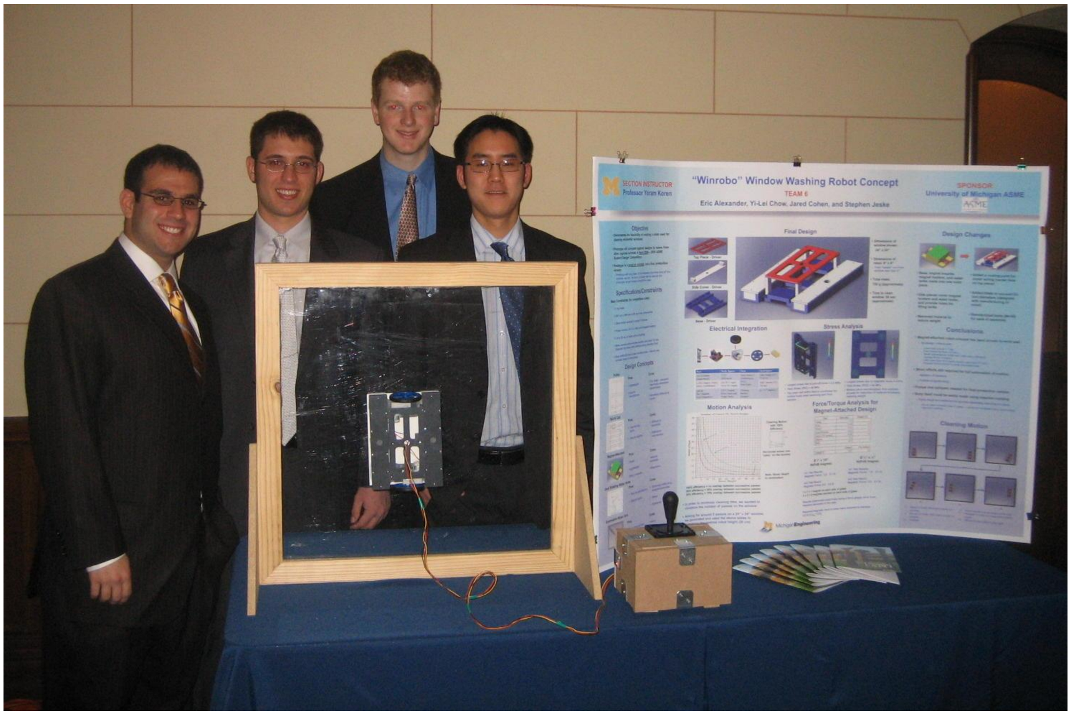
WINROBO WINDOW-WASHING ROBOT



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ABSTRACT

This project demonstrates the feasibility of creating a window-washing robot for use especially by the handicapped in cleaning residential double-hung sash windows. Under strict weight and size limits it is required to be placed on a window and either autonomously or via remote control clean the outside of a window with no other human intervention. This particular robot moves over the window as if cleaning it, wipes off a series of 12 mm-diameter dry-erase dots, and carries 50 mL of water to simulate the cleaning fluid used in the final device.

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1. INTRODUCTION

Cleaning a residential window in one's home is much easier said than done. First of all, most windows are too tall to be reached from outside the house, and a person would need to stick their arm out from inside to clean it. Trying to clean the outer surface of a window from the inside involves an awkward motion because a person would have to reach around the bottom or top and therefore can only clean parts of the window within their reach. It can also be a very messy endeavor with cleaning fluids inevitably dripping onto both the person's arm and the floor inside. On top of all this, the handicapped community has an even tougher time cleaning windows due to their limited mobility and restricted range of motion. Taking all of these factors into account would lead one to believe that a machine, which would clean the outside of the window for you automatically or by remote control, would be a profitable product.

The American Society of Mechanical Engineers (ASME) has decided to hold a competition to determine the best method for creating an automatic window washing robot. The competition will test various prototypes of machines that automatically clean the outside of a residential window with little to no effort from the user. It will involve teams from different universities across the region, and will be taking place in April 2008. The University of Michigan chapter of ASME has decided to sponsor a team consisting of four volunteer members to participate in the competition.

The test will be to run the prototype on a window, on which there will be 25 "dry-erase" dots which it must clean within the specified time limit. The competition has many requirements and limitations, including strict time and size limitations, as well as an extremely strict weight limit (less than 1 kg). In addition, there is a bonus for a completely automated machine with no remote, and points will be deducted for touching the machine or any fluid leaks that may occur.

When a schedule for the design process was developed, the team decided that within this class (ME 450) ending in December, and with the competition not until April, some of the requirements for the competition could be relaxed when creating the prototype for this project. The two biggest things were deciding to have the design be remote controlled (since we have time to create an automation system after the class ends), as well as relaxing the weight limit, focusing now on keeping our design under 5 kg.

In summation, it is the goal of this team to create a machine that will allow a person to clean the outside of a residential, double hung window, using a remote control, that will weigh less than 5 kg and fit into a 300 mm x 600 mm x 800 mm box, in less than 5 minutes. A complete list of the design specifications can be seen in further detail in Section 3 of this report.

2. INFORMATION SEARCH

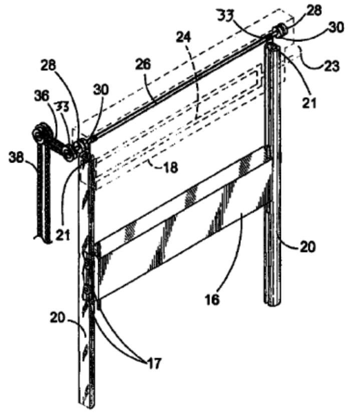
The first step of our design process was to research already-existing designs with similar functions. First we looked at the commercial market. Using the internet we found companies that dealt with cleaning windows on skyscrapers. Klearview Systems' window washer works by installing fixed frames on each side of a window, which spray large amounts of water onto the window in order to clean it. Figure 2.1 below displays how this window washer attaches to a window.

FIGURE 2.1: Klearview Systems' window washer attached to window (virtual product) [1]

This particular design isn't what we were looking for because it needs large amounts of water. This design also requires purchasing a set for each window you want to clean, which is not practical for a residential home. The only window washing methods for cleaning residential homes offered by home improvement stores like Lowes and Home Depot are cleaning solutions and squeegees. The internet provided information about products currently out on the market but didn't inform us about window washers from the past.

The next place to look was the United States Patent Office. Patents are a useful tool for locating designs of past window washing devices because patents are never destroyed. Current patents are similar to the Klearview Systems washer, which are more washers that are attached to permanent frames. This is the case for patent number 7,231,683 filed on Sep. 2, 2003 on Figure 2.2.

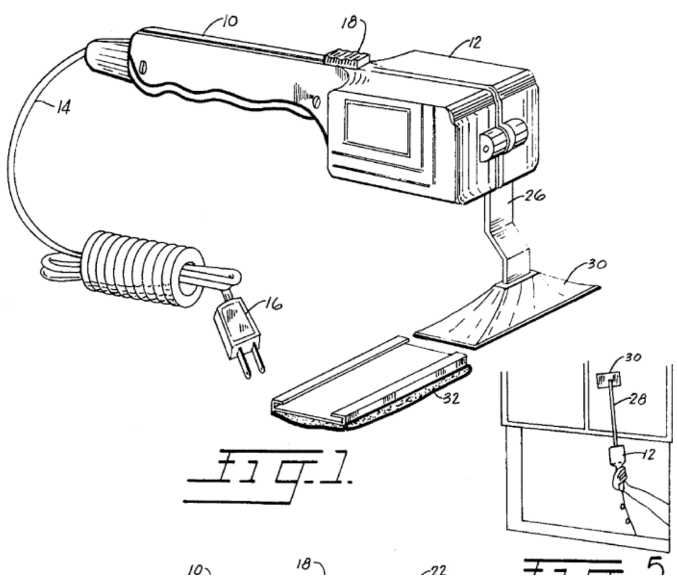
FIGURE 2.2: Patent # 7,231,683 device for cleaning windows



This design would not work for the same reasons as the Klearview Systems device. Again, it requires too much water and cannot be used on multiple windows.

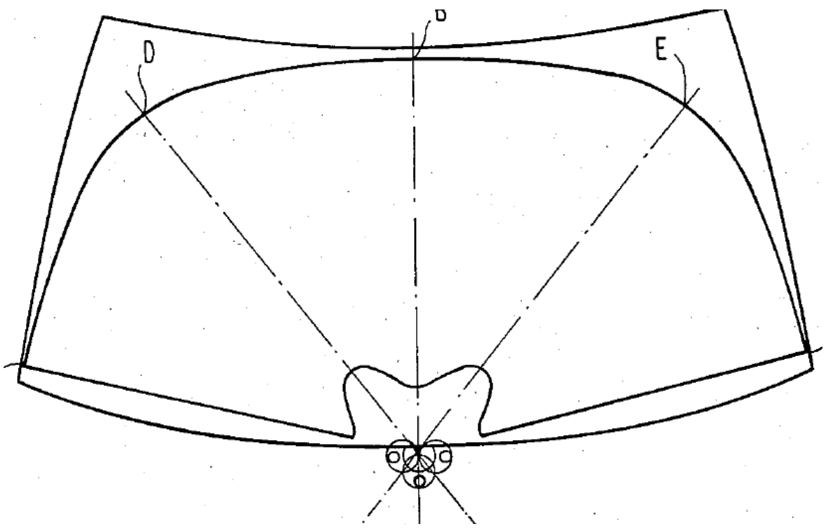
There are numerous patents on automatic cleaning devices but they all follow this same basic principle. They involve flowing water, fixed frames, or are simply too large for any residential window. There is, however, one window cleaning mechanism that was particularly designed for residential use. This invention is patent number 3,629,893 filed on Dec. 28, 1971. This washer would plug into an outlet and would require the operator to stick his or her arm out of the window. The device is then turned on, causing a sponge to vibrate back and forth in order to clean the window. Refer to Figure 2.3.

FIGURE 2.3: Patent # 3,629,893 device for cleaning residential windows



Despite being designed for residential use, this device does not meet our requirements for several reasons. The washing mechanism is not automatic, the device does not meet ergonomic requirements and it cannot be used by a handicapped person.

Figure 2.4: Patent # 4,630,327 windshield wiper system



This patent is not like any others shown because it takes advantage of cylindrical coordinates instead of only Cartesian coordinates. Patent number 4,630,327 issued Dec. 23, 1986, shown in Figure 2.4, is a windshield wiper for a car with only one wiper. The wiper sits in the center of the windshield and rotates 180 degrees in order to cover the entire window. This concept is generally only in use for moving vehicles but it could be applied to residential windows. This device does meet some of our design requirements. This device pumps no water, is automatic, and is fairly lightweight. The problems with this system are that it cannot cover the entire window and it cannot traverse both window panes.

In summary, there are no devices that meet our needs for one reason or another. They either pump water, are too large, are not automatic, or do not clean the entire window surface.

3. CUSTOMER REQUIREMENTS & ENGINEERING SPECIFICATIONS

Because of the unique format of our project, the ASME Student Design Competition's regulations and guidelines were translated into a format fitting of customer requirements. These requirements are regarded as the interests of a hypothetical customer that would adapt our device for consumer use. Table 3.1 lists the customer specifications (in order of relevance) and the competition rules that they are derived from. The order of relevance is derived from the ASME scoring criteria. A complete list of competition regulations as well as scoring criteria can be found at the following URL:

http://www.asme.org/events/contests/designcontest/2008_student_design.cfm

TABLE 3.1: Customer specifications

Customer Requirements	Corresponding ASME Requirements
Lightweight	#14) 1 kg weight limit
Portable	#13) Can be packed in 600 mm x 800 mm x 300 mm box
Battery Powered	#9) Must be battery powered, 24 Vdc max, rechargeable
Safety Mechanisms	#4) Must have safety cord #10) Must come with "safe mode" (low battery mode)
Stays within Window	#1) May only touch within 25mm of any part of clear window
Cleaning Fluid Allocation	#6) Must carry 50 mL H_2O without leaking
Efficient/Clean Window	#5) Must clean dry-erase ink to simulate dirt #12) Must complete all processes in 5 min
Automated	#2) If autonomous, cannot be preprogrammed to clean only 1 size of window #3) If under remote operation: (a) must control through umbilical cord, (b) cord must connect by 9 or 15 pin sub-D connector, (c) cord cannot be more than 2mm in its thinnest, (d) cord must withstand repeated clamping between window • *Scoring bonus also awarded for automated cleaning*
Shutdown Process	#11) Must turn off all cleaning operations and go to lower-left corner and signal when it is finished
Mobility	#7) Must not leave any uncleanable portions of window #8) Scoring bonus for traversing window panes
No Risk of Damage	#15) May not damage window or frame
Handicap Friendly*	N/A
Low Cost*	N/A

* Indicates a **non-competition** specification inferred from the ASME Design Competition problem description

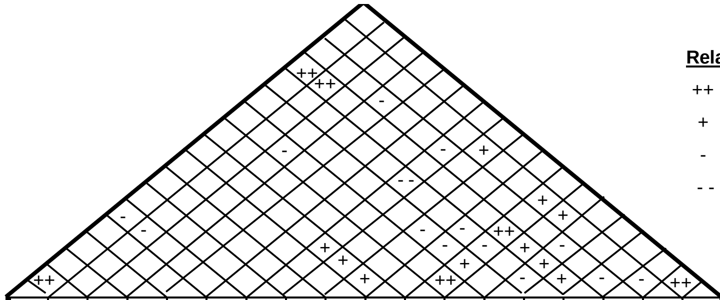
From the above table, we are now able to define the engineering specifications for our design. Table 3.2 provides a summary of the engineering specifications and their relation to the customer requirements. You may note that in some instances, multiple engineering specifications have been classified under a single customer requirement. This has been done to reflect the ASME Design Competition requirements.

