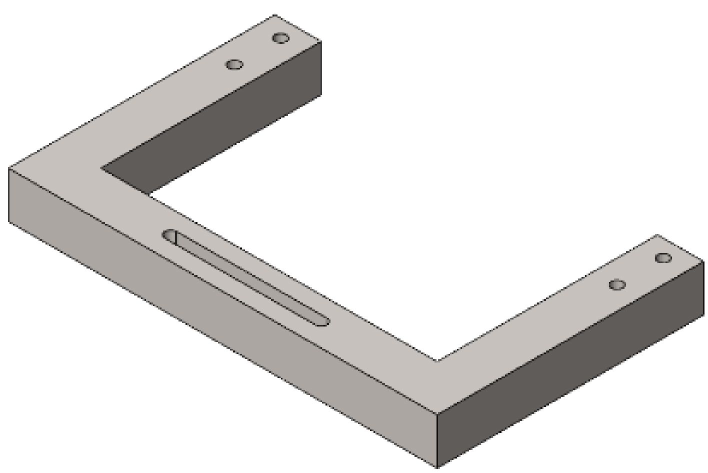

Figure 10. Initial piping link

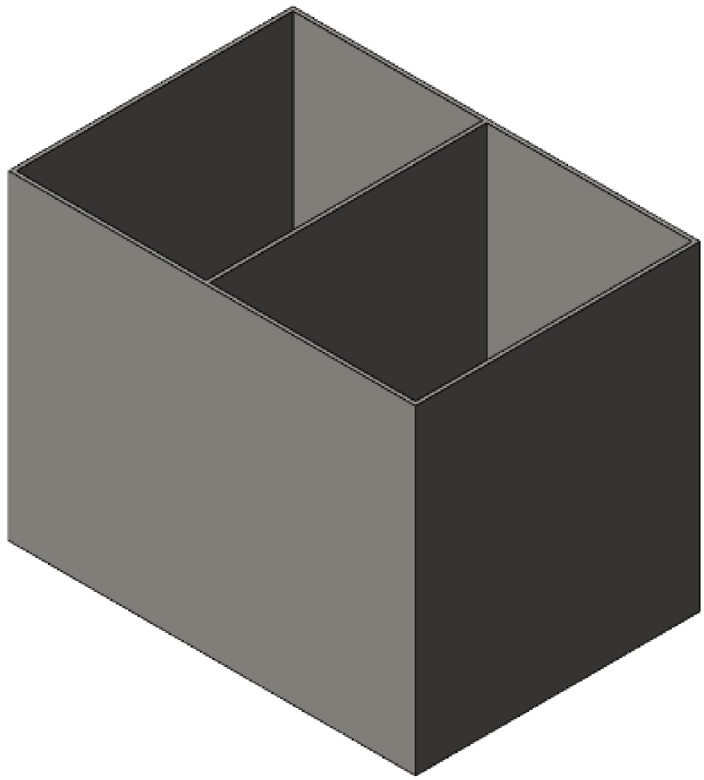

Figure 11. Preliminary body

The next version of the piping link added internal piping. This was a large development in the design. It combined part of the piping system and the piping link into one piece. This had several benefits: it decreased the number of parts, eliminated two wall penetrations, and simplified the piping. This version also added a 90 degree bend at the end of the link. This directed the cleaning medium towards the paintbrush and allowed the nozzles to be threaded into the end of the link. This version can be seen below in Figure 12.

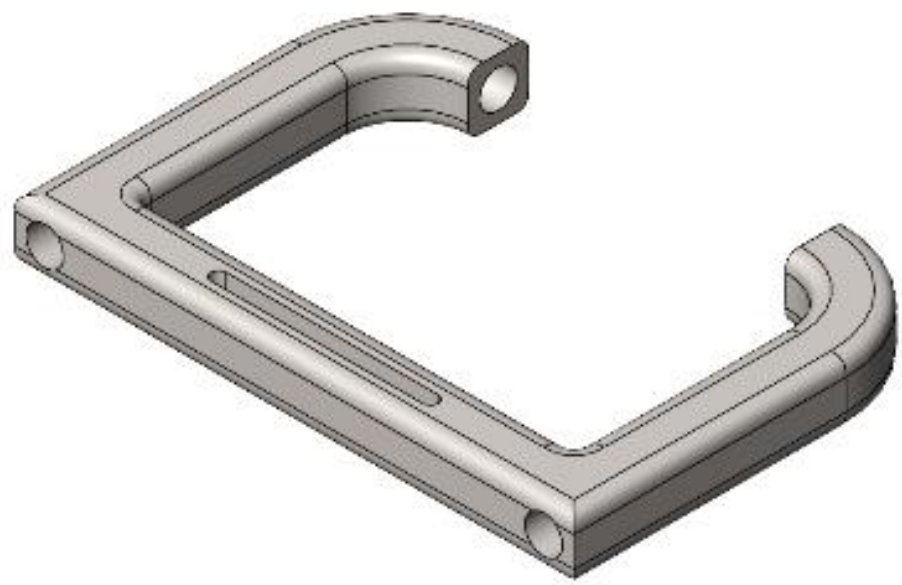

Figure 12. Second version of the piping link.

As a way to support the piping link shown above in Figure 12, the next version utilized a dovetail system. A diagram of a dovetail system can be seen below in Figure 13.

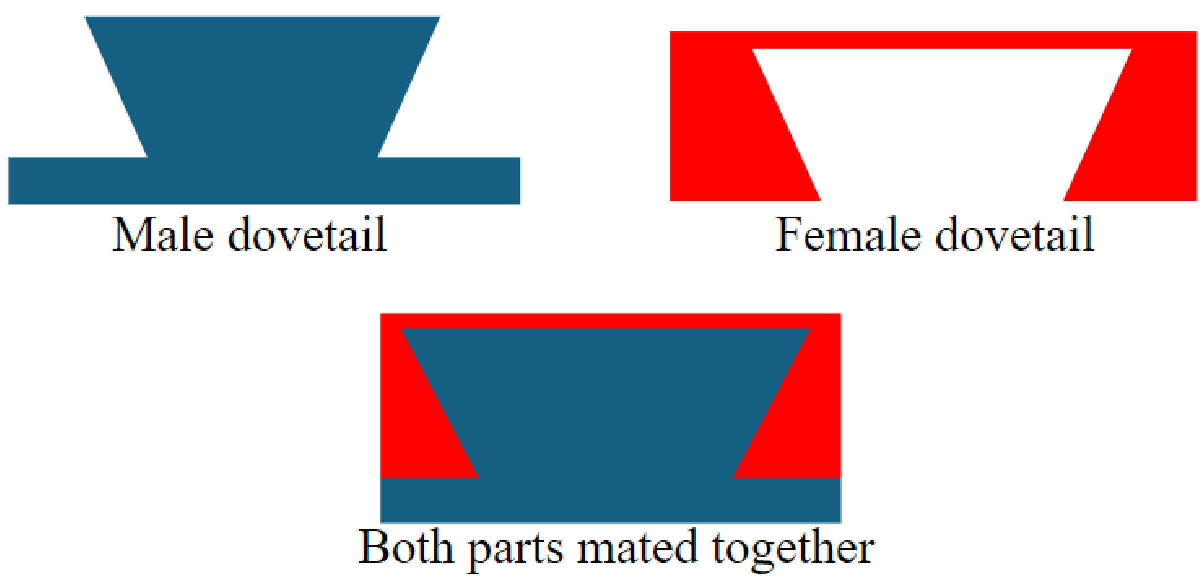

Figure 13. Dovetail diagram.

A male dovetail was added onto the sides of the piping link which would support the end of the link. This version required the addition of a female dovetail piece which would be attached to the external walls of the body. This added extra holes through the external walls of the body which would be prone to leaking. This version is shown below in Figure 14.

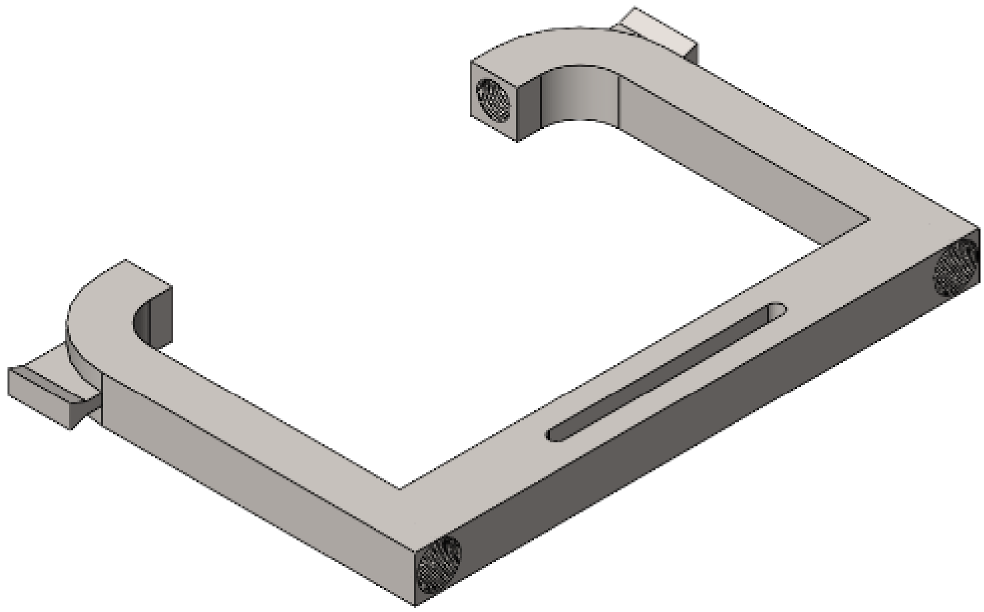

Figure 14. Third version of the piping link

Concerns about sealing the holes in the external walls and middle wall (known as the isolating wall in the concepts) contributed to the decision to move to the next version. The next version added a male dovetail to the top of the piping link which eliminated the need for a female dovetail on the external walls. This version also added threads for a pipe connection at the back of the link which will be where the pipe from the pump connects to the link. This version can be seen below in Figure 15.

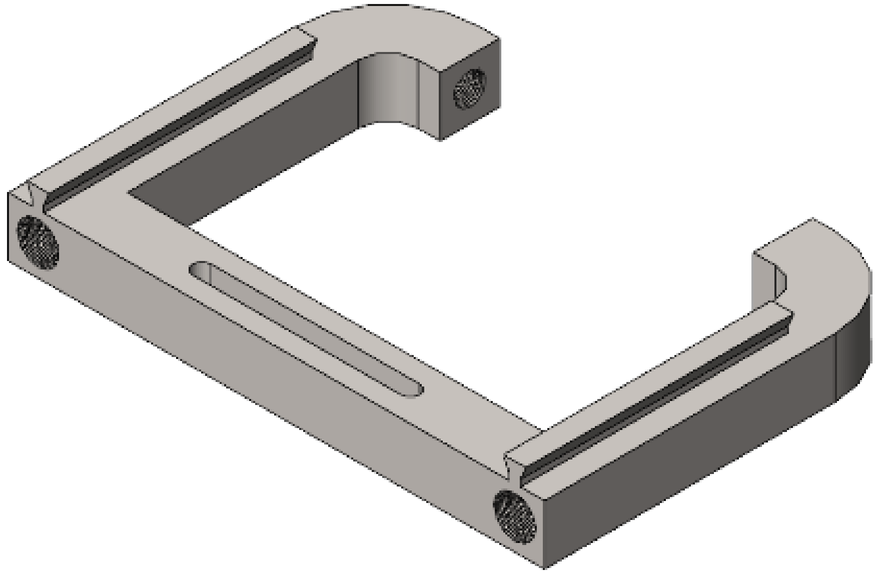

Figure 15. Fourth version of the piping link

The female dovetail that supports the link is featured as part of the upper middle wall. The upper middle wall used to support the piping link can be seen below in Figure 16.

