Automated Window Washer: Final Report

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ME153

Introduction

The best window is one that is never noticed. Smudges and marks on windows are often the last things that are cleaned in the house, and for second story windows, professional cleaning is expensive while doing it yourself can be dangerous and a lot of effort. On average, cleaning a house ranges from $150 to $370, with a national average of $260. Many services additionally charge other fees. We wish to address these challenges with an affordable and discrete one-time window attachment that cleans windows periodically, easing the burden on customers. We proposed an automated squeegee system that is pulled across the window while spraying the glass surface. Figure 1 shows the design proposition.

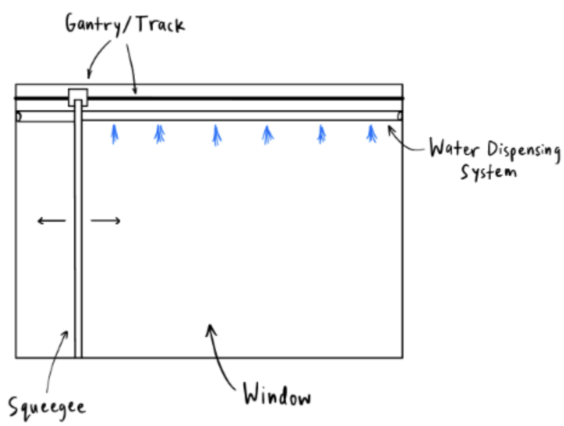

Fig. 1 Initial Proposed Solution

Prototype 1

Plan

Prototype 1, the critical function prototype, aimed to test the necessary force on the squeegee necessary to clean a window. For the final prototype, it is critical to know this minimum value to ensure that we will be able to clean well, and know the amount of friction that will need to be overcome. Depending on the amount of force required this can the decision on whether to construct a lateral or vertical wiper system, and what sort of attachments can be used to connect the wiper to the system. This was accomplished by designing and printing a PLA contraption, seen in Figure 2, that held 4 inches of a rubber squeegee while being held vertically under a platform that can hold various weights. Household items of increasing mass were placed onto the system and the wiper was pushed across a glass surface with purely lateral force. The glass surface had varying amounts of dirty residue, constructed with dirt, water and honey. The calculated force per length of the wiper blade with the 33 g system was

$$F/L = \mathrm{g} \cdot \frac{33g + m_{\text{object}}}{4\text{ in}} \tag{1}$$

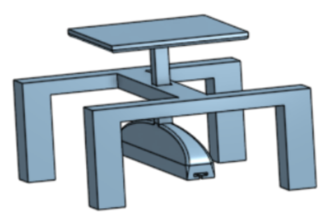

Fig. 2 Critical Function Prototype Design

Test

Each mass on the critical function prototype was tested cleaning just water, water and soap, water and dirt and water with honey and dirt. All weights cleaned the water and soap mixtures successfully, and the dirt was swept away with relative ease under the application of over 100 g. The residue left from the honey required higher forces to clean. In order to ensure the design can handle any realistic window scum, the design must have the required force to clean this honey residue. Table 1 shows the data from the critical function prototype while Figures 3 and 4 show the test set up.

Table 1 Critical Function Test Observations

Additions (g)	Total (g)	Evaluation
122	155	Very nice, not good with sticky
382	415	Good, still leaves some sticky residue behind
543	576	Cleans most all sticky residue well

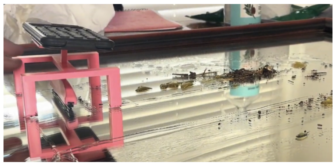

Fig. 3 Test With Honey, Dirt and Water

Fig. 4 576 g test with lateral force

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From the data, we can calculate that the wiper performs best with 5.65 N of force per 4 inches, or 0.556 N/cm. Additionally, the T-slot design used to hold the squeegee rubber in this prototype performed very well and should be carried forward into future designs. This information led us to conclude that a single wiper design, fixtured at one end with a rigid bar, would be the best design. A stringed design would not have the necessary force or rigidity to hold this in place.