TABLE 3.2: Engineering specifications

Customer Requirements	**Engineering Specifications**	
	Description	*Value/Attribute*
Lightweight	Operational mass	≤ 5 kg
Portable	Dimensions	≤ 600 mm x 800 mm x 300 mm
Battery Powered	Power source	24 Vdc max, rechargeable
Safety Mechanisms	(I) Safety cord (II) "Low power" mode	
Stays within Window	Operating boundary	≤ 25 mm of glass
Cleaning Fluid Allocation	H_2O allocation	50 mL
Efficient	Operating time Remove all dots	≤ 5 min 25 dry-erase dots
Automated	Choice: automated/remote	
Shutdown Process	(I) Ends in lower-left corner (II) End signal	
Mobility	(I) Traverse both panes (II) No "blind spots"	
No Risk of Damage	No damage	Window & frame receive no permanent damage/marks
Handicap Friendly	Handicap Ergonomics	
Low Cost	(I) Low Cost (II) Reliability	

By combining both the customer requirements and engineering specifications we can then determine the relative importance of each aspect of our design through the use of the QFD model. Figure 3.1 below summarizes our QFD results. The weights of the customer requirements are given in accordance to the scoring criteria provided by ASME's Design Competition rules. The highest weights (value of "10") are awarded to the requirements that were immediately disqualifiable upon entry in the competition. Weights of "9" are awarded to requirements that are disqualifiable but only after repeated failure to meet that criterion. All other weights are based purely on a hierarchy of the competition's point values. A "1, 3, 9" scale is used to quantify the relation between the customer requirements and engineering specifications.

FIGURE 3.3: QFD diagram



Relationships
- ++ Strong Positive
- \+ Medium Positive
- \- Medium Negative
- \- - Strong Negative

(+) => more is better
(-) => less is better

	Weight*	Operational Mass	Dimensions < 0.6x0.8x0.3	Operating time	Battery: Voltage	Battery: Rechargeable	Fluid: H_2O Allocations	Safety Cord	Low power mode	Operating boundary	No damage	Ends in lower left	End signal	Automation/ Remote	Traverse both window panes	Handicap Ergonomics	Low Cost	Reliability	Cleans Dry Erase		*Patent 3,629,893 - Brown*	*Patent 7,231,683 - Cruz*	*Squeegee*
Lightweight	10	9	3	1			1				1			1		9	3				4	1	5
Portable	10	3	9													9	1				4	1	5
Battery Powered	10	9	3		9	9			9				9				3				1	1	1
Safety Mechanism	10	1	3		3			9	9		9			1				3			1	4	1
Stays within Window	9		9					1		9	3			3	3			1			4	5	4
Cleaning Fluid Allocation	9	9	3				9												1		1	5	1
Efficient/Clean Window	8	3	1	9								3		3	9				9		2	3	2
Automated	7	3		3					3			9	3	9	9	9	3	3			2	5	1
Shutdown Process	7	1	1						3			9	9	3		3		1			2	4	1
Mobility	6	3	1	9				3		3		3			9						3	1	3
No Damage Risk	5				2			9	9	3	9			1				1			4	5	4
Handicap Friendly	3	9	9		3							9		9	9	9		3			2	5	2
Low Cost	3	3	1	1	1	1		1						3	1		9				3	1	5
Measurement Unit		kg	m^3	min	VDC	-	mL	-	-	mm	-	-	-	-	-	-	$	-	-				
Target Value		< 1	<14	<5	<24		<50			<25							400						
Importance Rating		**1**	**2**	**11**	**12**	**15**	**16**	**10**	**4**	**14**	**9**	**6**	**8**	**7**	**5**	**3**	**13**	**17**	**18**				
Total		407	339	160	142	93	91	165	267	114	172	195	174	196	246	291	118	81	81				
Normalized		0.13	0.10	0.05	0.04	0.03	0.03	0.05	0.08	0.04	0.05	0.06	0.05	0.06	0.08	0.09	0.04	0.02	0.02				

Benchmarks **

Key:
9 => Strong Relationship
3 => Medium Relationship
1 => Small Relationship
(blank) => Not Related

***Weights are figured on a scale of 1 to 10**
(ten being most important)

****Benchmarks are figured on a scale of 1 to 5**
(five being most important)

From this, we are then able to determine the relative importance of each engineering specification through the use of the following algorithm, Eq. 3.1.

$$\sum_j E_i C_j \qquad \text{Eq. 3.1}$$

Where:
E_i = engineering specification number,
C_j = customer requirement weight
i = each engineering specification's column
j = each customer requirement row.

The summations can be viewed in the "Total" row of Appendix A. We find that the following order of importance for the engineering specifications is observed:

1. Operational Mass
2. Dimensions
3. Handicap Ergonomics
4. "Low Power" mode
5. Traversing both window panes
6. Ending in lower-left corner
7. Automation vs Remote control
8. End signal
9. No damage
10. Safety cord
11. Operating time
12. Battery: voltage
13. Low cost
14. Operating boundary
15. Battery: rechargeable
16. Water allocation
17. Reliability

As expected, weight and size come out as most important factors of our engineering specifications. Surprisingly, handicap friendliness weighed in at third. This is a result of the fact that handicap friendliness is heavily related to how lightweight and portable our device is (which are high priorities for our customer). The remaining factors follow closely after each other in value and more or less reflect competition scoring criteria accordingly.

4. CONCEPT GENERATION

The generation of our concepts can be seen as a four-step process. The first step is to understand our customer's needs which are expressed in our QFD analysis in section 3. The next step is to conduct a functional analysis of our problem so that we can better see how our entire system should behave. This has been expressed in the form of a FAST diagram in section 4.1.1. The third step is to derive solutions for each functional problem which are expressed as a Morphological chart in section 4.1.2. The final step of this process is to combine our results from the previous steps to brainstorm working concepts. Discussion of this is given in section 4.2.

4.1 Methodology

Once an understanding between customer requirements and engineering specifications has been made, a framework for bridging the gap from problem to solution can be created. To do this we must first examine the functional issues of the overall problem – cleaning a window. From this we can then propose elemental solutions to each issue which will later be synergized into a system of solutions for the overall problem.

4.1.1 Function Analysis

Our functional analysis begins with defining our functional objective: to clean a window. From this we branch into two primary active functions (cleaning glass and traversing pane) as well as three primary passive functions (assuring dependability, assuring convenience, and enhancing product). A complete FAST diagram can be seen in Figure 4.1.

In order to clean the glass, a cleaning surface must be engaged on the window. This means that both a normal and tangential force must be applied to the window from the device: a normal force to provide cleaning friction, and a tangential force to move the robot along the window.

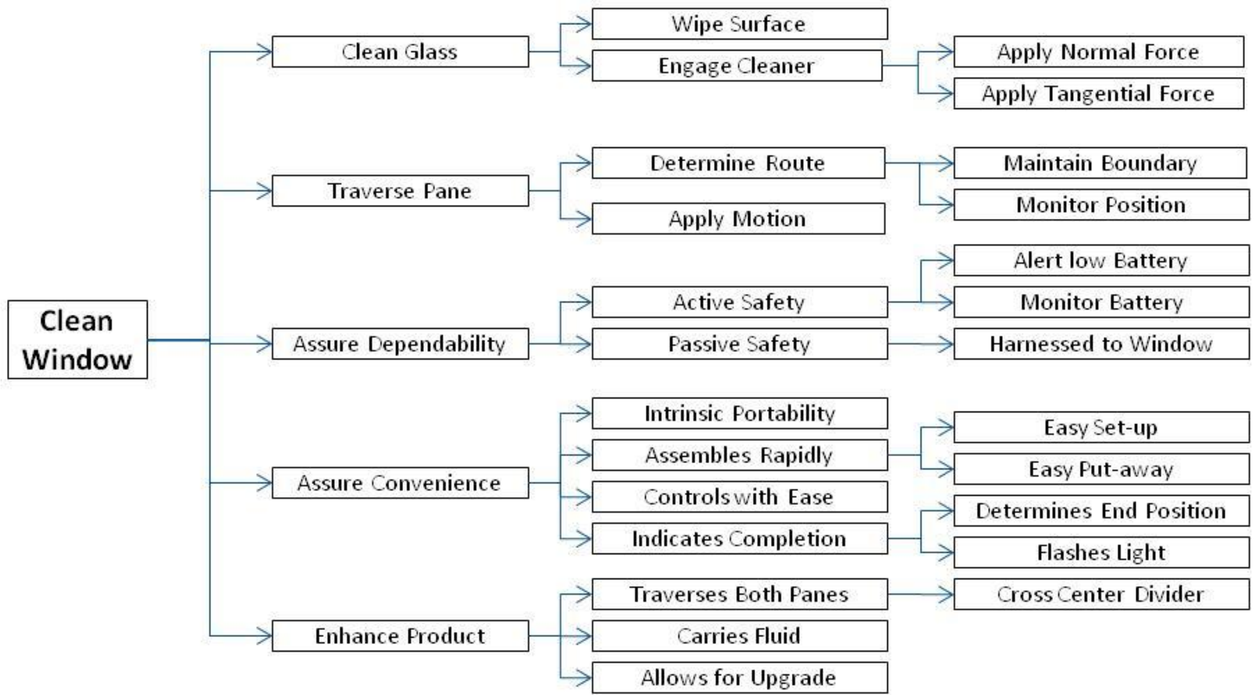
Traversing the window pane can be seen as a two-part process. The first part, determining a route, requires two additional sub-functions: maintaining a boundary and monitoring the position of the robot. The second part of traversing the window is applying motion, thus moving along the already-determined route.

To ensure dependability, three basic functions must be addressed. The unit must exhibit active safety, passive safety, and indicate completion of cleaning process. The active safety function should contain two sub-functions: battery monitoring, and low battery alert. The passive safety function contains just one sub-function which is to be harnessed to the window frame. Another important aspect of dependability is for the unit to know when it has completed. Therefore it must have the function of indicating completion with the sub-functions of flashing a finish light and determining a finish location.

Ensuring convenience relies on three functions: its intrinsic portability, ease of assembly, and ease of control. Intrinsic portability refers to the unit's inherent size. In both the assembled and disassembled states the unit should be no greater than 600 x 800 x 300 mm. The unit should also be easily assembled and disassembled, minimizing time and effort for the customer. Easy control of the unit while operating is also a necessary function of convenience since the underlying goal of the robot is to eliminate effort on the user's end.

For product enhancement, we chose the primary functions of traversing both panes, carrying fluid, and allowing for upgrades. To further reduce labor for the customer, the unit's ability to switch from one window pane to another is a key step in reducing the number of times the customer would need to physically handle the robot. The robot's ability to carry a representative load of 50 mL of water greatly enhances the product in that we could later adapt a pump and spray mechanism to expand the unit's ability to handle different cleaning jobs. Finally, the unit should be designed to allow for upgrades. This is important since our prototype will be a proof of concept that will later be improved. This means that we must be aware that our functional solutions should in some way allow room for improvement.

FIGURE 4.1: FAST diagram



4.1.2: Functional Solutions

By examining the FAST diagram, we are then able to create possible solutions to address each function. To organize these solutions into a visual table, we constructed the following Morphological chart with examples (Table 4.1).