Figure 16. Upper middle wall with dovetail

An image of the piping link and the upper middle wall assembly can be seen below in Figure 17.

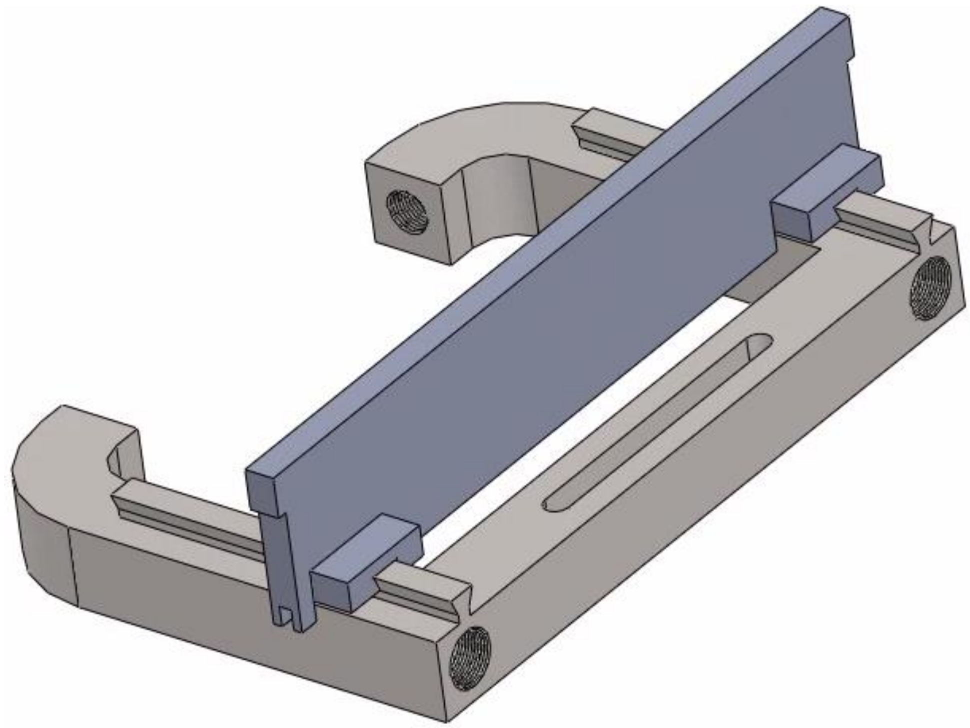

Figure 17. Piping link and upper middle wall assembly

These parts were 3-D printed, and the motion was tested. The dovetail design caused binding in the piping link when in motion. Several modifications were experimented with to try and solve the binding issue. The tolerances between the male and female dovetails were changed but this had no effect. A flexure was then used to connect the female dovetail and upper middle wall in order to mitigate these binding issues. This flexure was tested but proved to be unsuccessful. An image of the compliant dovetail part tested can be seen below in Figure 18.

Figure 18. Upper middle wall with flexures

With the binding issues unresolved, another way to support the piping link was explored. The next method used drawer sliders to support the piping link. The set of drawer sliders used can be seen below in Figure 19 **[9]**.

*Figure 19. Drawer sliders **[9]***

As can be seen in Figure 19 above, the drawer sliders have two parts: one attached to each side of the body, and one attached to each side of the piping link. Once each half is assembled, they are only able to move in one direction. These drawer sliders help to eliminate the binding issues associated with the previous version. One part of each half is mounted on the piping link via bolts while the other part is welding onto spacers. An image of the drawer sliders mounted onto the piping link can be seen below in Figure 20.

Figure 20. Fifth version of the piping link with one half of drawer sliders attached

The spacers are needed to properly position the linkage and were welded onto the body walls. An image of the sliders and spacers mounted on the body can be seen below in Figure 21.

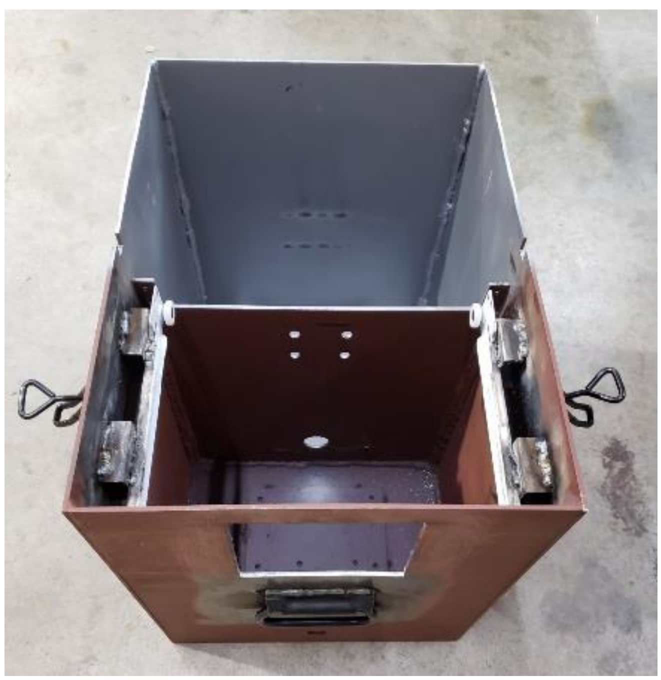

Figure 21. One half of drawer sliders mounted in the body

The next version of the piping link was made longer to accommodate the addition of bellows and allow them room to compress. A full discussion of the bellows can be found in Section 4.3.5. Bellow keepers were also added onto the end of the piping link. This would secure the bellows to the end of the link and force them to move with the link.

When new bellows were chosen, the bellow keepers had to be modified. This change resulted in the final version of the piping link which can be seen below in Figure 22. This version also included small holes on the sides of the link in which brass inserts would be installed. The drawer sliders would then be bolted onto the link using the brass inserts. The link was 3-D printed with polyethylene terephthalate glycol (PETG). PETG is stronger and is more chemically resistant than other common filaments such as polylactic acid (PLA). This material prevents deterioration of the piping link from paint thinner. **[12]**

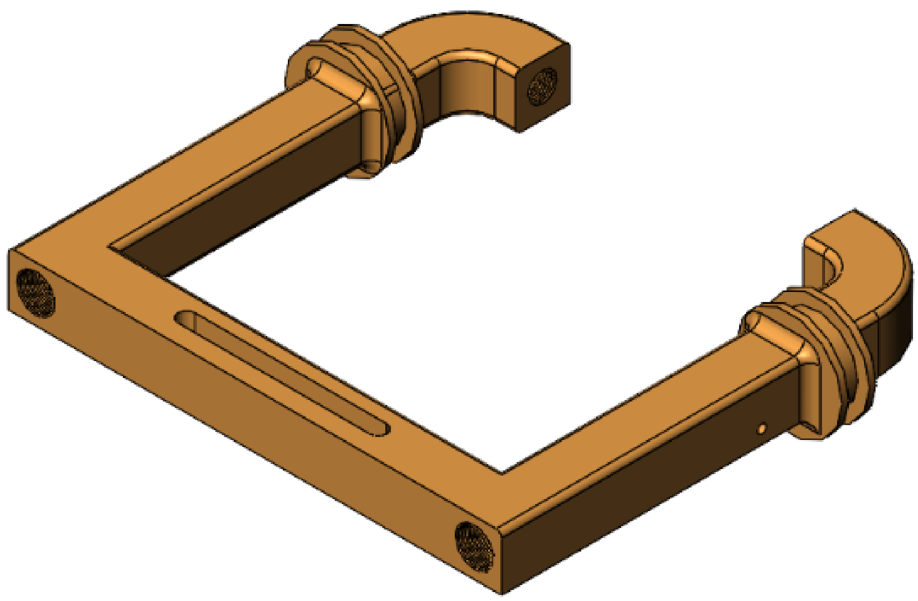

Figure 22. Final version of the piping link

4.1.2 Motor

A motor was required to fully automate the nozzle movement system. Several small AC motors with different options for rotational rates were found. To select the motor, calculations were performed to find the time it takes for the nozzles to make one pass across the paintbrush.

Using Equation 1 below, the time for one pass was calculated for multiple motors with different rotational rates.

$$t_p = \frac{1}{2}\left(\frac{60}{R}\right) \qquad 1$$

Using Equation 1, the time it takes for one pass across a three-inch paintbrush for a rotation rate of 2.5, 5, and 10 revolutions per minute was found to be 12, 6, and 3 seconds respectively. The team experimented with these times and decided that six seconds per pass was ideal, so the motor with the rotational rate of five revolutions per minute was selected. This time was chosen because it allows the nozzles enough time to fully penetrate the bristles while keeping a high number of total passes per cleaning cycle. This allowed the nozzles to have enough time to thoroughly wash out the paintbrush. An image of the motor used can be seen below in Figure 23 [3].

Figure 23. Selected motor ***[3]***

A motor mount was designed to properly position and support the motor. The motor mount has slots which will be used to bolt it to the lower middle wall. Small screws were threaded into the holes through the motor and in the top of the motor mount to prevent the motor from spinning. An image of the motor mount can be seen below in Figure 24.

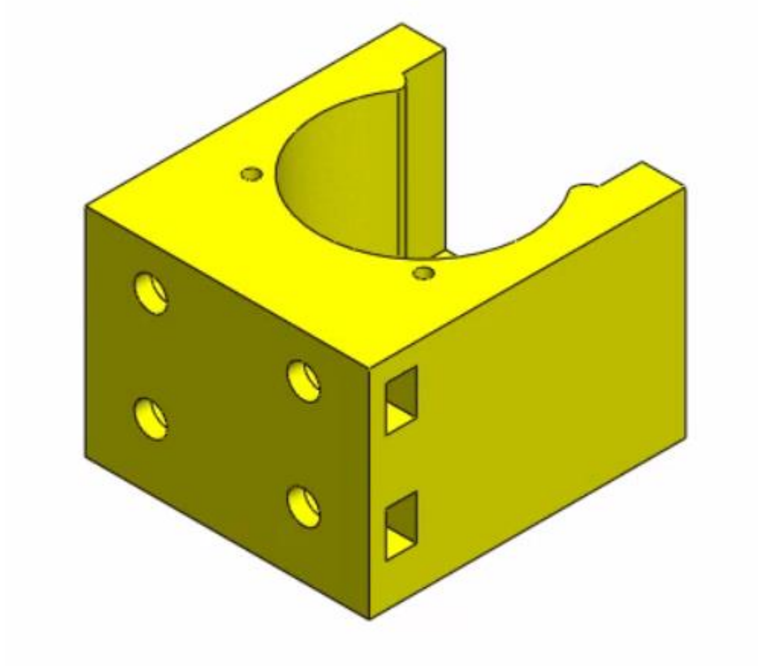

Figure 24. Motor mount

4.2 Pump and Piping System

4.2.1 Preliminary Experiment

Two important parameters that would affect the performance of the paintbrush washer are the flow rate and the nozzle exit velocity. Of these, the most important parameter is the cleaning medium exit velocity from the nozzles. The high velocity medium would be responsible for penetrating through the bristles to ensure that all paint was dislodged from the brush. The flow would be responsible for carrying dislodged paint from the bristles. To determine a desired nozzle exit velocity for the system, an experiment was conducted. A simple pump was purchased, and a preliminary nozzle was 3-D printed. Both the pump and the nozzle allowed the team to experiment and understand how the flowrate and nozzle exit velocity needed to be manipulated to successfully clean a paintbrush. In Figure 25, the system used is shown.