Prototype 2

Plan

For Prototype 2, our aim was to control movement in the x direction. To achieve this, we attached a motor to one side, which was connected to electronics controlled by an Arduino. Our plan involved attaching a platform that would move along a track using a belt that linked the stepper motor to a pulley on the opposite side. This design is pictured in Figure 5. To inform our design, we calculated the torque required for our stepper motor. Based on our CFP, we determined that 5.65 N of force was needed per 4 inches of the squeegee to ensure effective cleaning. Using this information, we extrapolated the total force required for a window we estimated to be around 3 feet in length, with a coefficient of friction of 0.3 between wet glass and rubber. From the net force on the window, we calculated that our motor needed to provide 0.122 Nm of torque.

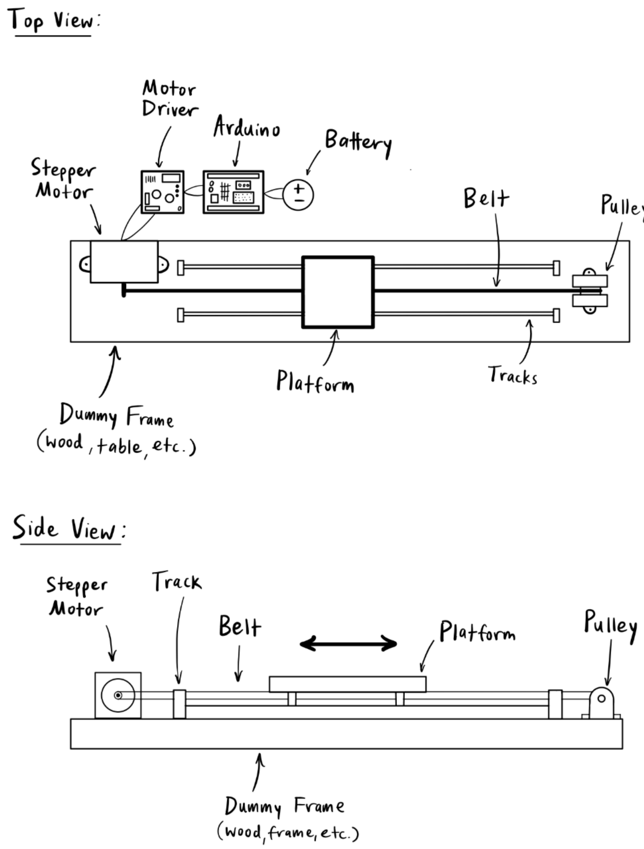

Fig. 5 Prototype 2 Design Plan

Test

For our track, we used an 800 mm 2020 T-slot rail to guide the gantry, which we made using a laser cutter. We powered the stepper motor with a 12-volt supply. We also 3D printed motor mounts and a pulley for the design and tested the mechanism on an polycarbonate window, represented by figures 6 and 7. Our prototype 2 is pictured in Figure 8.