TABLE 4.1: Morphological chart

FUNCTION	**OPTIONS**			
Wipe Surface	Scraping Media *(squeegee)*	Porous Media *(sponge)*	Brushed Media *(dry-eraser)*	
Apply Tangential Force	Pulley *(pulls wiper across window)*	Track *(means for cab "push" against to move across window)*	High-Friction Wheels *(frictional force moves robot across window)*	Articulated Motion *(push cleaning surface across window)*
Apply Normal Force	Magnets *(attractive force is balanced by normal force)*	Clamps *(direct application of normal force)*	Spring *(spring in tension pulls material onto window)*	Strings Looped Around Window *(pull material closer to window)*

Maintain Boundary	User Control *(remote)*	Optical Sensor *(infrared, ultrasonic)*	Physical Sensor *(pressure sensor, toggle bumper)*	Stepper Motor Position Control
Monitor Position	User Control *(visual reference)*	Software Mapping *(onboard computer)*	Implicit Mapping *(record trajectory & speed)*	
Apply Motion	Servo Motor	Linear Actuator	Stepper Motor	DC Gear Motor
Harnessed to Window	Safety Cord *(bungee cord, rope)*	Clamp to/in Window *(U-bracket set in window)*		
Intrinsic Portability	Minimal Parts	Low Volume Design	Low Mass Material	
Easy Set-Up	Minimal Parts *(all-in-one unit VS entire assembly)*	Eliminate need for Tools *(snap-to-fit pieces)*	Easy Mounting	Low Volume & Mass *(plastics for low density)*
Easy Put-Away	Minimal Parts *(all-in-one unit VS entire assembly)*	Eliminate need for Tools *(magnets allow for quick, tool-free detachment)*	Easily Removed from Mounting Position	Low Volume & Mass
Controls with Ease	User Control *(remote)*	User Prescribed *(articulated motion, guided path)*	Automatic *(computer/sensor interface)*	
Determines End Position	Optical Sensor	Pressure Sensor	User Input	
Flashes Light	LED	Incandescent		
Cross Center Divider	Step-over *(uses legs/arms)*	Roll-over *(treads, elevated front/rear wheels)*	Manual Placement on Both Panes	Engage both Panes Simultaneously
Carries Fluid	Hard Container	Soft Pouch		
Allows for Upgrade	Free Space	Flexible Dimensions *(i.e. do not restrict placement of parts)*		

4.2 Concept Brainstorming

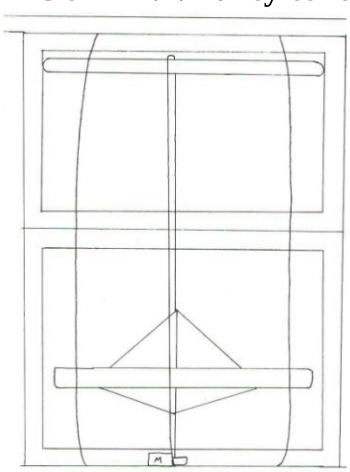
Addressing the functional problems from the previous section, we are now ready to assimilate our functional element solutions into a full system. In total we have produced five possible concepts which will be discussed next.

4.2.1 Pulley System

The main mechanism of this device uses a simple pulley system (Figure 4.2). A light rod is placed outside the window at its highest point; this rod is secured by either a spring or a screw. A small motor is placed at the bottom of the window, with a large piece of string attaching the cleaning device to the rod and motor. The motor then turns on and the cleaning device moves up the window.

Although the windows can vary in size, it is only by a few inches and therefore a large cleaning device that slightly shifts side to side could clean the entire window. This extra movement, however, requires another motor or actuator. The cleaning device is pulled up vertically and thus the cleaning surface does not exert much force onto the window. This problem is fixed by installing one or two guidelines around the back of the cleaning device. These lines start from the top of the window, travel around the outside of the device, and reattach at the bottom of the window. They are pulled in tension which would apply the force needed between the cleaning device and window. They also serve as a safety mechanism in order to prevent the device from falling; the lines partially attach to the rod and motor so that if either falls, the lines would catch it. The lines would have a round object, such as a ping-pong ball, attached to the ends which would not allow the guidelines to move while the window is shut.

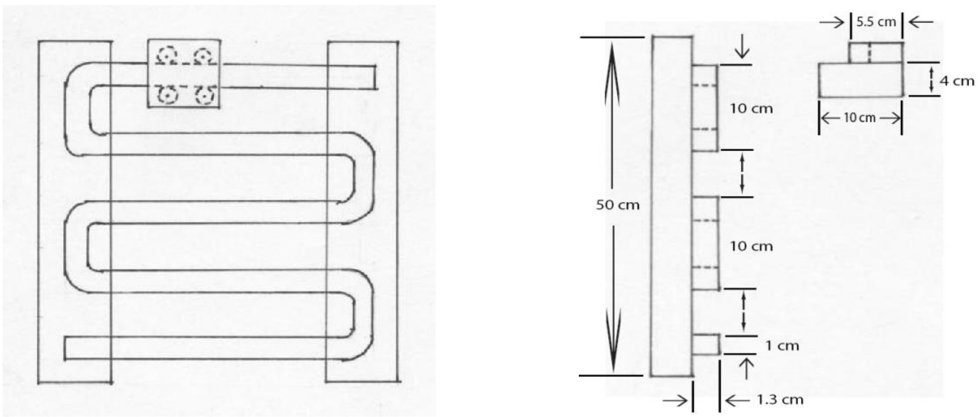
FIGURE 4.2: Pulley concept



4.2.2 Rail & Cab

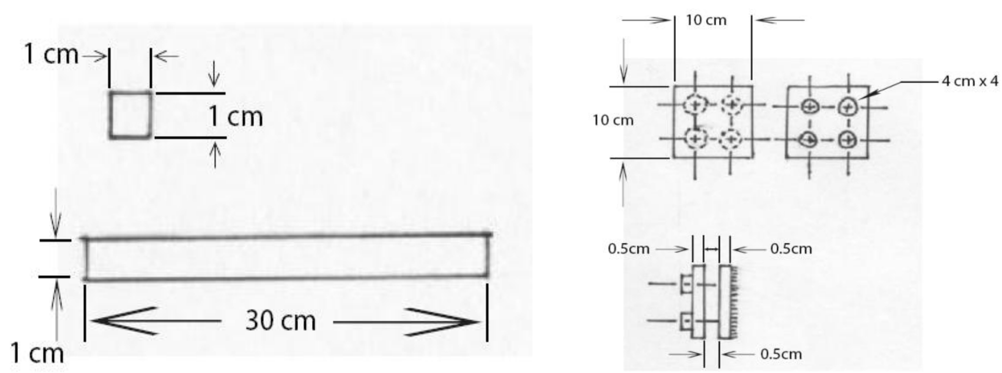
The Rail & Cab concept operates using similar principles as the pulley system in that a rover (the cab) is guided by a preset route (the railing). As seen in Figure 4.3, an adjustable frame roughly the size of the window is fitted within one pane of the window. The cab is placed on the frame during assembly so that its movement is restricted to the railing.

FIGURE 4.3: Complete assembly and end support



The frame itself is broken down into two unique components with seven total parts. The first parts are the end supports. As seen in the above figures, they consist of cedar wood blocks with the bends of the rails milled out of them. Figure 4.3 provides more detailed dimensions of the end supports. The other five parts of the frame are the intermediate rails. These consist of long tubes with a 1 cm square cross-section. A dimensioned engineering drawing can be seen in Figure 4.4, along with a detailed sketch of the cab unit. This unit consists of four wheels on one side, powered by a choice of a single motor. The center space of the cab will house the motor and electrical systems, while the side opposite of the wheels will have a cleaning surface.

FIGURE 4.4: Intermediate support and cab unit

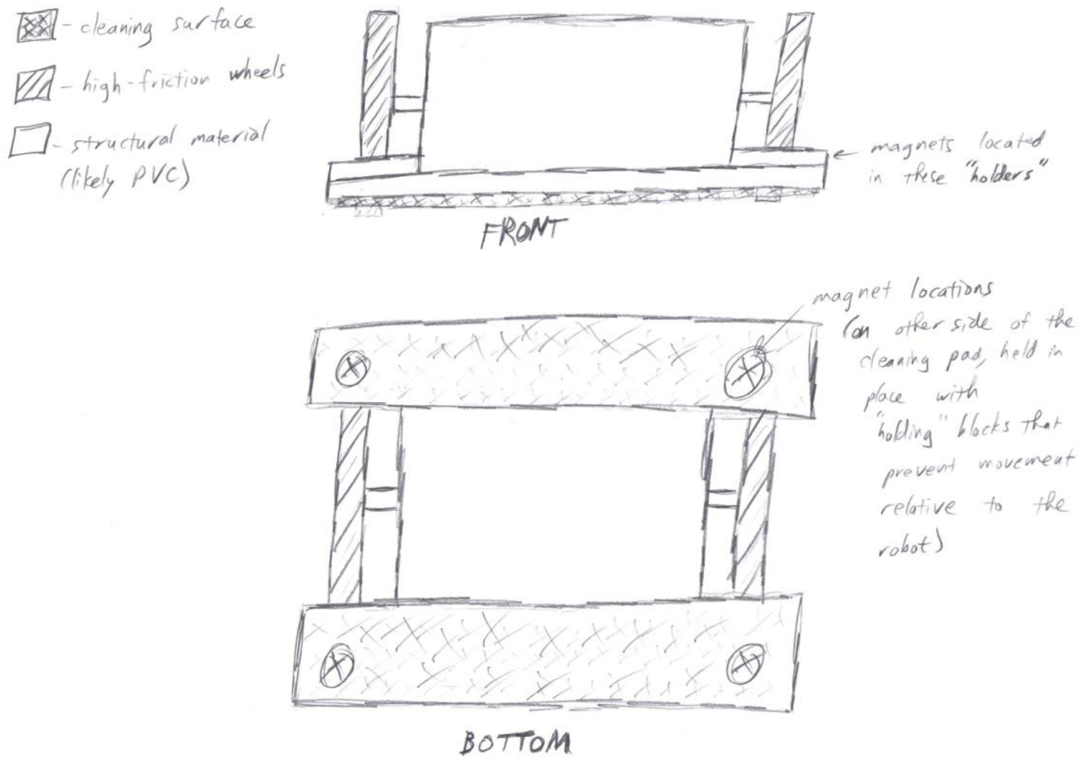


The entire window cleaning assembly is estimated to weigh approximately 550 grams including a 50 mL water compartment allocation. The mobile cab unit is estimated to weigh 300 grams fullyloaded. With a safety factor of 2, this allows for an estimated 0.40 Nm of necessary torque to allow the cab to climb upwards along the end supports without difficulty.

4.2.3 Magnet-Attached

This concept uses magnetic force to attract through the window onto a "follower" pad on the other side, eliminating the need for an anchor point on the window. Refer to Figure 4.5.

FIGURE 4.5: Magnet-attached robot concept sketch



By incorporating high-strength neodymium iron boride (NdFeB) magnets, the weight of the magnets can be kept to a minimum while providing a very strong force of attraction through the window, which translates into a high normal force. This allows for a frictional force that is large enough to keep the robot upright on the window, and high-friction rubber wheels will be used to move the robot across the window. High torque, low speed DC geared motors can be used to accomplish this task; alternatively, stepper motors can be used for more precise open-loop positioning, if necessary. DC geared motors would be the preferred design due to their lower weight and high torque, providing more than the torque required by this design.

This concept would use a joystick to control the direction of the motors. Both motors could be moved in one direction for forward motion, one motor could be moved forward and one backwards for turning, both could move backwards for reverse motion, and one reverse and one forwards for turning in the other direction.

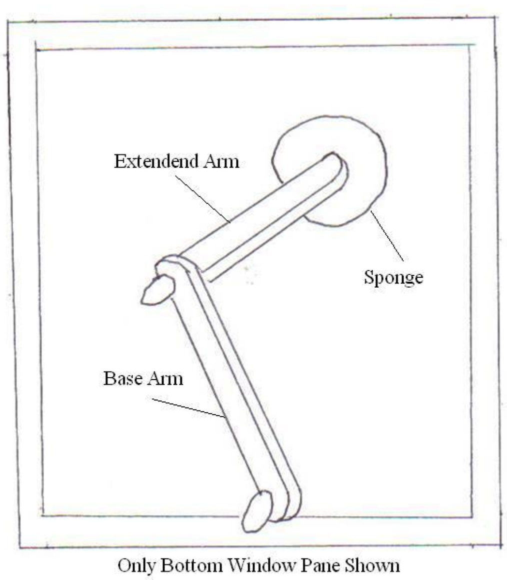
A moderate-to-low friction pad on the window side of the robot would be used for cleaning, as well as upward frictional force on the window (in addition to the frictional force generated by the wheels) to counteract the downward force from the weight of the robot. The “follower” pad on the opposite side of the window would likely also have a cleaner pad, or it could be outfitted with a multi-directional wheel to minimize the frictional force on that side of the window if there were problems with the “following” action due to too much kinetic friction.

4.2.4 Dual Rotating Arms

The dual rotating wiper arms concept is a design based off of two rotating arms at the center of the window. The base arm pivots at the bottom center of the window using a motor, which turns the arm up to 360 degrees. The extended arm attaches to the end of the base arm and can similarly rotate, and also has a cleaning surface attached to its far end. These two arms would correlate their motions to move the cleaning surface over the entire surface of the window, thus cleaning the entire window. Refer to Figure 4.6 for a front view of the device.

The base motor is clamped at the base of the window. This clamp is the only part of the device that is applying normal force to the window to clean it. The optimal length of the base arm is 28 cm while the extended arm is 20 cm.