Figure 25. The system used for experimentation

The team created a preliminary system with the pump and nozzle connected by 0.5 inch diameter hose of 18 inches in length. The system was used to clean one side of a saturated paintbrush. The team observed that the exit velocity and flow supplied by the system adequately cleaned one side of the paintbrush. The pump was used to fill a one-gallon bucket in five consecutive trials, and the average time was 27 seconds, giving an average flow rate calculated to be 2.2 gallons per minute. Using Equation 2, the nozzle exit velocity can be calculated from the flowrate being pushed through the nozzle which has an exit area of 0.068 square inches.

$$V = \frac{Q}{A} \tag{2}$$

The flow rate of 2.2 gallons per minute through the nozzle gives an exit velocity of 10.4 feet per second. Because the final paintbrush washer contains two nozzles, cleaning medium would need to be supplied at both sides of the brush.

4.2.2 System Manipulation

Both the flowrate and nozzle exit area affect the cleaning medium nozzle exit velocity. Either an increase in flowrate or a decrease in area would increase the cleaning medium nozzle exit velocity. To achieve 10.4 feet per second exit velocity from both nozzles, the pump capacity would need to be doubled or the nozzle exit area would need to be halved. The team foreshadowed changes to the general model of the nozzle later in the design process. If the system depended on the area being changed to supply the cleaning medium to both sides of the brush, then the nozzle evolution later in the design process would be constrained. The team decided to only manipulate the flowrate and not exit area to ensure that the nozzle design could freely evolve without being inhibited by a maximum exit area. Therefore, the pump capacity would need to be doubled summing to a total flow rate of 4.4 gallons per minute for the system.

4.2.3 Pump Sizing Process

To select a pump, there are two values that need to be known: the desired flow rate (which was previously found to be 4.4 gallons per minute) and the head losses in the system. Head losses in the system came from changes in elevation, major losses, and minor losses. The head losses in the system were preliminarily calculated based on the piping requirements of the oscillating nozzle concept, and then conservatively overestimated to ensure that the pump capacity would be sufficient when changes to the piping system were made. Overestimating also aimed to combat uncertainties to design a system capable of the desired capacity.

4.2.4 Initial Piping System

The preliminary piping system associated with the oscillating nozzle concept is shown in Figure 26. The pipe system begins at the inlet of the strainer and rises just less than 12 inches where it meets a pipe tee. From there, the flow splits into two identical branches containing two 90 degree bends, one reducer, and one nozzle.

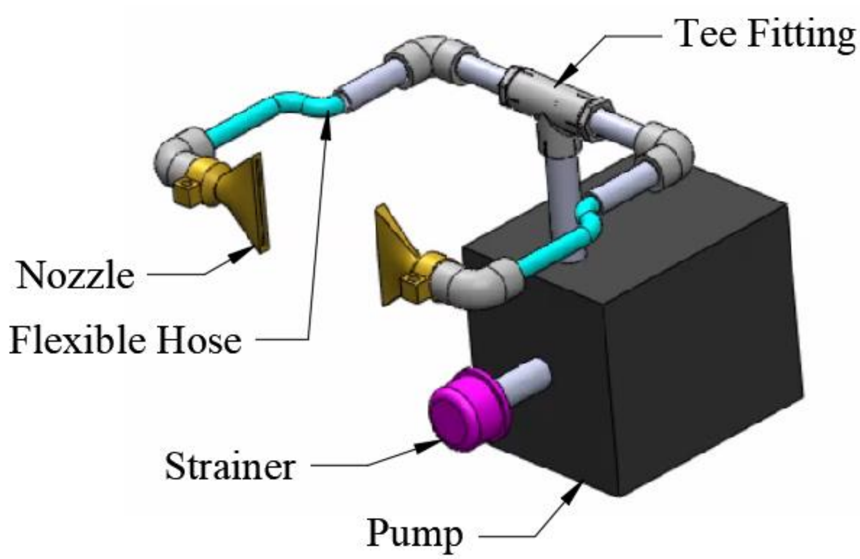

Figure 26. The preliminary piping system associated with the oscillating nozzle concept

The total head loss was calculated with Equation 3 summing the loss from both sections. The first section is from the strainer through the tee and the second section is one of the two identical branches from the outlet of the tee through the nozzle.

$$h_{L\,total} = h_{L1} + h_{L2} \quad (3)$$

Figure 27 shows the nomenclature used to define the sections of the piping system.

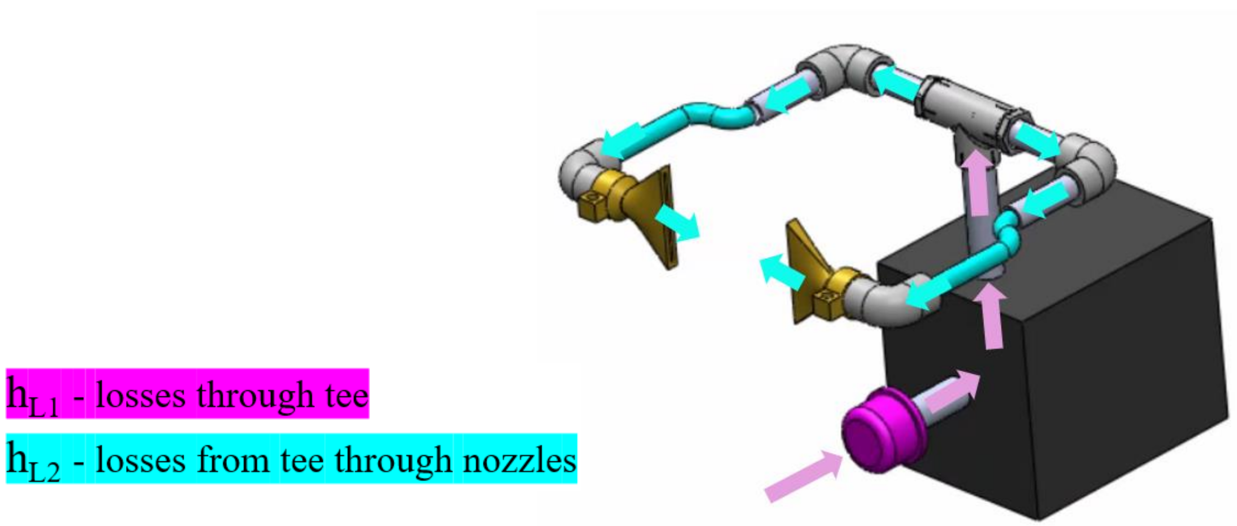

Figure 27. Piping system nomenclature

The total head loss of both sections was calculated with Equations 4 and 5. These equations sum the first and second section's respective elevation and frictional head losses.

$$h_{L1} = h_e + h_f \tag{4}$$

$$h_{L2} = h_e + h_f \tag{5}$$

In each section h_e is the loss from the change in elevation. It was calculated with Equation 6 where z_f and z_i are the final and initial heights respectively from the inlet of the strainer.

$$h_e = z_f - z_i \tag{6}$$

Frictional losses from both major and minor losses were calculated using Equation 7. Major losses result from friction in the pipe. They are calculated from the product of the friction factor and the length of the pipe divided by the diameter of the pipe. This product is then multiplied by the velocity of the fluid in the pipe squared divided by two times the gravitational constant. This is the total major loss. The friction factor is pulled from a Moody Diagram based on the relative roughness and Reynolds number. The relative roughness and Reynolds number equations are seen in Equations 8 and 9 respectively. The surface roughness is divided by the diameter to get the relative roughness. The Reynolds number is the product of the density times the velocity times the diameter all over the dynamic viscosity.

$$h_f = \left(f\frac{L}{D} + \Sigma K_L\right)\frac{V^2}{2g} \tag{7}$$

$$Relative\ Roughness = \frac{\epsilon}{D} \tag{8}$$

$$Re = \frac{\rho V D}{\mu} \tag{9}$$

In Equation 7, the minor losses are the sum of the K_L values times the velocity squared divided by two times the gravitational constant. A K_L value is a coefficient of loss from a change in piping and can be obtained from *Fundamentals of Thermal-Fluid Sciences* **[4]**. The K_L values that are used are shown in Table 1.

Table 1. Pipe configurations and their KL values

Pipe Bend Characteristics					
Configuration	180° Pipe Tee	90° Pipe Bend	Pipe Reducer	Nozzle	Strainer
K_L Value	2.00	0.75	0.33	1.03	2.00

Figure 28 shows the spreadsheet calculating the total head loss in the first section. The total head loss was calculated to be 52 inches ± 3 inches. The uncertainty compensates for error in all K_L values and friction factors.

System Charachteristics Water

Section 1 (Strainer through Tee)

Design Parameters					
Flow Rate (gallons per minute)	Pipe Diameter (inch)	Velocity in Pipe (inch per second)	Friction Factor for PVC (0.5 inch Ø)	Length of Pipe (inch)	Change in Elevation (inch)
4.40	0.50	86.27	0.013	6.00	12.00

SYSTEM LOSSES

Elevation Head Loss	
Initial Height (inch)	0.0
Final Height (inch)	12.0
Head Loss (inch)	12.0

$$h_e = z_f - z_i$$

Frictional Losses	
f(L/D)	0.2
KL (Strainer)	2.0
KL (Wye)	2.0
V^2/2g	9.6
Minor Loss (inch)	40.1

$$h_f = \left(f\frac{L}{D} + \Sigma K_L\right)\frac{V^2}{2g}$$

Total Head Loss	
Elevation Head Loss (inch)	12.0
Frictional Loss (inch)	40.1
Total Head Loss (inch)	52.1

$$h_{L1} = h_e + h_f$$

Figure 28. Spreadsheet used to calculate total head loss for the first section

Below, Figure 29 shows the spreadsheet calculating total head loss from one of the two identical branches in the second section of piping. The loss is calculated from the pipe tee through the outlet of the nozzle. The total head loss was calculated to be 24 inches ± 3 inches.

Similarly to the calculation for the first section of pipe, the uncertainty compensates for error in all K_L values and friction factors.

System Charachteristics Water
Section 2 (Tee through Nozzle)

Design Parameters							
Flow Rate (gallons per minute)	Pipe Diameter (inch)	Velocity in Pipe (inch per second)	Friction Factor for PVC (0.375 inch Ø)	Friction Factor for Flexible Rubber (0.375 inch Ø)	Length of PVC Pipe (inch)	Length of Rubber Pipe (inch)	Change in Elevation (inch)
2.20	0.375	76.89	0.01	0.01	6.00	4.00	0.00

SYSTEM LOSSES

Elevation Head Loss	
Initial Height (inch)	12.0
Final Height (inch)	12.0
Head Loss (inch)	0.0

$$h_e = z_f - z_i$$

Frictional Losses	
f(L/D) PVC	0.2
f(L/D) Rubber	0.1
KL (2 - 90° bends)	1.5
KL (Reducer)	0.3
KL (Nozzle)	1.0
V^2/2g	7.7
Minor Loss (inch)	24.2

$$h_f = \left(f\frac{L}{D} + \Sigma K_L\right)\frac{V^2}{2g}$$

Total Head Loss	
Elevation Head Loss (inch)	0.0
Frictional Loss (inch)	24.2
Total Head Loss (inch)	24.2

$$h_{L2} = h_e + h_f$$

Figure 29. Spreadsheet used to calculate total head loss for one branch of the second section

Table 2 shows the total head loss by summing the first section of pipe and one of the two identical second sections. The total head loss is calculated to be 6.4 feet ± 0.5 feet. The same calculation process was performed for paint thinner. The total head loss for the system when paint thinner is used as the cleaning medium is 6.4 feet ± 0.5 feet. Its total head loss can be seen in Table 3. Because the total head loss of paint thinner is the same as that of water, the two fluids can be analyzed simultaneously.