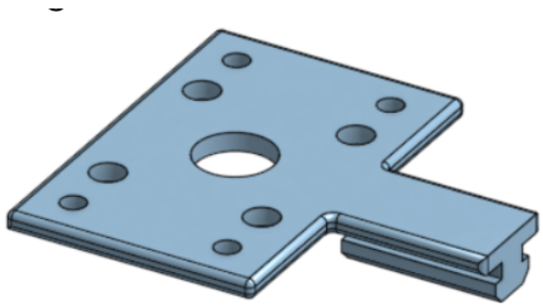

Fig. 6 Motor Mount Design

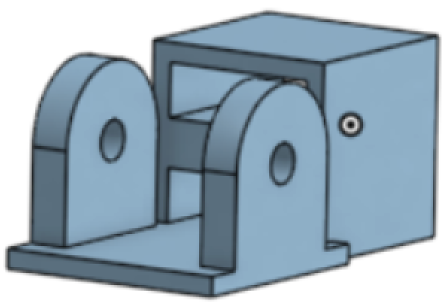

Fig. 7 Pulley Design

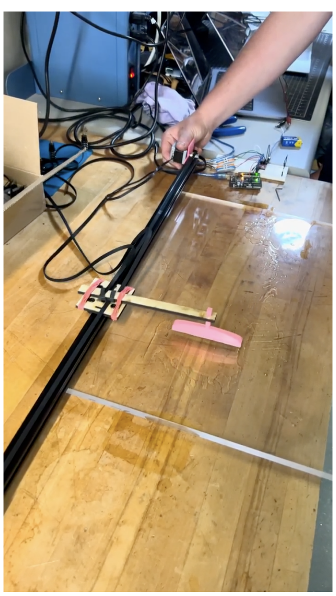

Fig. 8 Completed Prototype 2

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We encountered several challenges while working on Prototype 2 but were able to resolve them in time. Initially, we planned to use a V-slot track and ordered a compatible gantry. However, we accidentally ordered T-slot tracks instead. Since the gantry was incompatible with the T-slot system, we laser cut our own gantry. Initially, we also had issues with our stepper motor and thought it wasn't working. During testing, we discovered that the motor wasn't receiving sufficient voltage, we needed at least 12 volts to operate it correctly. Once resolved, the gantry successfully moved in the x-direction and wiped the window pane, achieving the goal of this prototype. Moving forward, we realized we would need a system that spans the entire window, which would require incorporating limit switches. Additionally, since we tested the prototype on polycarbonate, we noticed significant friction between the squeegee and the pane. We decided to test future iterations on a glass pane for more realistic testing. We also knew we needed to properly tension the belt for optimal gantry movement.

Prototype 3

Plan

For Prototype 3, our goal was to complete the water dispensing system, a plumbing setup that would span the length of the track, as shown in 9. We also realized that purchasing a full window was beyond our current budget, so we opted to buy a single glass pane instead, which we planned to mount on a wooden frame we had already acquired. To support our design, we calculated the number of rotations required for the mechanism to span the length of the glass pane. Using the formula:

$$L = N \cdot \pi \cdot D \tag{2}$$

where L=500 mm and D=16 mm, we solved for N, the number of rotations. This was approximately 9.95 rotations to span the full distance of the pane.

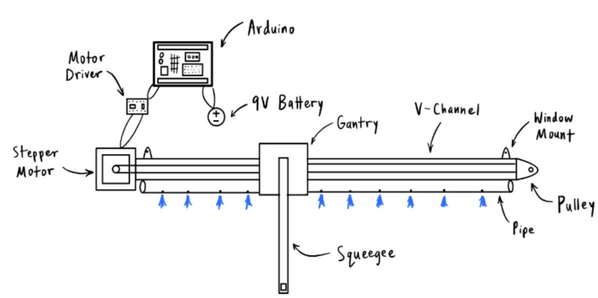

Fig. 9 Prototype 3 Design Plan

Test

To mount the glass pane onto our wooden frame, we 3D printed attachments (Figure 10). We also designed and printed a separate attachment to secure the T-slot track to the wooden frame(Figure 17). Furthermore, we ordered a barrel jack adapter and limit switches to integrate into Prototype 3 for power delivery and motion control.