FIGURE 4.6: Front view of the dual rotating wiper arms concept

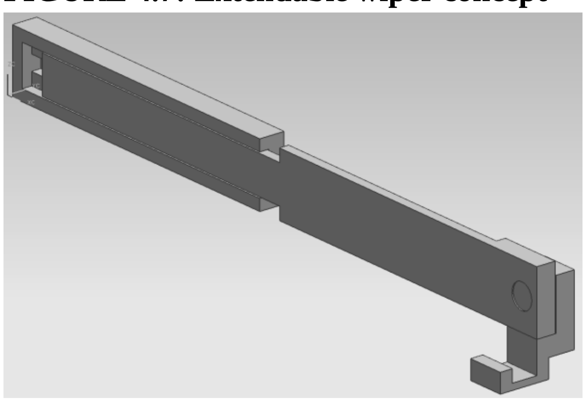


The cleaning surface is a cylindrical sponge with a 5 cm radius. The sponge is cylindrical in shape so it can clean all four corners of the window regardless of the orientations of the arms. This design cannot automatically clean the top window pane and requires the operator to manually move the device in order to clean the top pane. Preliminary analysis shows that the base motor would need to have a minimum torque rating of about 2.5 Nm and the extended arm motor would need a minimum torque rating of about 1 Nm. This translates into a base motor that would weigh approximately 1.7 kg and an extended arm motor that would weigh approximately 0.7 kg. The motor weights plus everything else places the overall weight at a minimum of 2.5 kg.

4.2.5 Extendable Wiper

This concept for a window washing robot would mimic a car's windshield wiper, with a slight twist making it possible to reach the entire window on one pass. The idea was inspired by a single wiper blade linkage system that is now being produced for some luxury automobiles, that extends the wiper blade outward before rotating in either direction. The concept involves a rotating wiper arm, based in the bottom corner of the window's frame that has an extension attached at the end and a cleaning surface between the window and the arm. As the arm rotates, the end of the arm extends radially towards those hard to reach points, increasing the cleaner's reach so that it can clean every portion of the window.

FIGURE 4.7: Extendable wiper concept



This design, seen above in Figure 4.7, which is being called the "extendable wiper" concept, is very straight-forward and would be easier to program than a two-rotating bar concept. It also can be very compact if necessary. It would require two motors, a linear motor – or some similar method of achieving linear motion, perhaps a DC motor with a rack and pinion system – to extend the cleaning surface and a stepper or DC motor at the base for rotational motion in order to achieve the desired motion. The only additional parts are the base and rotating arm, which would likely be made out of a lightweight material such as PVC, so this design is both simple in theory, and functionality.

One concern about this design is that the torque rating for the base motor would be very similar to that for the Dual Rotating Arms concept, and thus the motor required may be very heavy. Further analysis follows in section 5.

5. CONCEPT EVALUATION AND SELECTION

This section focuses on evaluating our design concepts through analysis of the merits and limitations of every design, as well as through the use of a Pugh chart.

5.1 Concept Evaluation

In order to evaluate our concepts, we determined the benefits and drawbacks of every design. This section outlines this analysis, which then is put into a numerical analysis through the use of a Pugh chart in Section 5.2.

5.1.1 Pulley System

There are a few advantages and many disadvantages to the pulley system. One of the strongest advantages for this system is that the overall weight is low. Since strings are used, the only substantial weight comes from the motor and the rod. This system is also easy to build and operate once in place. The fabrication involves a cylindrical rod, a couple motors, and a cleaning device. Since the horizontal movement is random there is no need for the accuracy of a computer or joystick. Once in the window the operator only needs to flip a switch to move the cleaning device up and down. The device really only needs to travel across the window one time and since the cleaning device is so large the cleaning time should be relatively low.

Ultimately, however, there are many limitations which make this design impossible to use. The first problem is that this device would be an absolute nightmare to attach to the window. The combination of string and loose pieces means the device will get tangled and mixed together. The device cannot traverse from one window pane to the next and it cannot clean the entire window. The angled strings make it impossible to clean the upper portion of the lower pane. Another large issue is that there is no good way to add a motor which causes the cleaning device to vibrate horizontally. The cleaning device is also supposed to finish in the lower left-hand corner of the window when complete. This device would most likely struggle to move back down the window after it has already moved up.

The main problem and the one that ultimately makes this design impossible is its size. The rules specifically state the device cannot be longer than 800 mm when assembled. This length is shorter than the length of the window (1300 mm). The pulley-system is at the full length of the window when assembled and therefore this device cannot be used.

5.1.2 Rail & Cab

The main advantages to this design lie in the cab unit. Since it runs on a guided route, the cab does not require parts other than the motor-wheel assembly and cleaning surface. Furthermore, the cab can be automated and needs only to be programmed to stop when it reaches the end. This means that only a small amount of power is required to move it along the rails. Also, the simplicity of the cab increases durability and reduces maintenance efforts. The overall assembly is light and can be cheaply made. The railing also provides for stability of the cab when in motion, adding to the consistency of the job done.

The main disadvantages to this design are its size and overall complexity. The assembly, when put together, is roughly the size of the entire window, which can be cumbersome to assemble and disassemble. Furthermore, the frame itself has seven pieces of two distinct types (5 identical intermediate supports and two opposite end supports). This means that when one piece fails, the entire assembly will be non-functional. This unit also loses out on versatility in that it cannot clean in patterns other than the one designed into the railings. It also cannot traverse the window panes without the entire assembly being moved, and there is no way to adjust the normal force applied by the cab onto the window.

5.1.3 Magnet-Attached Concept

There are several merits to this concept. Because of certain DC geared motors and controllers we have found, this concept can be relatively easily programmed to be driven by a joystick. Also, we can package the electronics and battery inside the base of the joystick, allowing for the robot itself to be very lightweight and thus require a smaller frictional force to remain on the window, translating into a weaker required magnetic force and smaller, lighter magnets. The robot itself can be very small and easily attached and removed from the window. Also, because of the geometry of the robot, there is plenty of room to attach a 50 mL tank (a requirement for the project). The components of the project are relatively cheap – around $150 total for materials, not including materials for building a test window.

Nevertheless, the concept does have some drawbacks. The motors we would likely use are very slow and would take close to the five-minute limit to clean the entire window. Attaching the magnets to the robot and preventing them from moving relative to the robot itself would take some work, as every suggestion so far has been large, bulky, and heavy within the scope of our project. Also, should the electronic components and especially the battery be required to be attached to the robot on the window, the weight would significantly increase to levels at or above those required by the competition, if not for this class. In addition to the added components, the robot would likely have to be made larger and sturdier, and heavier magnets would have to be used to provide a greater normal force.

5.1.4 Dual Rotating Arms

Advantages of the dual rotating arms concept are that this device is easy to manufacture and install. The manufacturing process would only be two bars, two motors, a clamp, and a sponge. This installation process would take the operator seconds to attach to the window. They could simply open the window, clamp the device to the window frame, and then shut the window.

There are also many disadvantages to this design. The first problem is operation. The operator would need the precision of a surgeon to be able to move each motor at the right time in order to clean the whole window. Alternatively, to coordinate the two arms so that someone would easily be able to operate them would require an extraordinary amount of programming that is probably outside of our current programming skills.

Another problem is this device can only clean one window pane at a time. The operator needs to move the device from the bottom pane to the top pane after the bottom one is cleaned.

The largest problem, however, is that this design is too heavy. The torque needed to move the bars requires large motors. Although weight is something that is relaxed for the time being it would be impossible to cut out this weight later in the design process. Therefore the weight and the complexity of this device make it impossible for us to continue on this design.

5.1.5 Extendable Wiper

The extending wiper concept would be very good for this project because it is a simple design involving very basic motor functions and it follows an angular path meaning our motors would not require sophisticated programming. The negatives however are a strong deterrent from this design. The two motors required, the linear actuator and the DC or stepper motor for the base, would both have to be very expensive and very heavy to perform the required tasks. Finding both motors for under $400 and under 1 kg (again, not a problem for the course, but the motors are not a scalable component for the design for the competition) would be very difficult.

Hitting corners accurately, and switching between the panes of the window would also prove to be very difficult with this design, and could probably not be done within the size limitations of our customer.

5.2 Concept Selection

In order to aid in our concept selection process, we made a Pugh chart for quantitative comparison of meeting customer requirements for each design concept. This chart is located in Figure 5.1.

FIGURE 5.1: Pugh chart

Customer Requirement	Weight	Pulley	Rail & Cab	Dual Rotating Arms	Extendable Wiper	Magnet-Attached
Light weight	10	0	-	-	-	0
Portable	10	0	+	+	+	+
Battery powered	10	0	0	0	0	0
Safety mechanism	10	0	0	0	0	0
Stays within window	9	0	+	-	+	+
Cleaning fluid allocation	9	0	0	0	0	0
Efficiently clean window	8	0	-	+	+	+
Automated	7	0	0	-	0	-
Shutdown process	7	0	0	0	0	0
Mobility	6	0	0	0	0	+
No risk of damage to window	5	0	0	-	-	0
Handicap friendly	3	0	0	0	0	+
Low cost	3	0	-	-	-	-
Total (+)		0	19	18	27	36
Total (-)		0	21	34	18	10
Net Total		0	-2	-16	9	26
Weighted Total (100 + Net Total)		100	98	84	109	**126**

We based all of our ratings against the pulley concept. From the Pugh chart, we can see that our two best concepts are the magnet-attached concept and the extendable wiper concept.

In order to achieve our weighted total, subtract the "Total (-)" number from the "Total (+)" number and add 100 (as a means for measurement). The "Total (+)" number was found by adding the weight of every customer requirement that received a plus for that concept, and similarly the "Total (-)" number was found by adding the weight of every requirement that received a minus for that concept.

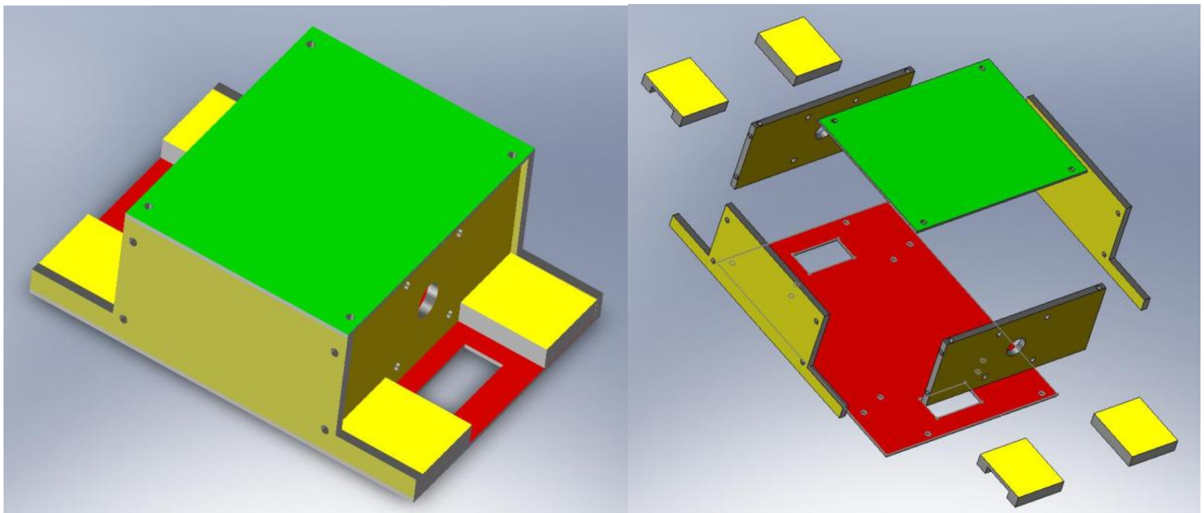
6. Selected Concepts

This section explains further details about our two selected concepts for further evaluation, the magnet-attached concept and the extendable wiper concept.

6.1 Magnet-Attached Concept

The magnet-attached concept consists of a box-like rover with four magnets on each pane of the window for providing attachment to the window and two motors for motion along the window. The initial design is shown in Figure 6.1.