Table 2. The total head loss in the system with water.

Total Head Loss (Water)	
Head Loss Section 1 (inch)	52.1
Head Loss Section 2 (inch)	24.2
Total Head Loss (inch)	76.3
Total Head Loss (feet)	6.4

Table 3. The total head loss in the system with paint thinner.

Total Head Loss (Paint Thinner)	
Head Loss Section 1 (inch)	52.1
Head Loss Section 2 (inch)	24.4
Total Head Loss (inch)	76.5
Total Head Loss (feet)	6.4

The two parameters that are needed to select a pump are the desired flow rate and total head of a system. The desired flow rate is 4.4 gallons per minute. As shown in Table 3, the total head of this system with water is 6.4 feet ± 0.5 feet. Finally, the team took the desired flow rate and total head of the system and browsed for a pump. Pump manufacturers will often provide pump curves with the pumps. The curves allow a customer to understand if the pump's capacity will be adequate for the customer's need. The team found the "Pondmaster PM 700 - 700 GPH POND-MAG® Magnetic Drive Submersible Fountain Pump". Figure 30 shows this pump **[8]**. For this particular pump, the manufacturer did not provide a curve. However, the manufacturer provided a table of flow rates at associated head values and the pump curve was generated. Figure 31 shows the pump curve associated with the PM 700.

Figure 30. Pondmaster PM700 ***[8]***

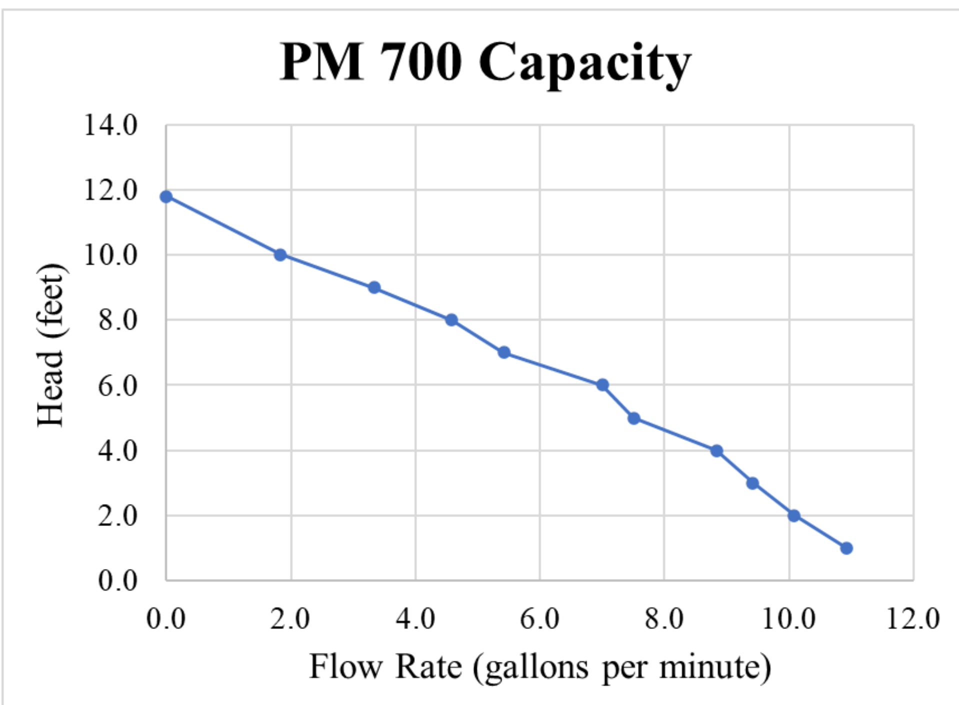

Figure 31. Pump curve for the Pondmaster PM700.

According to the pump curve, at 6.4 feet of head, the pump has a capacity greater than what is required of 4.4 gallons per minute. With the maximum amount of uncertainty added, the system's total head would be 6.9 feet. At this head value, the pump would still provide more than what is required. Therefore, the Pondmaster PM 700 was chosen as the pump for the paintbrush washer.

To obtain the theoretical operating point (the flow rate that the pump will provide for the system), further values must be found. At this point, the only head value known is the one associated with the minimum allowable flow rate. More head values need to be calculated for associated flow rates so that a system flowrate vs system head plot may be generated. This plot may then be overlayed on the pump curve to observe where the two lines intersect. This intersection point is the theoretical operating point. The systems' head was calculated for multiple flow rates ranging from 4.0 gallons per minute to 6.4 gallons per minute. The table of flow rates and resulting system head values are shown in Table 4.

Table 4. The piping system flow rates with corresponding total head values.

Piping System	
Flow Rate (gpm)	Total Head (ft)
4.00	5.42
4.40	6.35
4.80	7.36
5.20	8.47
5.60	9.66
6.00	10.94
6.40	12.29

A plot generated with the values from Table 4 was overlayed onto the pump curve from Figure 31. The result is shown in Figure 32, showing the intersection of the two plots. This intersection is the operating point.

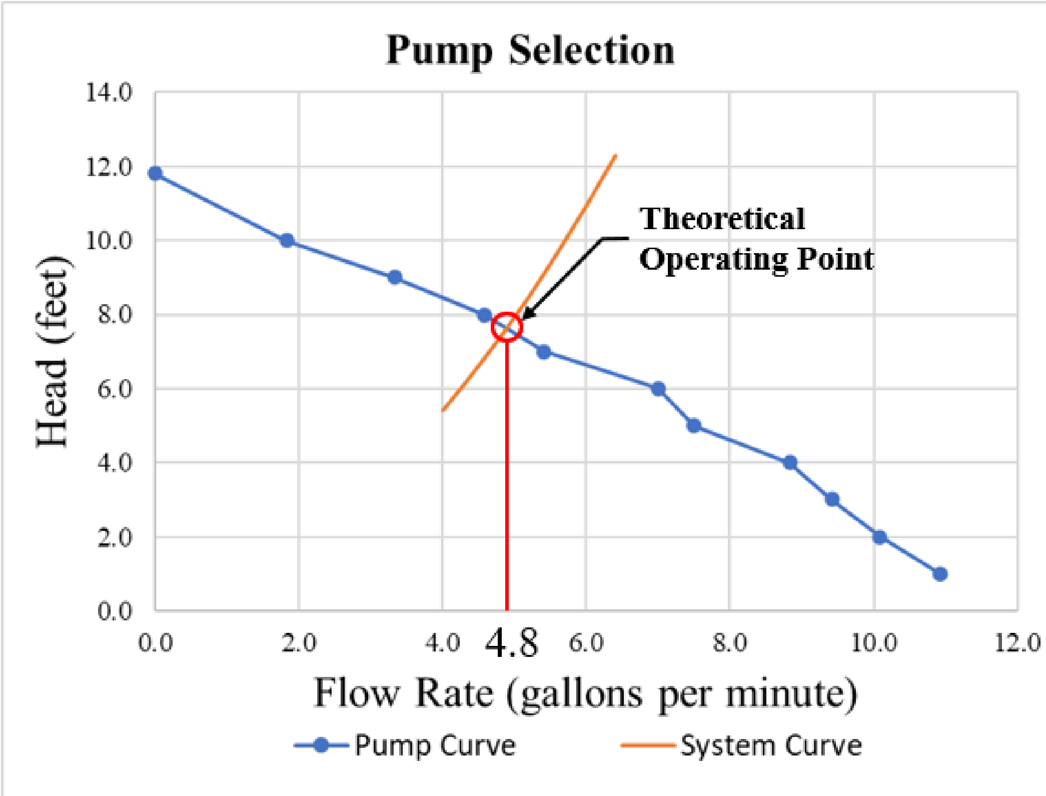

Figure 32. The operating point plot

The intersection of the system and pump curve lines occurs at 4.8 gallons per minute. Therefore, the Pondmaseter PM 700 should supply a flowrate of 4.8 gallons per minute for the piping system associated with the oscillating nozzle concept.

To verify the theoretical operating point, the actual operating point of the pump was tested. The time to fill one gallon out of both of the nozzles was an average of 12.2 seconds for five trails. This results in a 4.9 gallons per minute flow rate for the piping system associated with the oscillating nozzle concept. The built system is shown below in Figure 33.

Figure 33. The built piping system associated with the oscillating nozzle concept

The theoretical operating point was 4.8 gallons per minute. It was predicted that the flow rate would be higher than the theoretical operating point due to the team being conservative by overestimating lengths and heights to account for more energy loss than what was truly present. The actual system had a flow rate of 4.9 gallons per minute which is greater than the theoretical operating point. The flow experienced in the system would adequately clean a brush because the flow is greater than 4.4 gallons per minute which will supply an exit velocity of more than 10.4 feet per second out of each nozzle.

4.2.5 Piping System Changes

The pump was sized for the piping system associated with the oscillating nozzle concept. However, the horizontally translating nozzle concept was eventually chosen. The full piping system associated with this final concept can be seen in Figure 34.

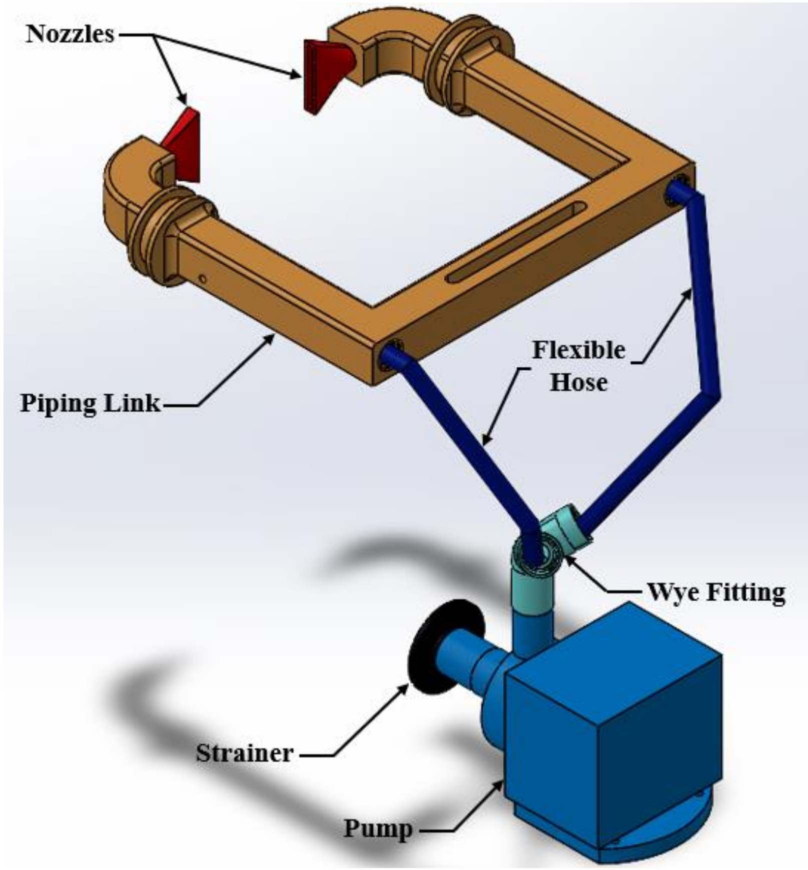

Figure 34. The piping system associated with the horizontally translating nozzle concept

The pump's inlet is connected to a section of 0.5 inch diameter PVC piping which penetrates through the middle wall into the cleaning medium reservoir and terminates with a strainer. The outlet of the pump is connected to a custom wye fitting with 0.5 inches diameter which diverts the medium smoothly to each of the two sections of flexible piping. The flexible piping has an internal diameter of 0.375 inches. The medium flows through the flexible sections of pipe to the inlet of the piping link. The medium travels through the inside of the link and out through the nozzles which thread into the end of link. 3-D printed materials are very rough. Measures needed to be taken to compensate for the increase in head that the piping link would introduce to the system. Because the tee fitting added a lot of head to the preliminary system, the team implemented a custom wye fitting. The wye fitting provides a gradual direction change to reduce head loss. The custom wye solid model rendering can be seen in Figure 35.