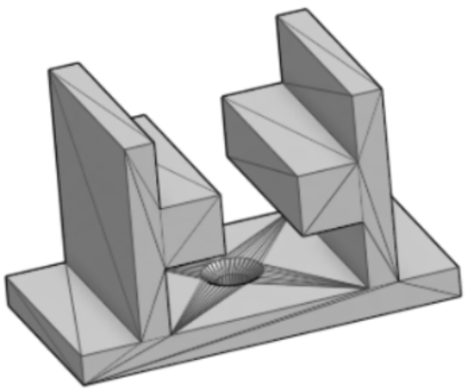

Fig. 10 T-slot Mount

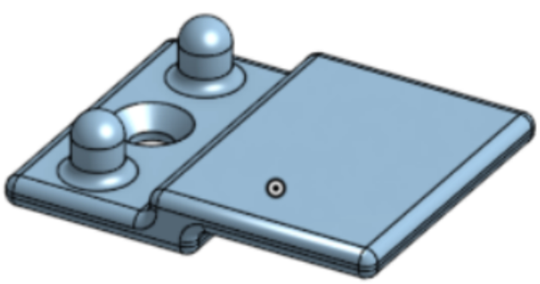

Fig. 11 Window Mount

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Ultimately, Prototype 3 was unsuccessful. We lacked access to a strong enough drill to secure our screws, and the clamps available in the Makerspace were ineffective for holding the glued wooden frame together. Additionally, our barrel jack adapter and limit switches did not arrive in time. While waiting for reprints and parts to be delivered, we were unable to complete Prototype 3 before the deadline. From this experience, we learned that when 3D printing critical components, it's better to print multiple variations or backups. Printing failures are common, and the turnaround time in the Makerspace can be the deciding factor in meeting a deadline. Fortunately, immediately after TA Meeting 3, we received our 3D printed attachments and were able to successfully assemble the window (Figure 12).

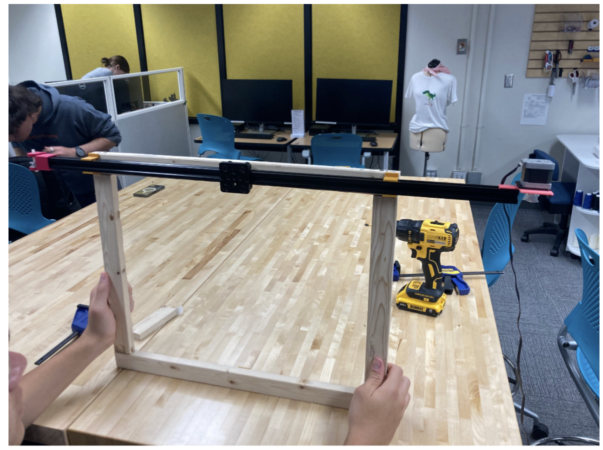

Fig. 12 Track Mounted on Window Frame

Prototype 4

Plan

Prototype 4 sought to remedy the shortcomings of prototype 3. While the window and frame were built immediately following the 3rd TA meeting, the water system components had only recently been ordered and now method had been determined to connect the wiper blade to the gantry. In this prototype, our goal was to construct a wiper arm that connected the moving gantry to the window pane we had just constructed, and piece together our piping components. We came up with 3 distinct designs for the arm to test. Figure 13 shows the first possible design, connecting the wiper onto the window via a bridge style, where in two gantry tracks would be required both above and below the window. Figure 14 shows the second possible design, a spring loaded arm that connects to a wiper blade on the window. Furthermore, after guidance from Professor Marks, we settled on a hose powered water system attached to the moving wiper. This was composed of a garden to 1/4 inch NPT Male adapter, 1/4 inch NPT Female to Male Ball Valve, two 1/4 inch Female to Barbed adapters connecting 3/8 inch outer diameter 160 psi soft polyethylene tubing to a 1/4 NPT Male Flat Spray Nozzle. The hose attachment can be seen in Figure 15, while the nozzle mounting differed among different wiper designs. Additionally, in order to control the gantry movement, the circuit in Figure 16 was constructed to detect the response of limit switches on either end, allowing the machine to home and rebound at the window's edges. In order to ensure the hose scheme would function under the house water pressure, the head loss through the pipe was calculated:

$$Q = 2\text{ L/min} \;=\; 2\times 10^{-3}\,\frac{\text{m}^3}{\text{L}} \times \frac{1\,\text{L}}{60\,\text{s}} \;=\; 3.333\times 10^{-5}\,\frac{\text{m}^3}{\text{s}},$$

$$D = 0.00635\text{ m}, \quad A \;=\; \frac{\pi D^2}{4} \;=\; \frac{\pi\,(0.00635\,\text{m})^2}{4}$$