FIGURE 6.1: Assembly and exploded views of magnet-attached concept

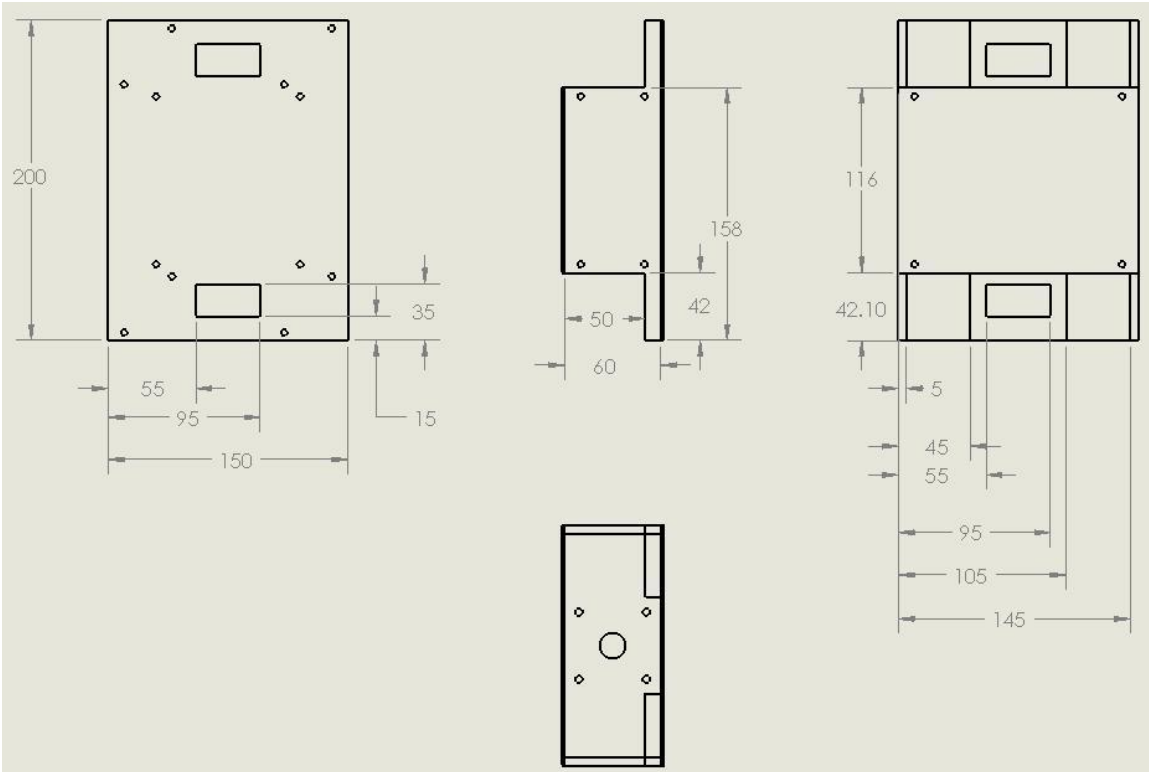


The “box” area in the middle of the rover houses the motors and 50 mL tank, as well as any electronics necessary, such as motor drivers. The holes in the middle of the sides of the rover allow an outlet for the motor shafts, which attach to high-friction rubber wheels that rotate on the glass through the rectangular holes in the base of the rover. The blocks on either end of the large rectangular holes in the base of the rover house the magnets and prevent them from moving relative to the rover. The spaces in these blocks for the magnets are toleranced tightly to the diameter of the magnets being used for minimal relative movement.

All pieces shown on Figure 1 above will likely be made of PVC because of its combined light weight and rigidity. The pieces attach through small-diameter screws, and the motors attach to the sides through the bolt holes surrounding the outlet holes for the motor shafts.

Figure 6.2 shows the dimensioned drawing for the rover. These dimensions are pending stress analyses, especially on the bottom block because of its very small thickness, but the parts will be made as small as possible to reduce weight. However, the sides attach by screws (likely 2 mm in diameter) running through their thickness dimension, so these will have to be made at least 5 mm thick in order to accommodate these screws. The overall size of the rover is small – 200 mm by 150 mm by 62 mm. This size needs to be optimized for weight considerations, taking into account the number of side-to-side “passes” we need to take on the glass at a given size of rover. The size affects the amount of time the rover takes to move over the entire window surface at a given speed, so this will be carefully determined. The size also depends on the motors selected for use in the project.

FIGURE 6.2: Engineering drawing for the magnet-attached concept



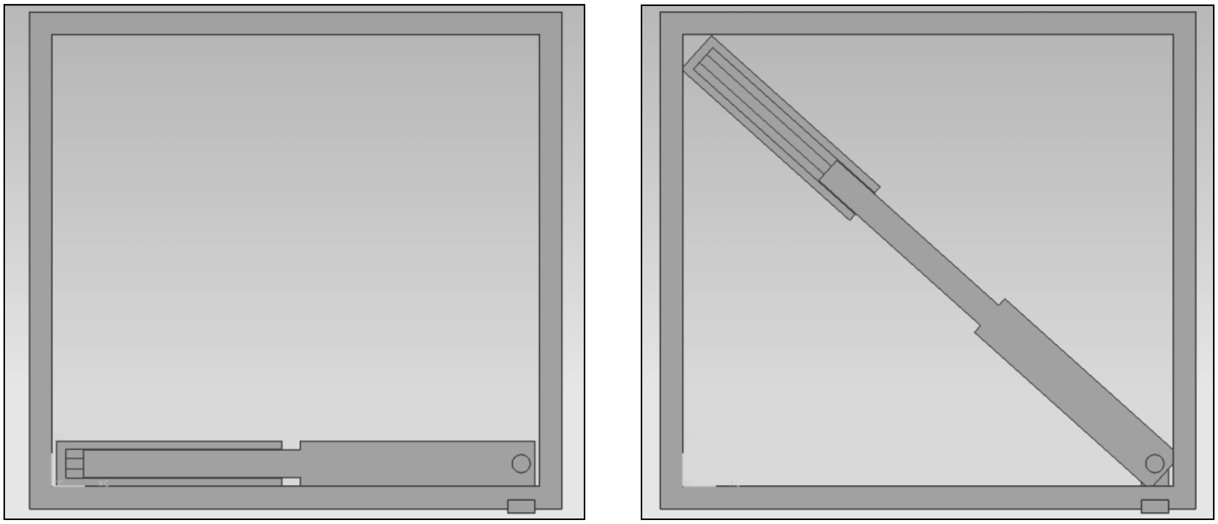
6.2 Extendable Wiper Concept

Drawing inspiration from the windshield wiper found on cars, a design was created that involves a wiping blade with cleaning material on the side that touches the glass. The design is clamped to the window in one of the bottom corners and has a motorized arm, which extends towards the opposite side of the window, connected to a motor on the base clamp.

One big problem with this concept, however, is that a car's windshield wipers cover only a portion of the glass window and not the whole thing. Another issue is the large torque required for a motor to overcome both the weight of the wiper blade and the friction on the glass.

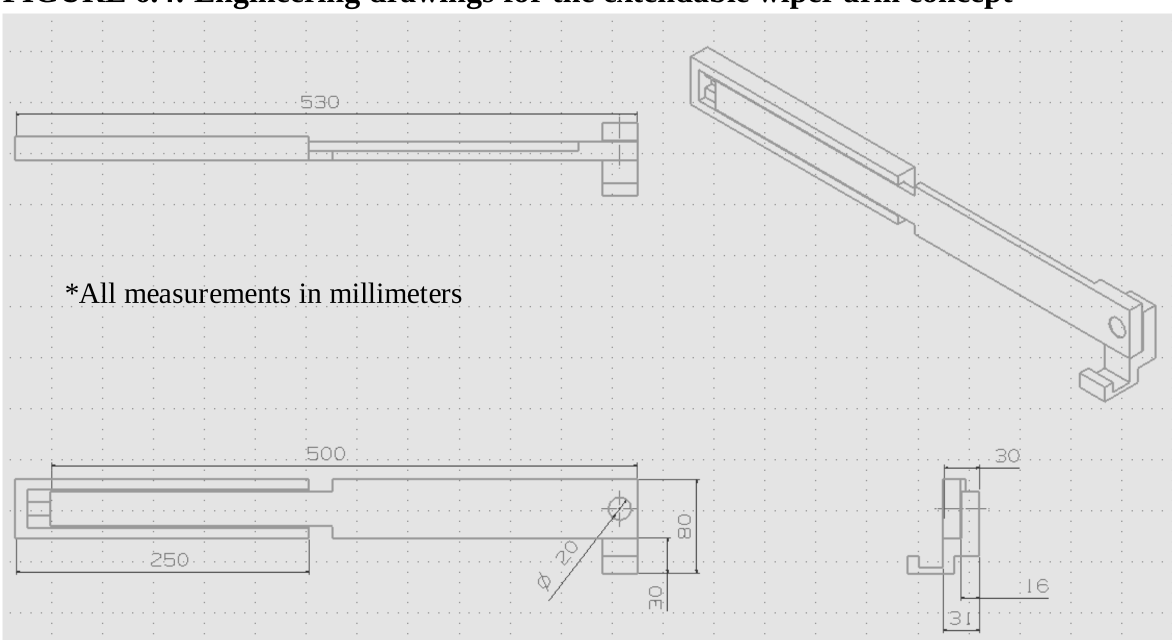
A basic concept design was conceived which addressed the limited portion of glass which it can reach by utilizing an extendable attachment at the end of the wiping arm. This extension makes it possible to vary the length of the arm depending on how far it needs to reach. The extending arm is powered by a linear actuator or linear motor that is attached to the back of the arm itself. This, however, only increases the difficulty of finding a lightweight motor that can provide the torque needed to move the entire extending arm. CAD models of this design can be seen in Figure 6.3.

FIGURE 6.3: Assembly drawing of the extendable wiper arm concept (starting, and fully extended positions)



The design is approximately the width of the window when the extending arm is retracted, and is the diagonal distance of the window when full extended. The dimensions of the design concept are shown in Figure 6.4 below, but due to the simplistic design, many of these measurements can easily be changed if necessary.

FIGURE 6.4: Engineering drawings for the extendable wiper arm concept



Initial calculations show that the base motor would need to have a max torque rating of about 2.8 Nm, meaning the base motor would have a mass of approximately 1.8 kg, based on a quick motor search. The extending linear motor used would have a maximum force of about 40 N and have a mass of approximately 0.6 kg. The motor weights plus the arms and clamp places the overall weight around 3.0 kg.   As seen in the weight and Torque Calculations in Table 6.1 below, a torque of nearly 2.8 Nm would be necessary to raise this arm (without a safety factor) which is nearly impossible to achieve with a motor mass of less than one kilogram. All of this is dependent on the window being approximately 50-55 cm wide and tall, with a 25 millimeter border on all sides.

TABLE 6.1: Weight and torque calculations for arm concept

PART	**MASS (kg)**	**Weight (N)**
Rotating Arm	0.2	2.0
Sliding Arm	0.3	2.9
Linear Actuator	0.6	5.9
Stand	0.1	1.0
Base Motor	1.8	17.6
Total	**3.0**	**29.4**

	(Nm)	**(Oz-Inches)**
TORQUE	2.8	390

7. Engineering Analysis

7.1 Extendable Wiper Re-evaluation

In order to determine if the extendable wiper could be a possible design concept for this project, further research was put into finding a suitable motor. The issue with the initial motors selected for this design was that to cover the required torque, any suitable motor weighed more than the acceptable weight for the entire prototype.

As stated in section 6.2, the weight allocation for this assembly comes dangerously close to our specified weight limitations. Because of this, we decided to look into other methods of providing the required torque and concluded that the speed of the base motor in this design was of little significance due to the limited motion required. It was then suggested that research into a possible gear system could be utilized to make this design possible.

Since this design required two motors, two arms and a base, the acceptable weight for a motor was estimated at less than 400 grams (0.882 lbs). In addition, the concept was estimated to only require one full wiping motion, meaning that a speed as low as 0.2 rpm could be acceptable, based on a half revolution total movement (¼ revolution forward, ¼ revolution reverse) in 2.5 minutes.

Through catalogs it was decided that a DC or Stepper motor with a gear set would be the best choice. A few compact motors were found that would come in under the required weight that could theoretically, through gear sets, provide the necessary torque and speed for this design. The smallest one, a DC motor with 0.12 Nm of torque and a speed of 8 rpm was found that weighed approximately 350 grams. With a 40:1 gear ratio, this motor could be made to work.

This motor was the only one found that was even close to providing the necessary power while coming in under the maximum weight for the project; therefore it is still not possible to use this design for our purposes.

7.2 Quantitative Analysis of Magnet Concept

In order to evaluate the physics and functionality of our design, three methods of quantitative analysis were performed. The first was a physical calculation of the mechanical forces acting on our device. The second calculation relates the device's geometry to its movement-path characteristics. Finally, we performed a static finite element analysis for situational forces on our device.

7.2.1 Mechanical Calculations

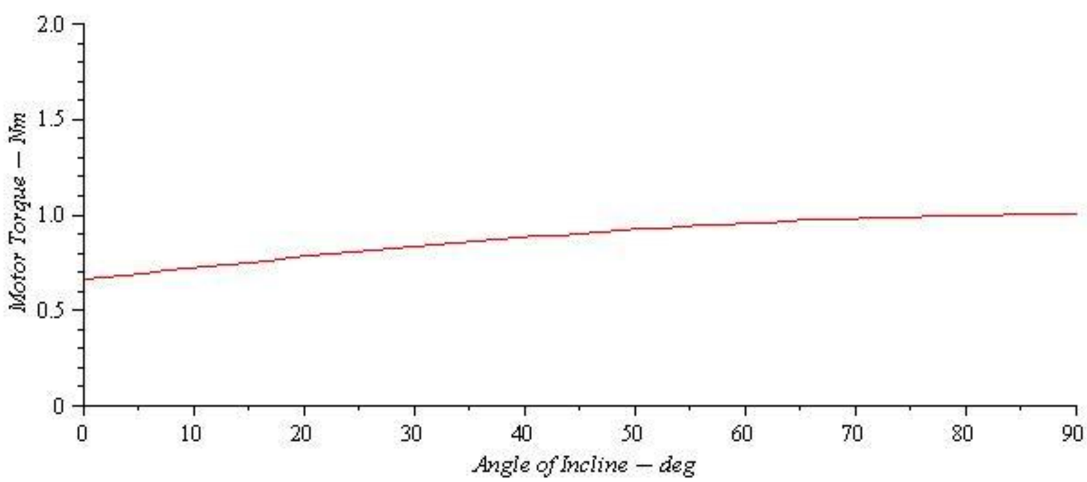
For our mechanical calculations, our goal was to determine the maximum load that our device's motors will need to overcome. The free-body diagram in Appendix B shows this force to be in the vertical direction against gravity and starting from rest.