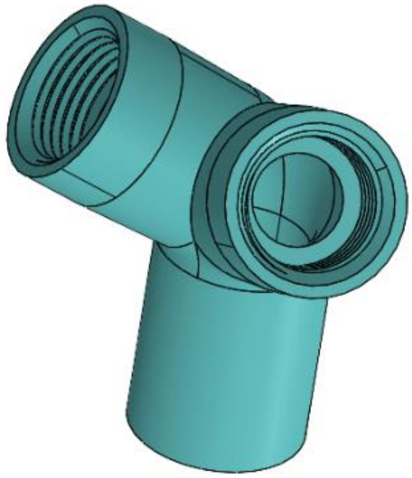

Figure 35. Custom wye fitting

Additionally, the diameter of the pipe is held constant from the outlet of the wye fitting to the inlet of the nozzles to limit head loss from reductions.

4.2.6 Nozzle Evolution

The first nozzle tested was modeled after a coolant supply fan-style nozzle for industrial milling processes seen on the far left in Figure 36 below. This nozzle was chosen due to its spray pattern and high flow rate.

Figure 36. Nozzle evolution

The exit area of the first nozzle was approximately 0.068 square inches. This nozzle had adequate flow rate and exit velocity, but the spray pattern was not wide enough to cover an entire brush. This nozzle was then scaled up to have a wider spray pattern, but the exit area increased too much which decreased the exit velocity. To fix this issue, the gray nozzle above was designed and printed. This nozzle aimed to have a small exit area and a wide spray pattern. However, during testing, there was not enough flow through the nozzle to fill the entire spray pattern. A new style of nozzle was then tested. This new nozzle was modeled after a high-pressure fan-style nozzle and can be seen in blue above. The new nozzle had adequate exit velocity and flow, but the spray pattern was a jet and not a flat fan. This led to the final nozzle shape which can be seen in black above. This nozzle shape had adequate flow, exit velocity, and spray pattern. This led to an iterative process of changing the nozzle exit area to determine the optimal balance of flowrate and velocity. These iterative nozzles can be seen below in Figure 37.

Figure 37. Nozzle optimization

The first iteration is the left-most nozzle above. This nozzle had a design width of 0.125 inches and a design length of 1.5 inches. It had adequate flow and velocity but was not optimal. The next nozzle iteration can be seen as the left-most white nozzle above. This nozzle had a design width of 0.1875 inches and a design length of 1.5 inches. This nozzle had adequate flow, but the velocity was decreased too much with this iteration. The next nozzle iteration is the right-most white nozzle above. This nozzle had a design width of 0.03125 inches and a design length of 1.5 inches. The exit velocity was greatly increased, but the flow was too low due to the small exit area. The final nozzle iteration can be seen above as the right-most gray nozzle. This nozzle had a design width of 0.0625 inches and design length of 1.5 inches. The exit velocity of this nozzle was adequate to penetrate the bristles of the brush. The flow rate from this nozzle was adequate as well to wash the paint from the brush. Due to the nature of 3-D printing, the actual exit area of the nozzle was smaller than designed. The designed exit area was 0.0625 square inches while the actual exit area of the final nozzle was 0.058 square inches.

4.2.7 New Piping System Performance

Although the pump was sized for the piping system associated with the oscillating nozzle concept, efforts to limit head loss for the new system allowed the pump to still be adequate. The pump supplied an exit velocity of 10.8 feet per second from the nozzles which is greater than the required velocity of 10.4 feet per second. The final nozzle exit velocity was calculated with Equation 2 using the observed flowrate of 3.9 gallons per minute and the exit area of the nozzle which is 0.058 square inches. The flow of the new system is less than that of the old system. This is due to an increase in head of the piping system and a change in the nozzle profile. However, it still supplies enough flow to carry dislodged paint into the cleaning medium reservoir.

4.3 Support System

4.3.1 Body

The nozzle movement system and the pump and piping system are housed in the body. Many other parts are mounted onto the body including: the handles, latches, motor mount, pump mounting plates, bellow brackets, upper middle wall, junction box, spacers for the linkage, and one half of the drawer sliders. The cleaning medium is also contained within the body. The body is made of 0.125 inch thick plain carbon steel. Each piece was cut out with a waterjet and welded together. Figure 28 below shows an external view of the body.

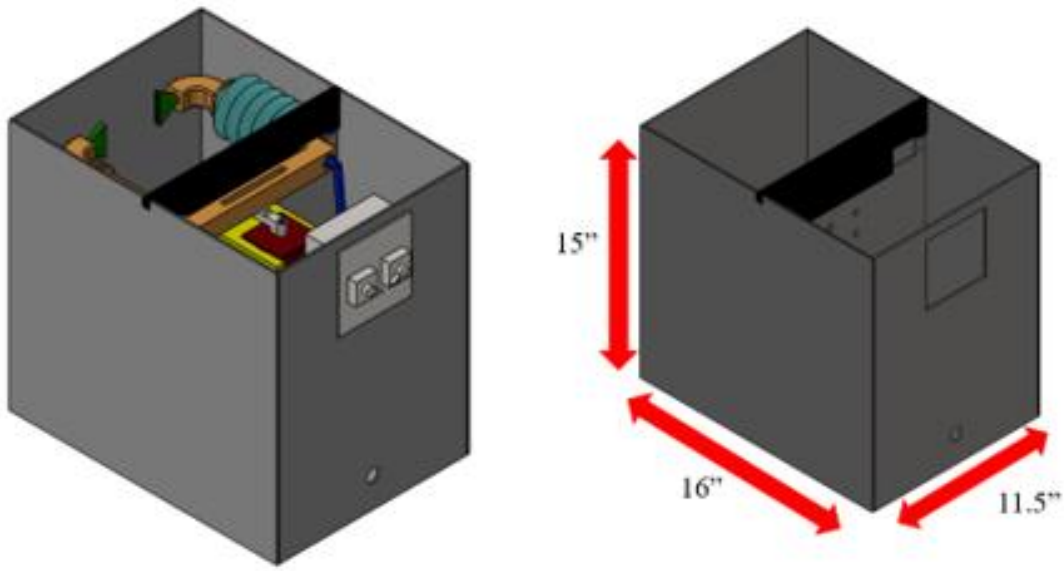

Figure 38. External view of the body

The body is divided into two compartments, the cleaning area and the plumbing area. The cleaning area holds the cleaning medium and is where the nozzles spray the cleaning medium onto the paintbrush. The cleaning area has a 2.5-gallon cleaning medium capacity. The bellow brackets are mounted onto the lower middle wall and upper middle wall in this compartment. The plumbing area houses the motor mount, pump mounting plates, junction box, spacers for the linkage, piping, pipe fittings, and one half of the drawer sliders. Figure 39 below shows an interior view of the body, with the left compartment being the cleaning area and the right compartment being the plumbing area.

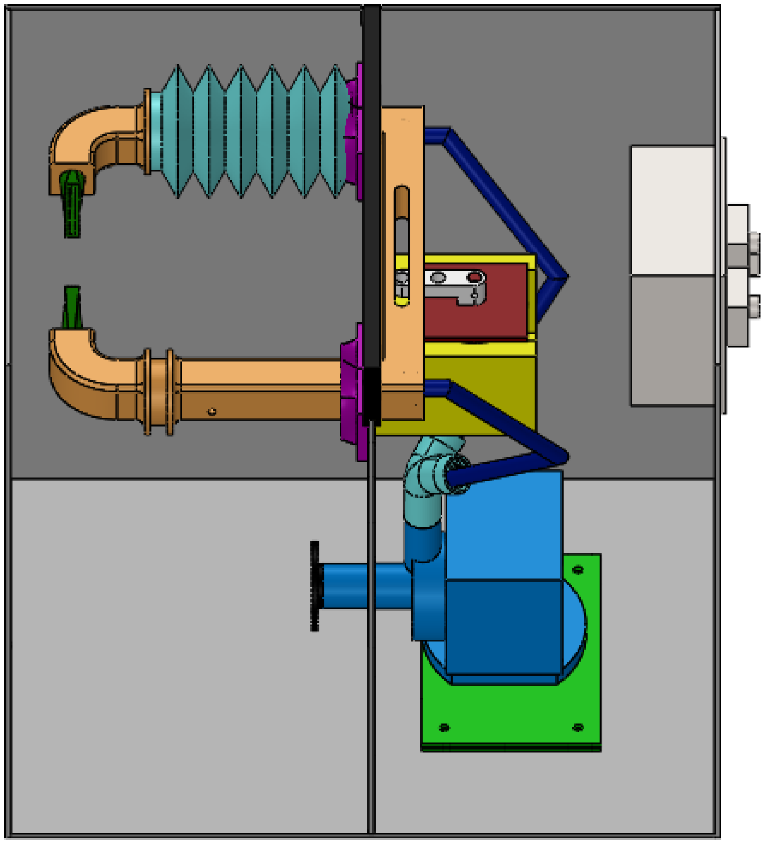

Figure 39. Internal view of the body

Other features were added including a cut out for the junction box and holes for a drain plug, motor mount, and pump inlet. The drain plug hole will allow the user to drain the cleaning medium after the cleaning process. A cork was used to seal the hole during the cleaning process. The middle wall was split into two pieces with the lower portion remaining as steel while the upper portion being 3-D printed with polyethylene terephthalate glycol (PETG). This was done to allow the piping link to be installed. The upper middle wall can be seen below in Figure 40.

Figure 40. Final upper middle wall

The upper middle wall is 0.375 inches wide with a 0.15-inch slot in the middle. The slot is 0.19 inches deep, and it fits over the lower middle wall. The slot can be seen below in Figure 41.

Figure 41. Slot in the middle wall

The middle wall assembly can be seen below in Figure 42. Note the large square holes that the piping link fits through.