$$=\; 3.167\times 10^{-5}\,\text{m}^2,$$

$$v = \frac{Q}{A} \;=\; \frac{3.333\times 10^{-5}\,\text{m}^3/\text{s}}{3.167\times 10^{-5}\,\text{m}^2} \;=\; 1.05\text{ m/s},$$

$$\text{Re} = \frac{\rho\, v D}{\mu} \;=\; \frac{(1000\text{ kg/m}^3)\,(1.05\text{ m/s})\,(0.00635\text{ m})}{0.001\text{ Pa}\cdot\text{s}}$$

$$=\; 6680,$$

$$f \approx 0.035 \quad \big(\text{from Moody chart at Re} \approx 6680\big),$$

$$h_f = f\,\frac{L}{D}\,\frac{v^2}{2g}$$

$$= 0.035 \times \frac{L}{0.00635\,\text{m}} \times \frac{(1.05\,\text{m/s})^2}{2\times 9.81\,\text{m/s}^2}$$

$$\approx 0.62\text{ m},$$

$$\begin{aligned} h_{\text{total}} &= h_f + h_{\text{elevation}} + h_{\text{minor}} \\ &= 0.62\text{ m} + 1.00\text{ m} + 0.12\text{ m} \\ &= 1.74\text{ m}. \end{aligned}$$

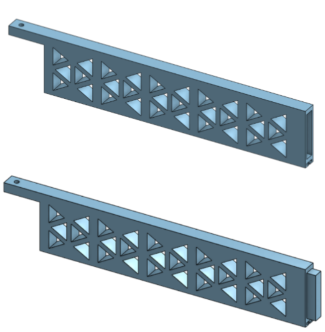

Fig. 13 Bridge Design

Fig. 14 Hinge Design

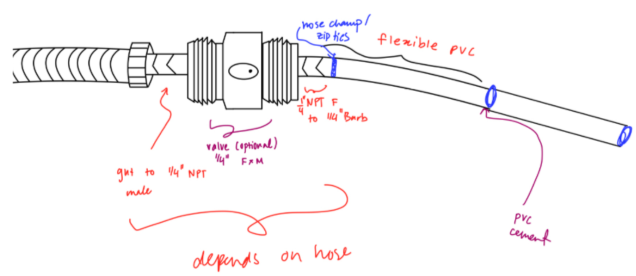

Fig. 15 Hose attachment system

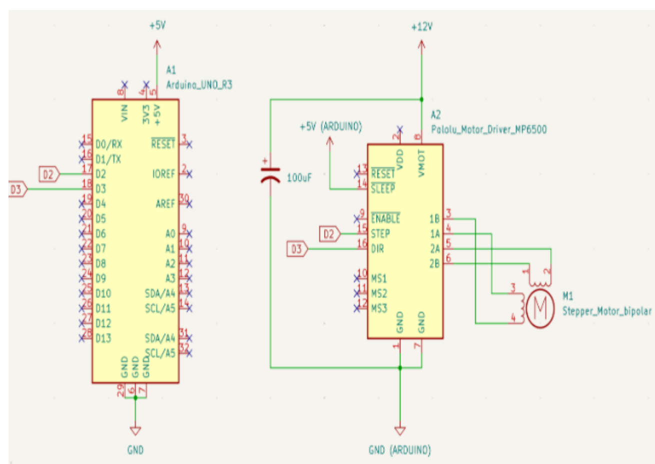

Fig. 16 Motor and Limit Switch Circuit

Test

Since the only component we were able to properly test for this prototype was the electronics, we performed a test of our code using our circuit powered by the power jack. After attaching the belt to the gantry and pulley system, we uploaded our code, and held a limit switch in place at one end of the window. This test proved successful, as the gantry was able to be pulled by the belt across the window, then changed direction once the limit switch was hit.