We were then able to develop a relationship relating the required motor torque (T_{motor}) for each motor to the angle of incline (θ). This relationship is shown in Equation 7.1 and its detailed derivation can also be found in Appendix B.

$$T_{motor} = (19.23 + 9.81\sin\theta)\times 0.0345 \quad N\cdot m \qquad \text{(Eq. 7.1)}$$

The previous relationship is represented in Figure 7.1 for a range of angles from 0° to 90°. We found that the frictional forces always dominate over the gravitational forces.

FIGURE 7.1: Plot of motor torque vs. angle of incline

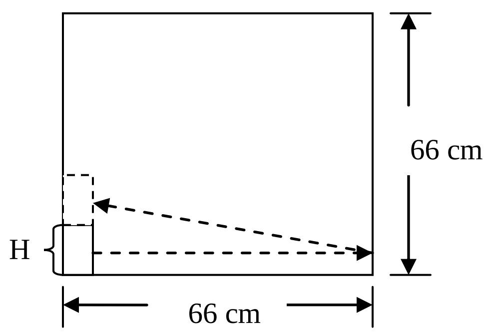


The stall torque of each motor is provided by the manufacturer to be T_{motor} = 0.51 N-m. We can therefore conclude that with two motors, our prototype will just barely be able to negotiate a vertical ascent (90 degree angle). Physical testing of our prototype later supports this claim. It should also be noted that in previous prototype designs, we used weaker magnets which resulted in a limiting angle of ascent. The introduction of higher powered magnets has allowed us to eliminate the angle ceiling of our final prototype.

7.2.2 Geometry and Required Pass Calculations

We have recognized that we can minimize the number of passes our device will need to make across the window by relating it to the height of the device. For the purposes of this calculation, we have defined a single pass as one horizontal movement and one diagonal movement. Figure 7.2 below gives a visual representation of this definition.

FIGURE 7.2: Example of one pass

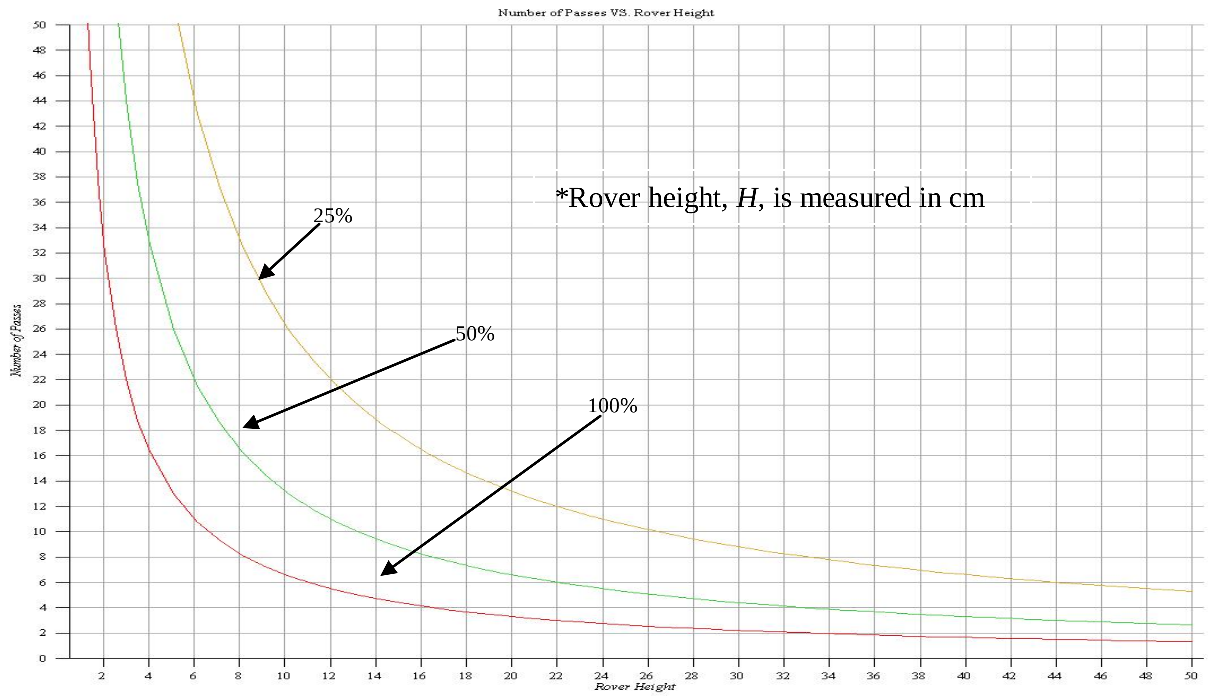


Assuming the cleaning surface is the same height as the robot, the relationship between the device's height *(H)* and the number of passes required to cover the entire window *(N)* can be represented in the following relationship.

$$N = \frac{66}{H} \times E \quad \text{(Eq. 7.2)}$$

In the above relationship, the value E is the efficiency factor and respresents the percentage of repeated area wiped. For example 100 percent efficiency would correspond to E=1, which in turn corresponds to zero overlap when cleaning in successive horizontal passes, while 50% efficiency would correspond to E=2, which indicates that half of the previously-cleaned area is overlapped in the next pass. We chose to show three degrees of efficiency to allow us to determine how many extra passes would be required if we wanted to reduce the extremity of the angle of each pass. The relationship in Eq. 7.2 was plotted below to allow for a better visual representation.

FIGURE 7.3: Number of passes *(N)* vs. device height *(H)*

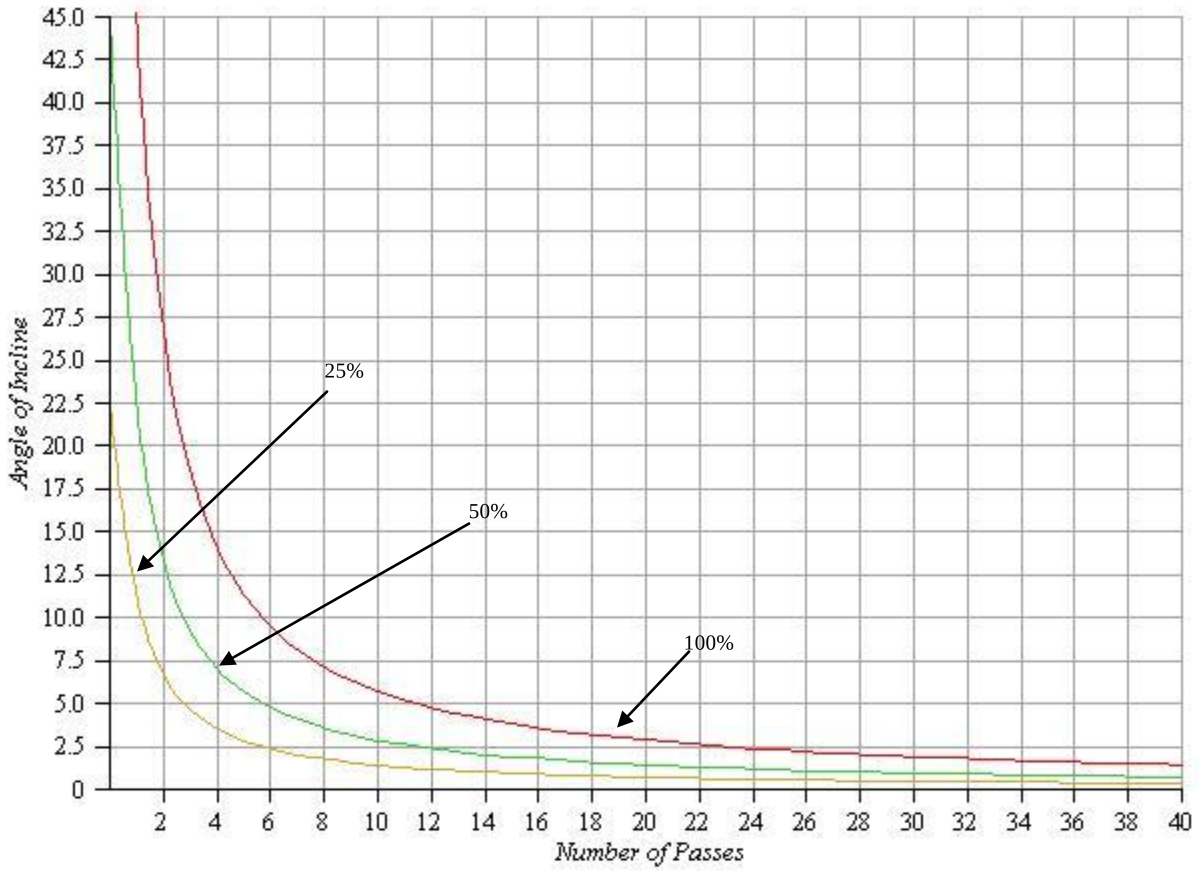


In conjunction with the previous calculation, we also examined the relationship between the number of passes and the angle of incline. The following equation was developed to show the relationship. As with the previous calculation, an efficiency factor was added to help visualize the result of changing the angle of incline.

$$\theta = \tan^{-1}\left(\frac{H}{66}\right) \times \frac{1}{E} \qquad \text{(Eq. 7.3)}$$

In order to better illustrate the above relationship, we plotted Eq. 7.3 with three degrees of efficiency. This is shown in Figure 7.4.

FIGURE 7.4: Angle of incline (θ) vs. number of passes (*N*)



7.2.3 Static Finite Element Analysis

In order to examine the effects of loading on our robot, we performed a static finite element analysis (FEA). For this analysis we examined two possible scenarios. The first was when there were no forces on the device other than the magnetic attractive forces. The second was when the device was removed with two hands. Our analysis was performed using the COSMOSWorks' iterative solver engine. The calculations were performed with approximately 36,000 tetrahedral elements and 110,000 degrees of freedom. Although we would have liked to further refine of our mesh for higher accuracy, we were forced to compromise for lower detail due to time and processing power limitations. To compensate for this, we added mesh controls to areas we determined to be of particular interest. These areas of slightly more refined meshing include locations where the magnetic forces would correspond and the areas of intended handling for removal. The boundary conditions for both magnetic stress and two-handed removal FEA's can be seen in the Figures 7.5 and 7.6, respectively.

FIGURE 7.5: Magnetic stress boundary conditions

(a) Side View (b) Isometric View

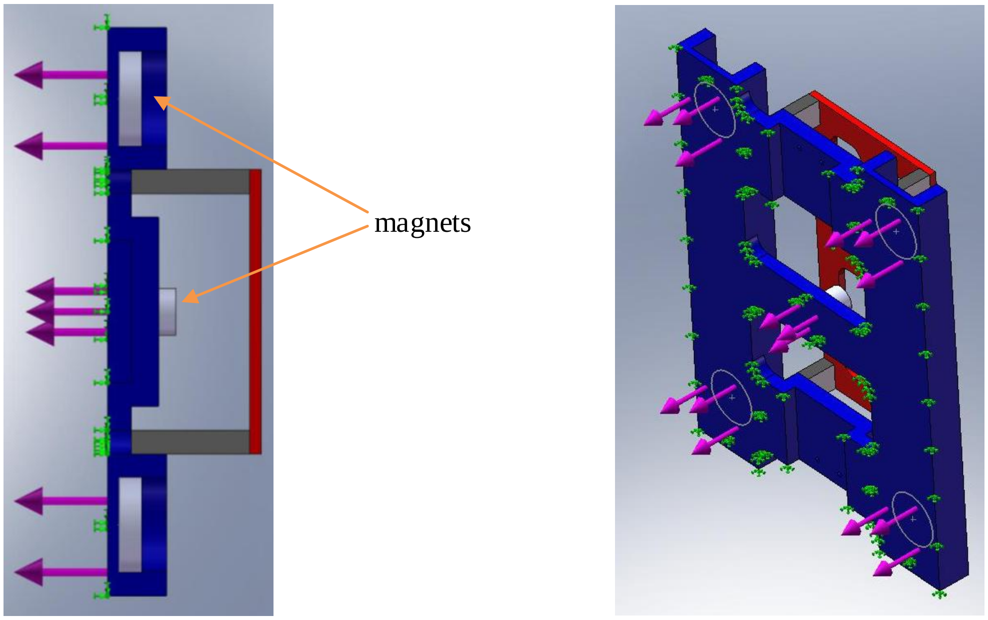
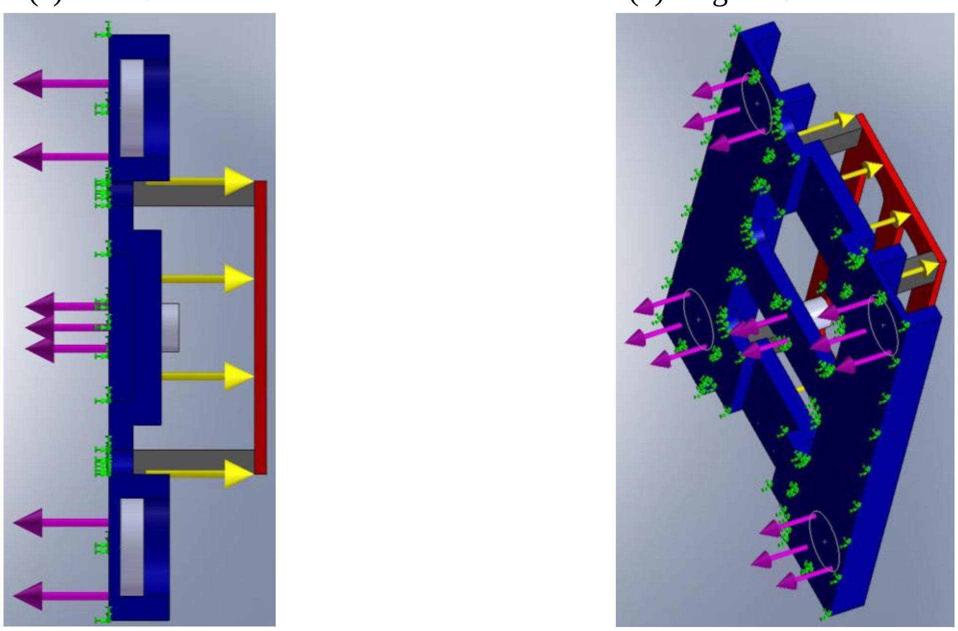


FIGURE 7.6: Two-handed removal boundary conditions

(a) Side View (b) Angled View



In Figures 7.5 and 7.6, green arrows (short arrows pointing to the left) indicate surfaces that have been fixed (which includes the entire bottom side of the base). Pink arrows (long arrows pointing to the left) indicate surfaces that have had magnetic forces applied, and yellow arrows (long arrows pointing to the right) indicate edges that have had pulling force applied. Note that all forces are symmetric, and pulling force was also applied to the opposite side of the top.