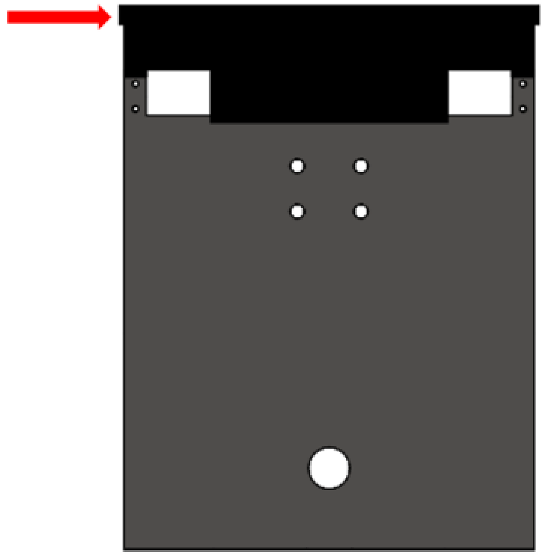

Figure 42. Middle wall assembly

The tabs, shown by the red arrow, that stick past the edge of the middle wall fit into groves in the long external walls of the body. This makes the upper middle wall more rigid.

4.3.2 Lid

The lid is responsible for sealing the top of the cleaning area. It prevents the cleaning medium from splashing out of the body or into the plumbing area. The lid features a slot for inserting the paintbrush for the cleaning process and hooks for the latches to latch onto. The clamp mounts onto the lid via a bolt through the lid. The lid is made of the same 0.125 inch plain carbon steel and is welded together. It was designed to have a total tolerance of 0.125 inch between the inner edge of the lid and the outer edge of the body. Figure 43 below shows the lid.

Figure 43. Top view of the lid

For the cleaning process to work properly, the brush must remain stationary. To accomplish this, a clamp was purchased and installed. The clamp features a ratchet so when the clamp is tightened around the brush, it can’t come loose. The clamp is mounted to the lid via a bolt. An image of the clamp mounted onto the lid can be seen below in Figure 44.

Figure 44. Body with lid and clamp installed

Brush style door sweeps were attached to the clamp to prevent the cleaning medium from splashing out around the paintbrush. The black and white door sweeps can be seen attached to the clamp on either side of the paintbrush in Figure 44 above.

4.3.3 Pump Mounting Plates

In order to mount the pump to the body, two mounting plates had to be designed. The bottom plate is welded to the body and has threaded holes for mounting the top plate. The pump bolts to the top plate which then gets bolted to the bottom plate. The two plates allow for the pump to be easily installed. Figure 45 below shows one of the mounting plates.

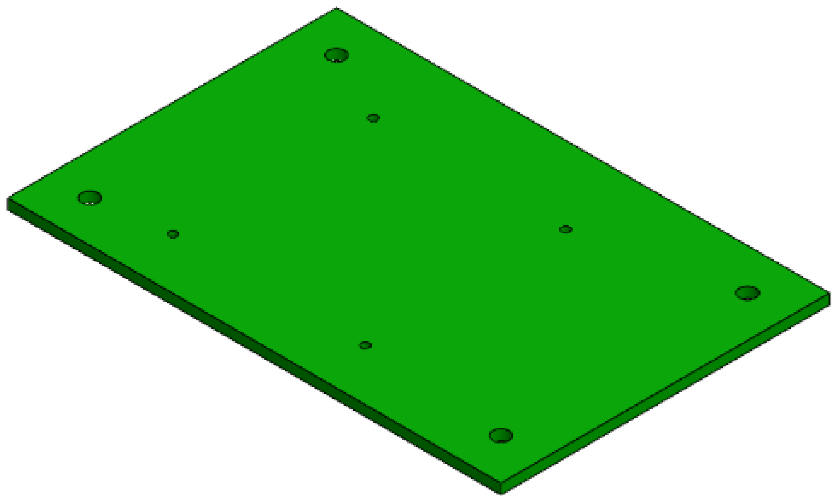

Figure 45. Pump mounting plate

4.3.4 Latches and Handles

To hold the lid onto the body, adjustable latches were purchased and installed. These latches allow for adjustment in how tight the latches hold the lid onto the body. The latch is welded onto the body while the hook is welded onto the lid. A total of five latches were attached to the body. Two on each long wall and one on the short wall next to the cleaning area. An image of a latch can be seen below in Figure 46.

Figure 46. Latch

Since the prototype is heavy, handles were purchased and installed to allow the prototype to be easily moved. The handles were welded onto the body with one on each of the short walls. An image of one of the handles can be seen below in Figure 47.

Figure 47. Handle

4.3.5 Sealing

In order to prevent the cleaning medium from entering the plumbing area, a few different seal mechanisms were used. The first and most important seal is the bellow shown below in Figure 48 **[11]**.

Figure 48. Bellow ***[11]***

Two bellows are used over each side of the piping link and are responsible for sealing the large hole in the middle wall that the piping link moves through. Bellows were chosen due to their ability to stretch and compress while maintaining an effective watertight seal. Many different bellows were tested to find the correct one. Some bellows tested were too stiff and caused too much stress on the linkage system during stretching. Others did not allow a full range of motion of the nozzles, especially during the compression of the bellows. Bellows used on dirt bike forks were observed to operate under similar conditions to the linkage system. This led to the finding of bellows used on Honda three-wheeler front forks. They undergo an accordion style oscillation during operation with minimal stress, all while maintaining a watertight seal. The smaller end of the bellow attaches around the bellow keeper built onto the piping link. This fixes it to the end to the linkage. On the larger end, the bellow fits around bellow bracket which are bolted to the middle wall. In Figure 49, the bellow bracket is shown.

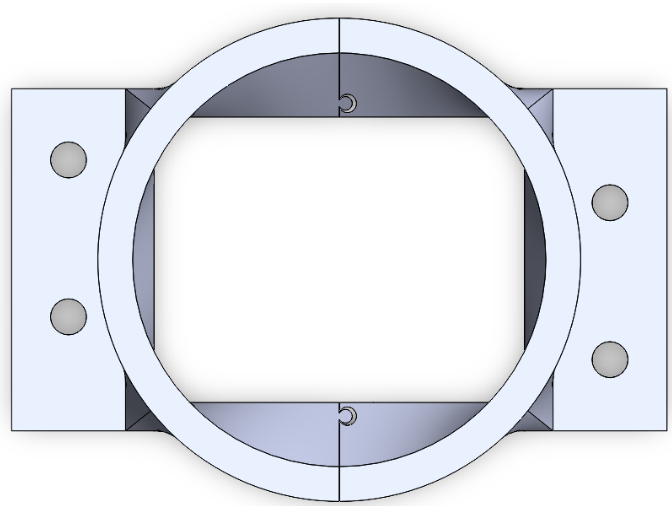

Figure 49. Bellow Bracket

The bellow bracket is composed of two pieces that assemble and mate together once the piping link is installed in the system. The upper middle wall overlaps and extrudes beyond the middle wall. The bracket’s rear surface profile varies to mate in a flush manner with the upper middle wall and lower middle wall. Two views showing the offset of the rear surface profile can be seen in Figure 50.

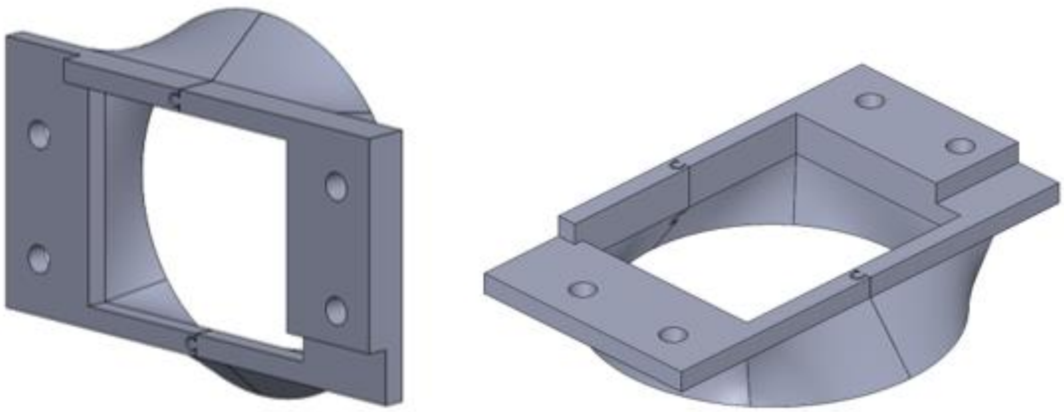

Figure 50. Two views showing the varying rear surface profile of the bellow bracket

Because the bellow is fixed to the bellow bracket on one end which is stationary and on the other end is fitted to the bellow keeper which translates, the bellow experiences it’s accordion style oscillation. A zip-tie was used to ensure the bellow wouldn’t slip from the bellow bracket. The next sealing mechanism used was metal-colored silicone. This silicone was used between the upper middle wall and the lower middle wall. This prevents the cleaning medium from seeping between the walls and into the plumbing area. The silicone was also used around the inlet of the pump, motor mount bolts, and around the SharkBite fittings.

Finally, weather stripping was used on the underside of the lid to prevent the cleaning medium from splashing out of the device. The weather stripping lines the edge of the lid as can be seen in Figure 51 below. A section of weather stripping was also used along the middle of the lid where the upper middle wall meets the lid. This piece is used to prevent splashing of the cleaning medium into the plumbing area.

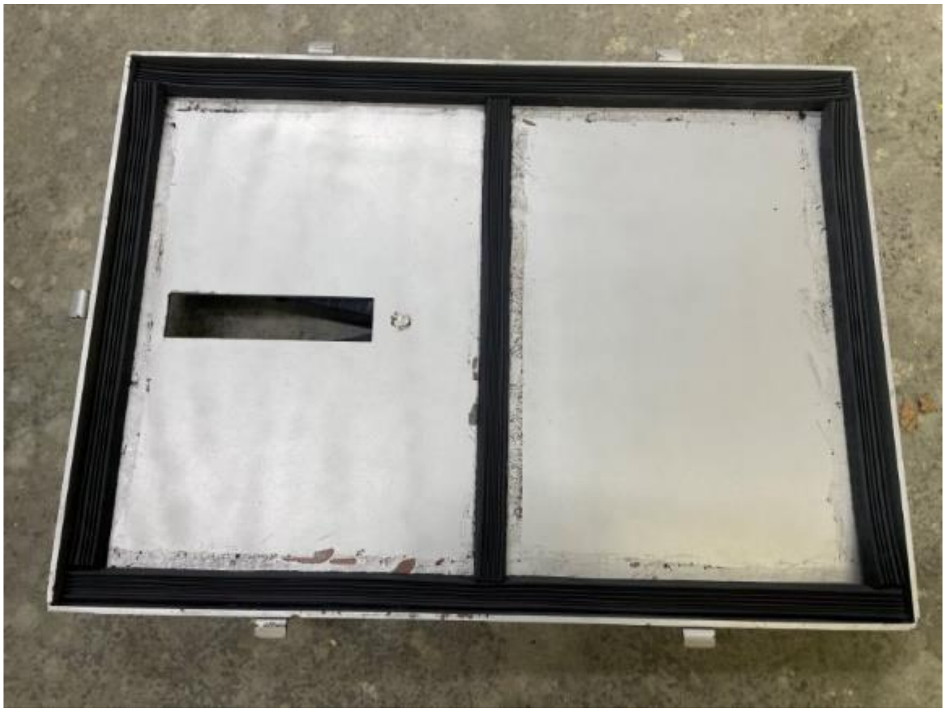

Figure 51. Weather stripping attached to underside of lid

4.4 Electrical

Minimal electrical components were needed for the paintbrush washer. These components included a weather-proof junction box, cover, two switches, three cord grips, and a ground fault circuit interrupter outlet (GFCI). The electrical diagram for the paintbrush washer can be seen below in Figure 52.