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Unfortunately, not all the water system components arrived in time, so the water dispensing system was not ready to be tested for this prototype. Additionally, we had issues with the initial 3D-printed arm designs due mostly to time constraints which prevented us from getting a functional design working. Still, we got a good idea of what needed to be fixed going forward, the dimensions that needed to be adjusted, and which design would work best for our project. We decided on going forward with the “hinge” style arm which was spring loaded and attached only to the top of the window, whereas the “bridge” style would be attached to both sides. The biggest accomplishment for this prototype was creating a working code and circuit for controlling the movement of the gantry. Even though the code worked, it was still imperfect. It could only be used with one limit switch, so we had to click it to get the direction to change. We learned that we needed to fix the code so that it was compatible with two limit switches, and we we’re also able to determine the correct position to permanently fixture them so that the wiper was able to span the window.

Prototype 5

Plan

We were left with a few tasks to complete for Prototype 5 which included: determining which wiper arm system would work best, attaching the piping system, soldering the electronic components to a PCB, building the electronics housing, and finally putting all of the components together. The goal of the final prototype was to ensure everything we had created individually would work in harmony, pictured in Figure 17. One of the largest remaining variables was the plumbing system, as we needed to determine the best way to dispense the water onto the window. Thus, to aid our approach we calculated the speed at which the water would need to be sprayed in order to cover the whole window using the conservation of momentum:

$$\sum \mathbf{F} = \dot{m}\left(v_{\text{out}} - v_{\text{in}}\right) \tag{3}$$

$$Q_{\text{up}} = \frac{Q_{\text{total}}}{2}$$

Equating the forces in the $\hat{y}$ direction yields:

$$v_{\text{up}} = \frac{v_{\text{in}}}{2}$$

such that

$$x = \frac{v_{up}^2}{2g}$$

$$\implies v_{in} = (8gx)^{0.5}$$

Therefore, at $x = 1\,\text{in}$, $v_{in} = 4.6\,\text{ft}\cdot\text{s}^{-1}$. This information informed us on the placement of our nozzle in order to reach the entire window. It also confirmed that the speed necessary, was well within what was possible using our hose and valve.
Additionally, we calculated that in order to properly clean the window, the wiper would need around 79.1 N of force applied across its entire length. The static coefficient of friction between rubber and glass, for wet conditions, is around 0.4. Therefore, we calculated a necessary torque of 0.079 Nm. From the motor datasheet, the stall torque for 12V input is 0.1467 Nm. This results in a factor of safety of 1.85.

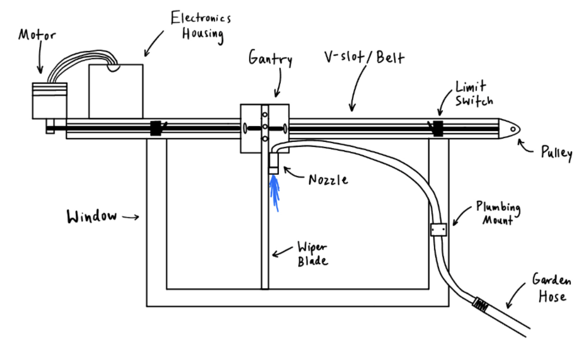

Fig. 17 Prototype 5 Design Plan

Test

We successfully assembled everything together using 3D-printed parts for the wiper arm, electronic housing, and plumbing fixtures. The driving belt was held in place, under tension by the wiper arm and gantry. Two limit switches were placed on either edge of the window on the linear track such that the wiper would know when it had reached the edge of the window. The flexible hosing and nozzle was attached to one side of the wiper arm such that it could then spray in front of the wiper in one direction, and could be turned off on the journey back, shown in Figure 18. Figure 19 shows the performance of the window washing system when clearing dirt from the window. The window was covered with a dirty water and successive wipes were performed. After each wipe the window was placed on a white background and the relative number of non-white pixels remaining was calculated from a photo of the surface. As the graph details, the first few wipes fractionally cleaned more and more dirt off the window, before some limitation was reached due to the edges and angle of the glass.