7.2.4 Magnetic Stress Finite Element Analysis

The magnetic stress FEA was performed by applying the appropriate magnetic forces to the structure of our device while grounding the bottom face of our device. Figure 7.5 below shows a bottom view of the device. The highest stress felt by the base of our robot is on the order of about 3 kPa. This falls well within the yield strength of 40 MPa for rigid PVC.

FIGURE 7.7: Bottom view

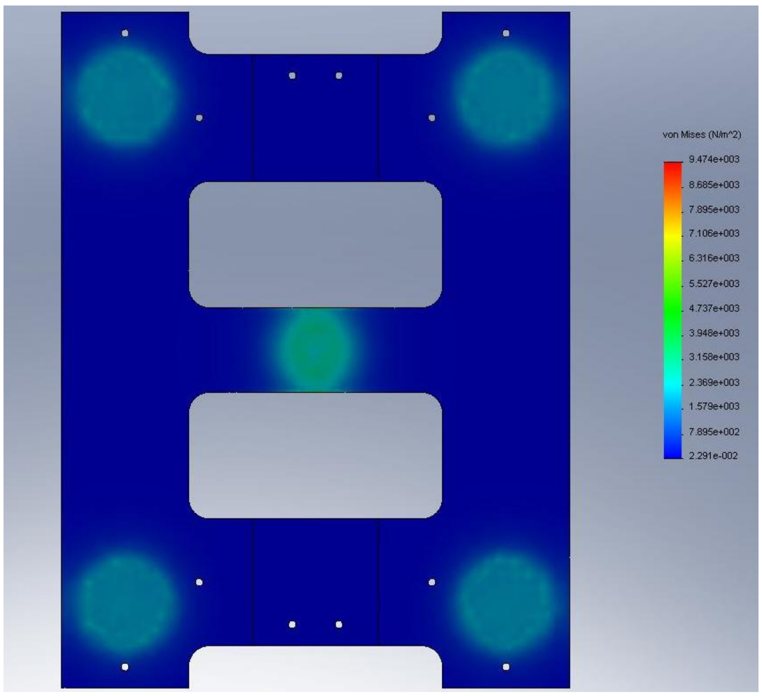
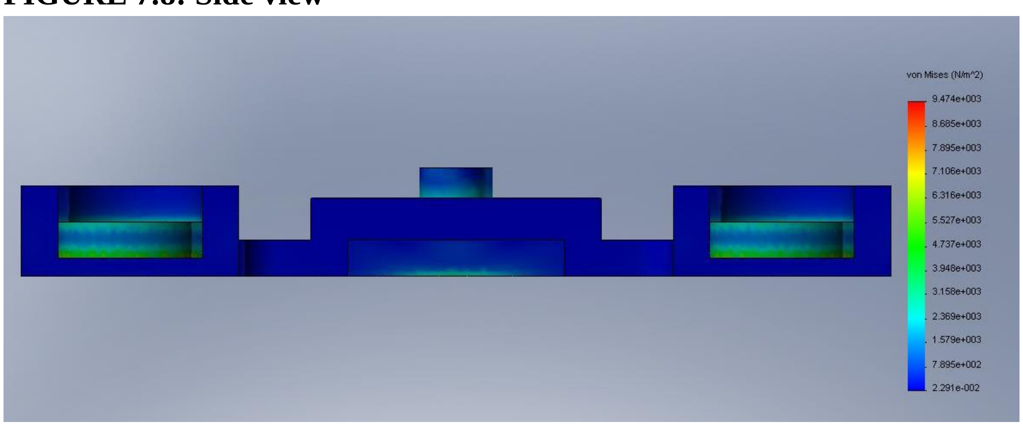


FIGURE 7.8: Side view



7.2.5 Two-Handed Removal Finite Element Analysis

The two-handed removal FEA was performed with two boundary conditions. The first was the placement of magnetic force in the same manner as in the previous FEA. The second boundary condition was that an equal amount of force was applied to the top side handles of our device. The figures below show the results of our analysis. The peak stress occurs along the handling area of the device. In particular, the center beam and inner corners show stresses of up to 0.5 MPa. Since the yield strength of the material is 40 MPa, there is no danger of yielding.

FIGURE 7.9: Isometric view

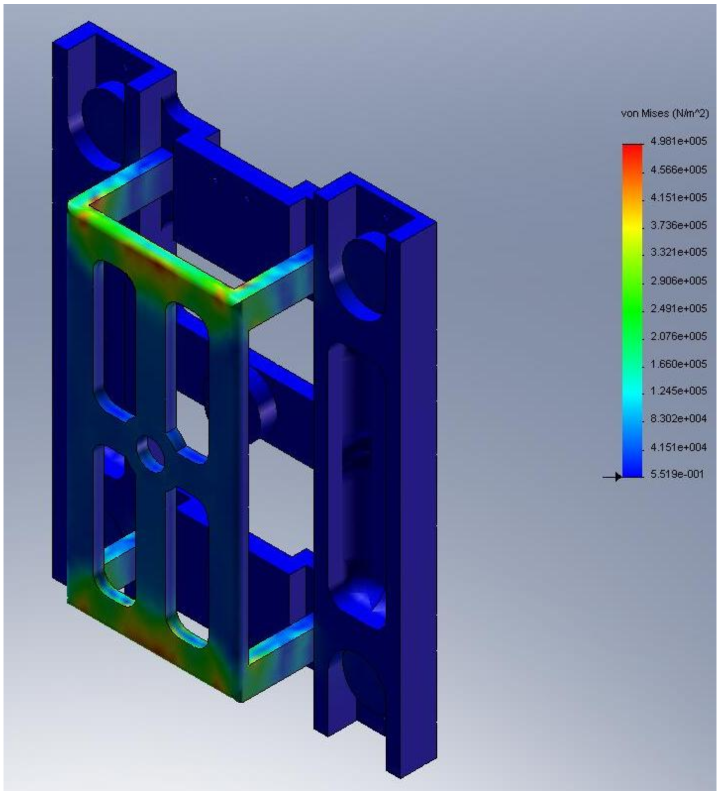
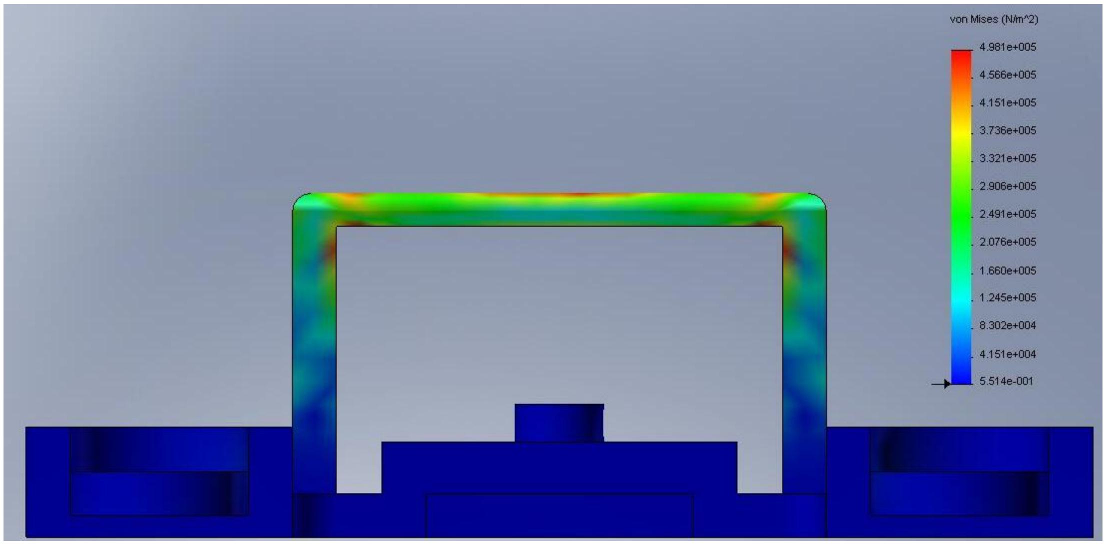


FIGURE 7.10: Side view



7.3 Qualitative Analysis of Magnet Concept

For a qualitative analysis of our design, we also took a three part approach. The first part of this analysis includes considerations on design for manufacturing and assembly (DFMA). The second part includes guidelines for designing for the environment (DFE). Our final approach was to troubleshoot potential problems with our robot by conducting a failure modes and effects analysis (FMEA).

7.3.1 Design for Manufacturing and Assembly

A good product must be engineered to be easily produced and distributed. Many different aspects of production must be considered and optimized in order to guarantee the best product and minimize the amount of defective models. In order to improve the manufacturability, as well as the assembly of our concept a few changes had to be made to the design of the window washing robot.

In order to improve the manufacturing process the most important variable to minimize is the amount of material used per piece. In order to do this, holes were put into the bottom base and top pieces. For large scale production of this product, these pieces would be injection molded, and therefore these holes would directly decrease the material required.

In addition to these holes, some parts had extraneous material removed. One example of this was in the bottom piece, where the engine mounts were located. The engine blocks had to be a height of 0.54 inches, whereas the thickness of our base piece only needed to be a quarter of an inch (0.25 inches), so the material beneath the engine blocks was cut out to make the thickness of the blocks 0.25 inches, while still being 0.54 inches off the surface.

In order to improve the assembly of the Winrobo design, many changes were made that resulted in a very efficiently assembled concept. The first change to improve the assembly was minimizing the number of independent pieces. Initially, the concept involved seven independent pieces: a bottom piece, a top piece, two motor mounts, two magnet holders and a water tank. The simplest way to minimize the number of pieces was to make the motor mounts, magnet holders and water tank be built into the bottom base. This makes the 6 independent pieces into three, being the bottom base and two side covers to keep water in the tank, and the magnets in place.

To this point the concept involved a base piece, a top cover piece, and the two cover pieces for both sides of the base which would create the water holding area and magnet mounts. In order to further improve the assembly, the two cover pieces would be united with the top piece creating only two separate pieces (in addition to the circuitry and wheels) for the entire design.

The next two improvements to the product assembly involved minimizing the different types of screws that would be required. First, the screws for all holes were made into one uniform screw type (#4-40, ½ inch long screws). This size screw was chosen to accommodate the pre-manufactured engine mounts that would fasten the motors to the bottom base. The next alteration was to have the two main pieces snap together instead of having to screw them into place. Eliminating the need for some of the screws made it easier to choose one uniform screw size, and also improved the manufacturability of the overall concept by reducing the number of holes that would need to be threaded.

To sum up the changes made for improved assembly and manufacturability, the entire concept was reduced to a top piece and a bottom piece (both injection molded), in addition to the wheels, motors, and circuitry. Only one type of screw is required and the number of screws was reduced, and also a significant amount of material was removed, reducing the total amount required. All of these changes reduce both the cost and the labor required per unit produced.

7.3.2 Design for Environment

Every day it becomes more and more important to design devices for the safety of our environment. If this robot went into mass production one of the first changes would be to manufacture it out of Polyethylene Terephthalate (PETE). The prototype is currently made of Polyvinyl Chloride (PVC) which is damaging to the environment. PETE is better for the environment because it is easier to recycle. Since this material is the same type that is used in plastic bottles our robot could be recycled at common US recycling plants. Another important note is PETE has similar engineering properties as PVC. For example the densities are within 1% of each other, the Young's Moduli are within 5% of each other, the tensile strengths are within 10% of each other, and finally they both cost about the same. These values help prove that PETE would be a promising choice to use instead of PVC.