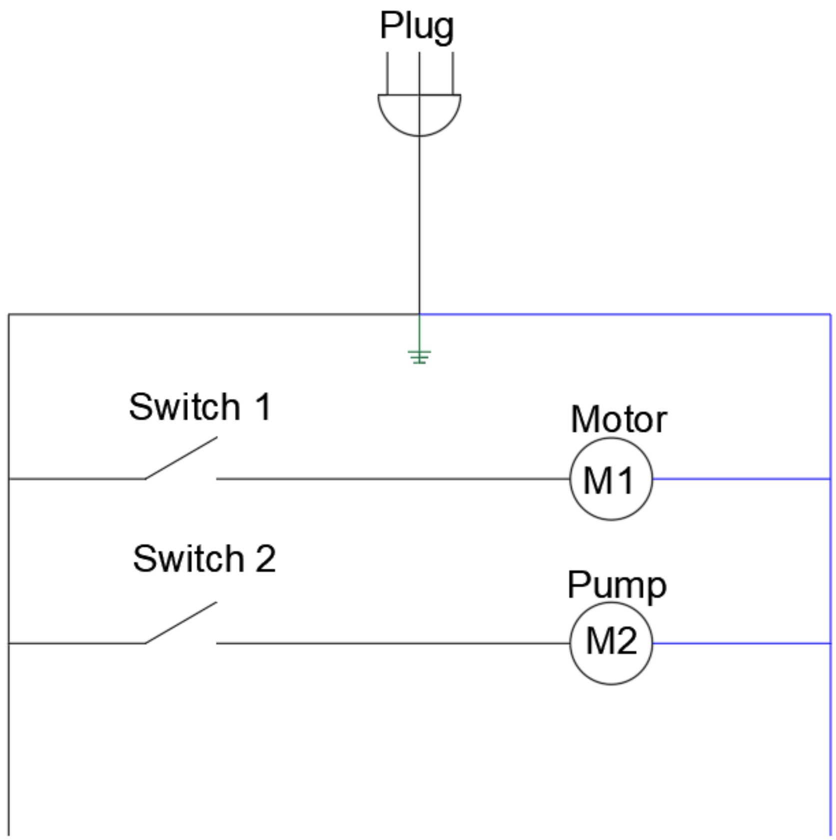

Figure 52. Electrical Diagram

Since the paintbrush washer is an appliance dealing with a liquid, it must be in compliance with the National Electric Code Section 210.8 **[5].** This code states that any appliance that deals with a liquid must be connected to a GFCI outlet. Not every outlet is GFCI certified, so a removable plug was installed to ensure compliance. The next NEC section that must be complied with is Section 314.28 **[9]**. This section states that if a junction box is needed in a damp area, a water-rated junction box must be used. Since the cleaning medium is being pumped near the junction box, a weather-proof box was used. In order to bring wire into and out of the junction box while keeping it watertight, cord grips were installed. An extra cord grip was installed at the rear of the device to allow a single power cord to exit the body without damaging the cord on the sharp edges of the hole. All of this equipment can be seen below in Figure 53.

Figure 53. View of the electrical junction box

5.0 Prototype Experimentation

Experiments were conducted with water-based paint. The minimum time needed to clean a paintbrush was 30 seconds under ideal conditions. This is well under the 3-minute cleaning time stated in the requirements. Another test was conducted to see how many cleaning cycles can occur before the cleaning medium is too saturated with paint to properly clean the paintbrush. The test ended at the sixth paintbrush due to not having any more dry paintbrushes. The sixth paintbrush was cleaned in 1 minute and 30 seconds. So, a full 2.5 gallons of cleaning medium should be able to clean at least 6 paintbrushes. Experiments with oil-based paint were also conducted and the time needed to clean a paintbrush was less than three minutes. Water was used to clean out the water-based paint and paint thinner was used to clean out the oil-based paint.

6.0 Budget

The team developed a budget for the prototype. This budget can be seen below in Table 5. The total cost to build the prototype was just under $440.

Table 5. Budget

Budget			
Item	Quantity	Price Per Unit	Total Cost
PETG 3D Printer Filament	1	$20.00	$20.00
0.125 inch Steel 4 feet x 4 feet Sheet	1	$70.00	$70.00
Spray Paint	3	$11.00	$33.00
Pondmaster PM700 Pump	1	$100.00	$100.00
Motor	1	$24.00	$24.00
Piping	1	$30.00	$30.00
Handles	2	$7.00	$14.00
Latches	5	$1.66	$8.30
Waterproof Junction Box Kit	1	$25.00	$20.00
Clamp	1	$11.00	$11.00
Hardware	1	$10.00	$10.00
Bellow Set	1	$19.00	$19.00
Silicone	1	$13.00	$13.00
Weather Stripping	1	$15.00	$15.00
Door Sweep	1	$10.00	$10.00
Drawer Sliders	1	$4.00	$4.00
GFCI Plug	1	$18.00	$18.00
Electrical Hardware	1	$20.00	$20.00
		Total Cost	**$439.33**

7.0 Lessons Learned

During this design and build process, the team learned a few important lessons. The first lesson was to allow more time for the manufacturing process. The time to build the design was underestimated, which caused delays in testing and progress on other work. If more time was allotted, parts could have been ordered earlier and the process could have started sooner. The next lesson learned was to document every experiment with pictures and videos. Once the build process was completed and the report was being worked on, the realization of how many experiments took place without documentation was apparent. This led to the recreation of experiments to validate previous decisions. Finally, using a third-party to help settle disputes was learned. When disputes about design or wording were had, a third party was sought after to help give insight to ultimately bring the group to a compromise.

7.1 Teamwork

While the team worked together on all aspects of the project, each individual took the lead in different areas of the project. Isaiah Kiesel took the lead in performing all calculations and designing the plumbing system. Joe Scheller took the lead in modeling and in designing the linkage and the body. Brandon Werner took the lead in the manufacturing of the prototype, especially in the 3-D printing process and in the nozzle design. When conflicts arose, the team used effective communication to make sure everyone fully understood the problem and then debated the advantages and disadvantages to make the best decision for the project.

8.0 Future Work

Since the goal of this project was to mainly prove the design of the chosen cleaning method was effective, several challenges need to be addressed during future work. Many of the challenges arose after the build of the device including issues with sealing and manufacturability. Material compatibility was also cause for concern especially with longevity of the device's components.

8.1 Improved Sealing

The first item to address during future work is a way to improve sealing. Every piping component and wall penetration needs to be sealed to keep the plumbing area dry. The silicone used to make these seals had a tendency to leak during testing. A few of these leaks developed as minor adjustments were made and the seal broke. However, two small leaks persist in the plumbing area. One of these leaks is around the custom wye fitting on the discharge of the pump. Pipe glue and silicone were used to try and mitigate this leak but to no avail. Another leak was found at the connection of the shark-bite fitting into the piping link. Again, silicone was used to try and mitigate this leak, but an improved design may be needed to properly fix the problem.

8.2 Material compatibility

The next item to address during future work is material compatibility. Material compatibility with paint thinner was not a factor during the material selection process for most parts. Spray painted steel will corrode over time, especially if paint thinner sits in the reservoir for an extended period of time. The seals and impeller in the pump will eventually fail due to the corrosiveness of the paint thinner. A small amount of material compatibility was considered with the piping link, wye, and nozzles. PETG was chosen for its increase in chemical resistance as opposed to PLA, but over time these parts too will fail.

8.3 Manufacturability

The last item to consider during future work is the manufacturability of the device. A lot of time and effort went into building the device including welding of the body and installation of the individual parts. After the body was welded, leaks were found at the welds. A better method of making the body, such as injection molding, would decrease the risk of leaks in the body. A lot of time went into 3-D printing each component of the device. Again, injection molding would decrease this time and ensure better connections between components.

9.0 Conclusion

The paintbrush washer was proven to be successful after testing. By spraying the cleaning medium into the bristles of the paintbrush, the horizontally translating nozzles concept adequately cleans 1 inch to 3 inch chisel style paintbrushes in under three minutes. The device retains the cleaning medium for future uses whether using water or paint thinner. It also features a drain hole and plug allowing the user to drain the cleaning medium. The prototype's pump and motor are powered from the same 110 volt outlet and the paintbrush washer occupies less than 1.5 square feet. Unfortunately, the fittings are faulty and did result in minor leakage within the device that will require attention in the future. However, through engineering calculation and experimentation, the design was iterated and optimized. The design and build of the paintbrush washer was successful and the prototype adequately cleans a paintbrush.

10.0 References

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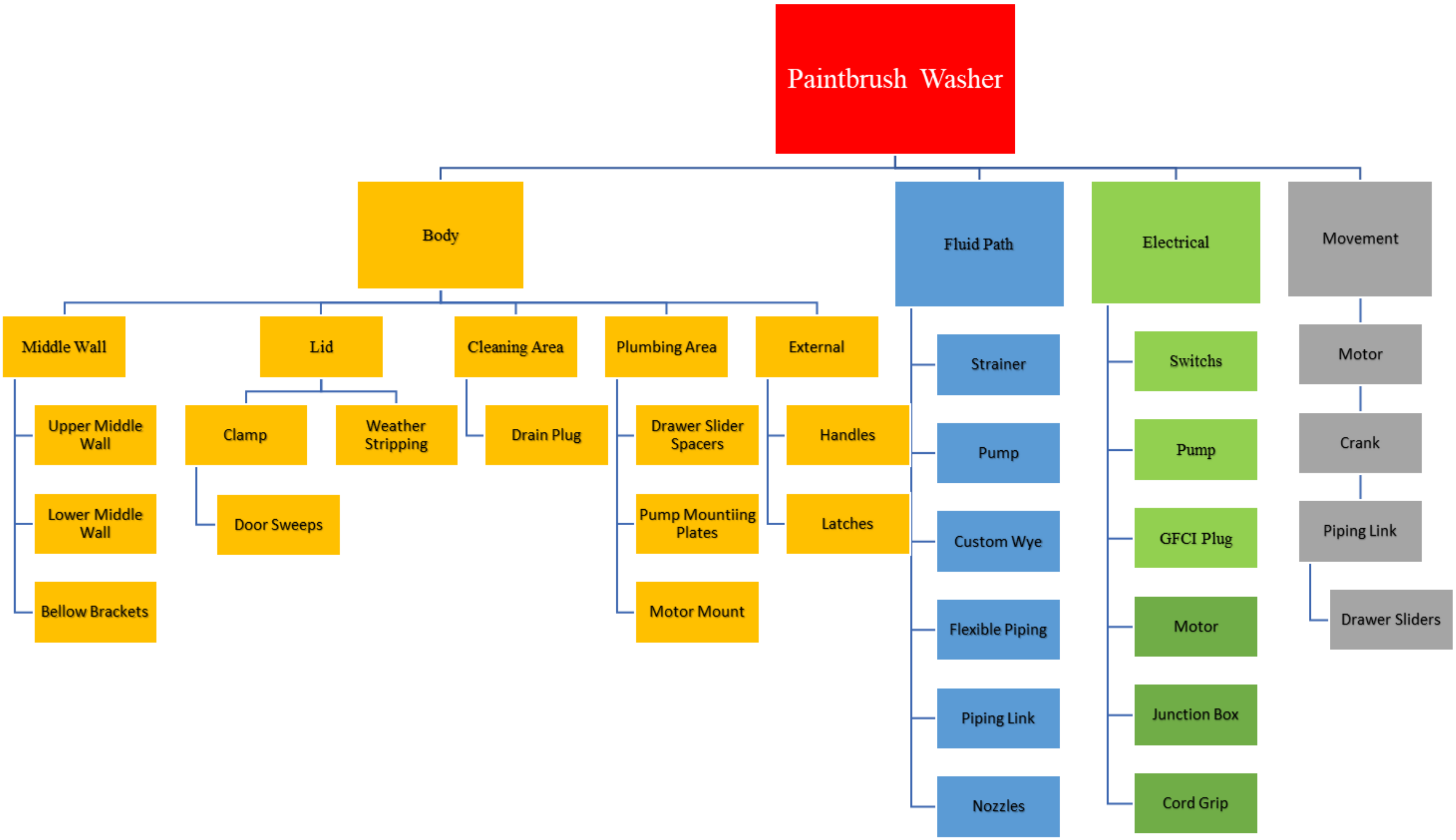
Appendices