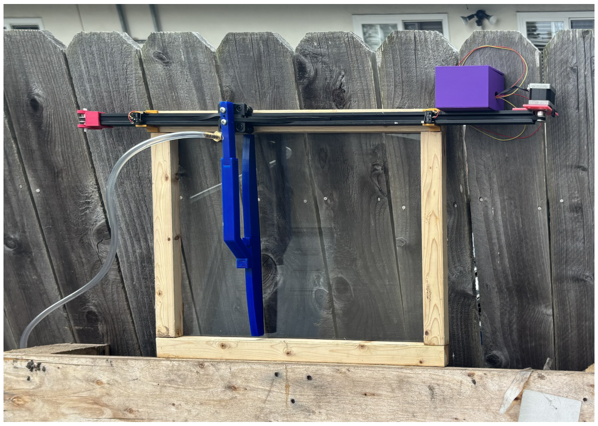

Fig. 18 Picture of Prototype 5.

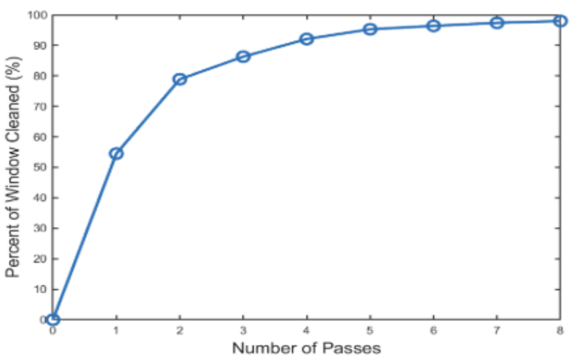

Fig. 19 Cleaning Performance Results

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Our main finding of prototype 5 was that the connection between the wiper blade and window was not perfect for the given wiper blade shape. Initially, the bottom third of the window was not in contact with the rubber and was thus not getting cleaning. To combat this we returned to our CAD software and iterated our wiper blade design to try and achieve a wiper that contacted the entirety of the window. This was the largest challenge from Prototype 5 as we needed to resign, send to the Makerspace to 3D-print, pick up and process the print, and test for each wiper blade. We iterated the design a handful of times before concluding that the window we had made was imperfect, and not vertical. This imperfection resulted in it being very difficult to create a wiper blade design that made contact with the entire window. Another large issue we learned about was the motor placement on its 3D-printed platform. Under the tension of the belt, the platform would begin to bend and cause the motor to break its orthogonal orientation with the pulley and belt. To fix this we placed the motor platform further along the guide rail such that it was being supported by the rail, instead of effectively being a cantilever beam. The last major finding of Prototype 5 was the importance of permanent electronics and electronic housing. At the time of prototype testing we were unable to complete the electronics soldering for multiple reasons, namely the lack of soldering stations during available working times. This resulted in some insecure connections while testing.

Final Touches

As mentioned in Prototype 5, we identified several improvements needed to finalize our design before the Design Fair. First, we created a 3D-designed housing for the electronics to protect them from water exposure. We also experimented with additional wiper arms at various angles to determine which one provided the best cleaning performance and selected the most effective design. Additionally, we 3D-printed an attachment to connect the plumbing to the window. Finally, we refined our code to enable the system to sweep across the window multiple times and switch directions more smoothly. Watch Our Prototype Video Here!

Reflection

The biggest surprise for the design process for this project was the large time delays that were out of our control, mainly for receiving products and 3D-printing. This means that when obstacles appear, you are partly limited in finding a solution by the time it takes to receive or make parts for the solution. The largest failures of our design were small calculation errors or misprints which were not detrimental to the design, however, it delayed the design process, as previously mentioned. The largest success of our team was being able to ideate and find solutions for problems we encountered. We initially had one idea in mind for our product, and after encountering many different obstacles we had to pivot from our initial idea and navigate our way to our final design. This process was very smooth as we were able to bounce ideas off of one another and find a practical solution. We believe that our product has a lot of promise, and would be worth developing further. With a few advancements, more time, and more resources we could slim the design down and make it more visually appealing. This is the largest area of emphasis for change as the process of cleaning the window works quite well. This quarter the work was organized such that each member had certain areas that they specialize in, and then everyone comes together and assembles the product. This is a good method, and we believe that it would translate well to Capstone for next year.