Appendix A: System Hierarchy



Appendix B: Schedule

Schedule	
Complete by Data	Item
10/6/2023	Design Proposal
10/11/2023	Preliminary Experimentation
10/16/2023	Design Proposal Oral Presentation
10/13/2023	Project Requirements
10/20/2023	Experimentation
10/23/2023	Three Concepts
10/30/2023	Final Concept
11/13/2023	Preliminary Design Review Oral Presentation
12/7/2023	Pre-Senior Design Report
2/2/2024	Completed Final Design
2/8/2024	Critical Design Review
2/9/2024	Order Materials
2/19/2024	Begin Fabrication
3/4/2024	Fabrication Complete
3/6/2024	Begin Testing
3/13/2024	Make Adjustments as Needed
3/22/2024	Final Prototype
3/29/2024	Design Presentation Review
4/5/2024	Report Draft for Advisor
4/19/2024	Senior Design Presentation
4/25/2024	Senior Design Poster
4/26/2024	Final Report for Advisor
5/3/2024	Submit Final Report to SOAR

Appendix C: Codes

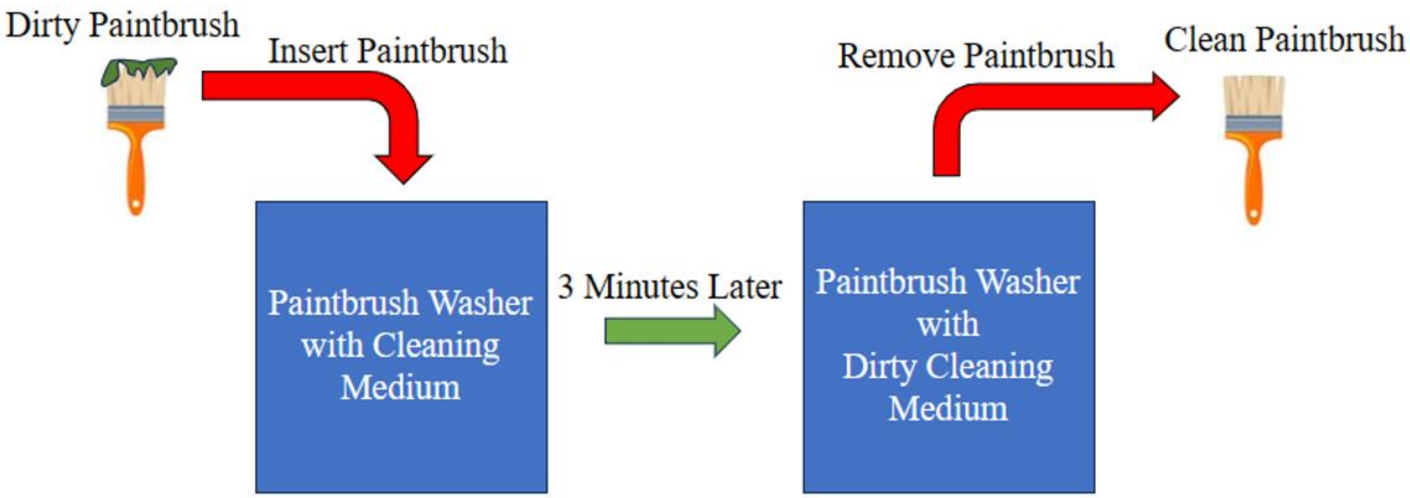
Electrical Codes

- NEC Section 210.8 - GFCI
- NEC Section 314.28 - Weatherproof Junction Box

Appendix D: Weight Table

Object	Qty.	Weight (lb)	Tolerance
Body	1	45	±20%
Pump	1	4	±5%
Nozzle	2	0.05	±2%
Piping Link	1	0.25	±1%
Motor	1	2.3	±1%
Motor Mount	2	0.2	±1%
Drawer Sliders	2 feet	0.32	±5%
Flexible Piping	2 feet	0.28	±5%
Strainer	1	0.2	±5%
Clamp	1	0.32	±10%
Switches	1	0.15	±5%
Junction Box	2	0.35	±5%
Handle	2	0.2	±5%
Latches	5	.25	±5%
Wye	1	.17	±5%
Pipe Fittings	2	.05	±5%
Bellows	2	.09	±5%
Lid	1	5	±5%
Total		36.95	±10%

Appendix E: Concept of Operations



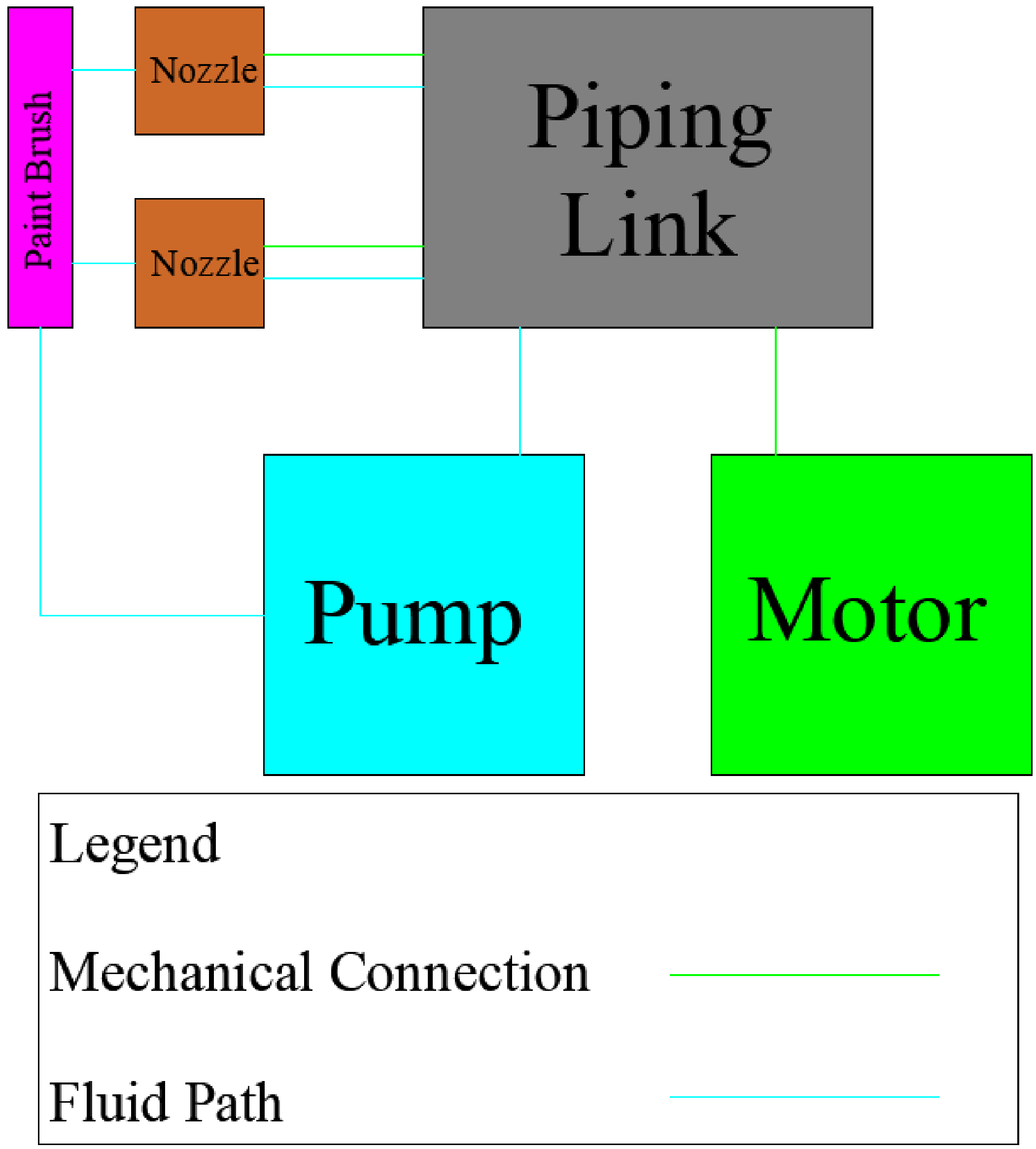
Appendix F: FMEA Before Final Prototype

FMEA Before Final Prototype						
Item	Failure mode	Cause of Failure	Possible effects	Probability	Level	Possible actions to reduce failure rate or effects
Pump	Cracked	a. Dropped b. Damaged during transport	A new pump is needed	Low	Critical	Careful handling of the pump
Nozzles	Wrong size	a. Chose the wrong nozzle b. Incorrect calculations c. Wrong nozzle was sent	New nozzles need to be order	Low	Critical	Double check calculations and the model number of the nozzles before ordering
Filter	Doesn't filter medium	a. A hole or cut in the filter b. Not sealed around the edges	Pump gets clogged Nozzles become clogged	Low	Moderate	Check condition of the filter before installation Check for leaks around the edges of the filter
Clamp	Breaks	a. Careless assembly b. Inproper design c. 3D printing issues	Clamp needs to be remade and reassembled	Medium	Moderate	Design with 3D printing constraints in mind Be careful when assembling
Body	Too Heavy	a. Weight of parts not accounted for b. Too restrictive of a requirement	Requirements not meet	Medium	Low	Double check the weights of all the parts Change the requirements

Appendix G: FMEA After Final Prototype

FMEA after Final Prototype						
Item	Failure mode	Cause of failure	Possible effects	Probability	Level	Possible actions to reduce failure rate or effects
Pump	Burns up	a. Lack of cleaning medium b. Faulty materials	Brush isn't cleaned	Medium	Critical	Proper design of filters large enough reservoir Properly sized piping
Nozzles	Clogs	a. Poor filtering b. Not enough Pressure c. Cracks	Brush isn't cleaned	Low	Medium	Proper nozzle selection Increase pump capacity
Filter	Clogs	a. Too restrictive	Pump burns up	High	Critical	Replace filter change the porosity of the filter
Clamp	Drops brush	a. Fatigue b. Poor materials c. Poor design	Brush falls into reservoir	Low	Medium	Proper selection or design of clamp
Body	Leaks	a. Faulty assembling c. Cracks	Cleaning medium leaks out of reservoir	Low	Low	Proper joining of pieces Use of gaskets

Appendix H: Mechanical Block Diagram



Appendix I: Functional Block Diagram