Another pro-environmental characteristic is that the batteries are rechargeable. Therefore each robot only should need one set of batteries instead of using many in its life cycle. We also minimized the amount of material needed which reduces consumption of both energy and resources. The mass production design also calls for reducing the amount of production steps which reduces energy consumption. These steps should help reduce the negative impact this product would have on the environment.

7.3.3 Failure Mode and Effects Analysis

As part of our effort to continually improve upon our initial concept, we have performed a Failure Mode and Effect Analysis of our design. To do this, we first distinguished the most basic functioning components of our system. Second, we examined the possible modes, causes, and effects of failure for each of these components. The likelihood of occurrence (O) and severity (S) for each mode of failure was determined on a scale of 1 through 10. The assignment of these values was based on our quantitative analysis, selected material properties, expected environmental conditions, and subjective discretion. Our third step was to establish our current and expected methods of control and testing for each failure mode. In general, most of our control methods were built-in features of our existing design while much of our planned future testing involves randomized mechanical testing per volume produced. Based on this, the likelihood of detection of failure was determined on a scale of 1 through 10, allowing us to calculate the risk priority number (RPN) using the following relationship:

$$O \times S \times D = RPN \qquad \text{(Eq. 7.4)}$$

Finally, we established recommended actions based on what our current and planned methods of control/testing were lacking. This allowed us to then re-evaluate our likelihoods of occurrence, severity, and detection for projected improved RPN. Our best improvements came in the form of the risk of damage to our circuit boards as well as robot base. The most affecting changes done were the relocation our sensitive electronics away from the mobile robot to the generally stable joystick. Other important improvements came in the form of improved material selection and minor geometry tweaks of the concept. Our full FMEA can be seen in Table 7.1 on pages 39-40.

TABLE 7.1: Failure modes and effect analysis diagram

Part # - Name	Function(s)	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes/Mechanisms of Failure	Occurance (O)	Current Design Controls/Tests	Detection (D)	Recommended Actions	RPN	New S	New O	New D	New RPN
1 - Motor Driver IC	1) Controls signal input to DC motor	1) Electrical failure: broken circuitry 2) Fracture 3) Solder failure	1) Burning of electrical components 2) Separation of IC components	9	1) Short circuit from exposure to: static discharge, moisture, improper voltage input 2) Sudden impact from mishandling 3) Disconnected wiring	3	1) Random functional testing per volume	5	1) Ensure supplier reliability 2) Provide battery specifications 3) Water-proof and electrically insulate housing 4) bundle/harness wires	135	8	2	5	80
2 - Master Base	1) Acts as chassis for Master components 2) Bears majority of loading 3) Connects cleaning surface	1) Bending 2) Fracture 3) UV deterioration	1) Uneven distribution of loads resulting in wheel misalignment, bowing, and uneven wear 2) Separation of components resulting in robot failure	8	1) Cyclic loading from continuous usage 2) Sudden impact from mishandling/magnet failure 3) Chemical/UV-light from exposure to environment	5	1) Random visual inspection per volume produced 2) Random mechanical inspection per volume by: stress, fatigue, and vibration testing 2) Periodic manufacturing equipment maintenance	3	1) Ensure proper material selection for mass production 2) Provide handling instructions 3) Estimate life expectancy and allowable loads	120	8	4	3	96
3 - Joystick	1) Allows user to communicate with robot by sending corresponding signals 2) Houses power source and Integrated Circuits (IC's)	1) Mechanical failure: fracture 2) Electrical failure: broken circuitry	1) Wearing of springs resulting in inability to send/change signal output 2) Burning of electrical components resulting in inability to send/change signal output 3) Physical separation of components	8	1) gradual wear of spring assembly from use/improper handling 2) Sudden impact from mishandling 3) Disconnected wiring	4	1) Random functional testing per volume produced	2	1) Ensure supplier reliability 2) Provide handling and maintenance instructions 3) Estimate life expectancy and allowable loads 4) Add bumpers 5) Bundle/harness wires	64	8	4	2	64
4 - DC Gear Motor	1) Converts electrical power into rotational motion in shaft	1) Mechanical failure: gear/shaft fracture 2) Electric failure: broken circuitry	1) Gear damage resulting in inconsistent rotational speed or wobbling 2) Coil damage from grinding against core resulting in motor breakdown 3) Burning of electrical components resulting in motor breakdown	9	1) Gear wear from misalignment or aging 2) Coil and core grind from wobbling 3) Electrical burn from: exposure to moisture, improper voltage input 4) Disconnected wiring	3	1) Random functional testing per volume produced	2	1) Ensure supplier reliability 2) Provide motor specifications including power input limits 3) Estimate life expectancy and allowable loads 4) Add housing for motor 5) bundle/harness wires	54	9	2	2	36
5 - Joystick Signal Conver-ter IC (PICAXE)	1) Converts digital joystick output to analog signal input to motor driver	1) Electrical failure: broken circuitry 2) Fracture 3) Solder failure	1) Burning of electrical components 2) Separation of IC components	9	1) Short circuit from exposure to: static discharge, moisture, improper voltage input 2) Sudden impact from mishandling 3) Disconnected wiring	3	1) Random functional testing per volume	2	1) Ensure supplier reliability 2) Provide battery specifications 3) Water-proof and electrically insulate housing 4) bundle/harness wires	54	9	2	2	36
6 - Wheels	1) Connects gear shaft to window surface	1) Surface build-up 2) Warping 3) Tire wear	1) Loss of traction resulting in reduced control of robot 2) Loss of Circularity resulting in reduced control of robot	5	1) Gradual wear of rubber on wheels from use/improper handling 2) Loss of friction from residue build-up 3) Exposure to extreme	5	1) Random functional testing per volume produced	2	1) Ensure supplier reliability 2) Provide handling and maintenance instructions 3) Estimate life expectancy and allowable loads 4) Provide	50	5	5	2	50

Part # - Name	Function(s)	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes/Mechanisms of Failure	Occurance (O)	Current Design Controls/Tests	Detection (D)	Recommended Actions	RPN	New S	New O	New D	New RPN
7 - Magnet (NdFeB)	1) Allows robot to grip window by applying magnetic force through window pane	1) Loss of Magnetic Force	1) Loss of wheel traction 2) Loss of "gripping force" resulting in robot falling off window 3) Loss of alignment 4) Uneven cleaning-surface/wheel wear 5)Potential for toxicity/flammability	9	1) Loss of magnet's polarity over time or from sudden impact 2) Loss of magnet's polarity from exposure to extreme heat and pressure 3) Separation from master/follower bases	5	1) Random magnetic force testing per volume produced 2) Visual inspection of magnet mounts 3) Magnets in removeable enclosure to reduce risk of falling out	1	1) Ensure supplier reliability 2) Provide handling and instructions 3) Recommend periodic replacement 4) Estimate life expectancy and allowable loads 5) Provide replacement magnets 6) Provide magnetic force gauge	45	9	4	1	36
8 - Mounting Bolts	1) Secure components together	1) Shearing 2) Stripped threads	1) Motor/wheel assembly separation resulting in misalignment/failure to move 2) Damage to electronics from vibration/contact with magnets	5	1) Cyclic loading from continuous usage 2) Sudden impact force mishandling/magnet failure 3) Continuous removal and re-screwing	1	1) Random vibration and load testing 2) Stress FEA with different applied loads	7	1) Provide replacement bolts 2) Provide schematic of bolt locations 3) Eliminate need for bolts by finding bolt locations that can be joined permanently	35	5	1	7	35
9 - Follower Base	1) Acts as chassis for Follower components 2) Bears majority of loading 3) Connects cleaning surface	1) Bending 2) Fracture 3) UV deterioration	1) Uneven distribution of loads resulting in bowing and uneven wear 2) Separation of components resulting in complete failure	7	1) Cyclic loading from continuous usage 2) Sudden impact from mishandling/magnet failure 3) Chemical/UV-light from exposure to environment	2	1) Random visual inspection per volume produced 2) Random mechanical inspection per volume by: stress, fatigue, and vibration testing 2) Periodic manufacturing equipment maintenance	2	1) Ensure proper material selection for mass production 2) Provide handling instructions 3) Estimate life expectancy and allowable loads 4) Add proper handles for removal	28	7	1	2	14
10 - Fluid Container	1) Carries 50 mL H_2O on robot	1) Fracture	1) Loss of fluid 2) Electrical failure of DC motor	9	1) Chemical/UV-light from exposure to environment 2) Exposure of DC motor to excessive moisture 3) Sudden impact from mishandling	3	1) Random visual inspection per volume produced 2) Random mechanical inspection per volume by: stress, fatigue, and vibration testing 2) Periodic manufacturing equipment maintenance	1	1) Ensure proper material selection for mass production 2) Provide handling instructions 3) Estimate life expectancy 4) Make removeable to prevent risk of spilling on other components when refilling fluid	27	5	3	1	15
11 - Master Canopy	1) Guides wiring to joystick 2) Adds Rigidity to Master Base	1) Bending 2) Fracture 3) UV deterioration	1) Loose parts may interfere with wiring and motor-wheel assembly 2) Difficult to mount/dismout from window	4	1) Improper handling by user 2) Sudden impact force mishandling/magnet failure 3) Chemical/UV-light from exposure to environment	2	1) Random visual inspection per volume produced 2) Random mechanical inspection per volume by: stress, fatigue, and vibration testing 2) Periodic manufacturing equipment maintenance	2	1) Ensure proper material selection for mass production 2) Provide visual handling instructions 3) Estimate life expectancy and allowable loads 4) Add proper handles for removal	16	3	2	2	12
TOTALS				***82***		***36***		***29***		***628***	***76***	***30***	***29***	***474***

8. Final Design

For our final design, we have provided CAD models and engineering drawings as well as the bill of materials that we used for our prototype.

8.1 CAD Models and Engineering Drawings

Figures 8.1 and 8.2 represent the final design of our window washing robot. Figure 8.1 shows the robot mounted on a window as well as the freestanding robot by itself, although it does not include the electrical components or wheels. Figure 8.2 on the following page outlines the important dimensions of our device. Engineering drawings for each individual piece can be found in Appendix C.

FIGURE 8.1 Prototype model

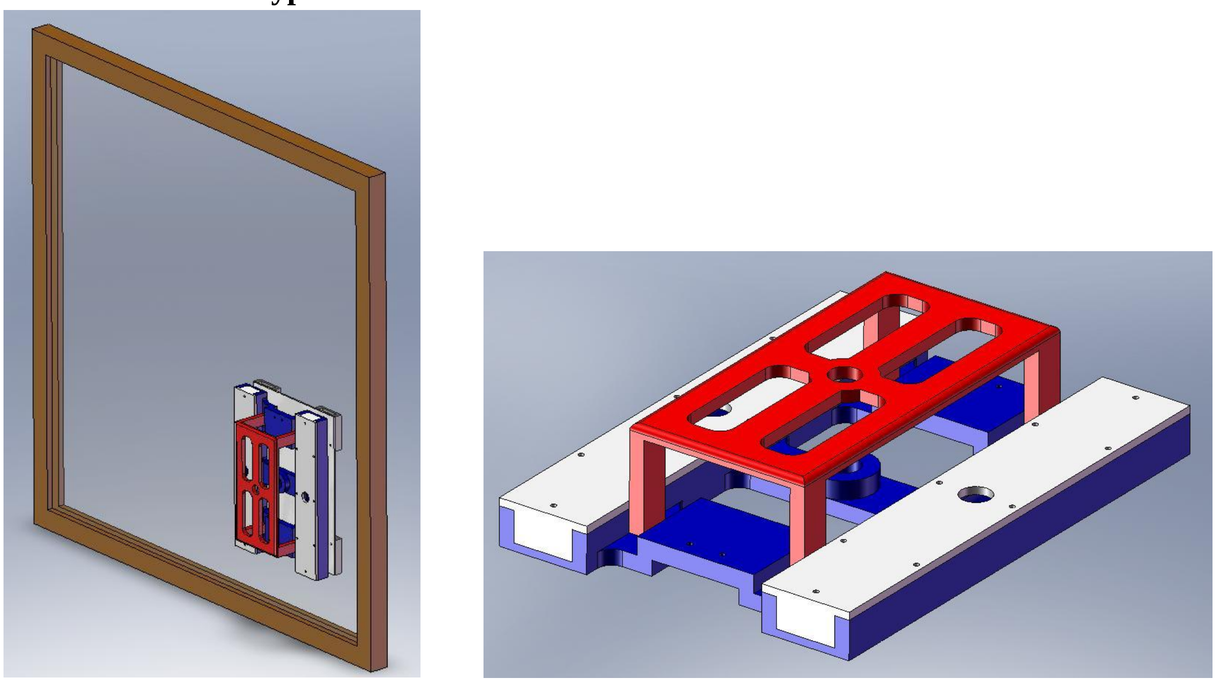
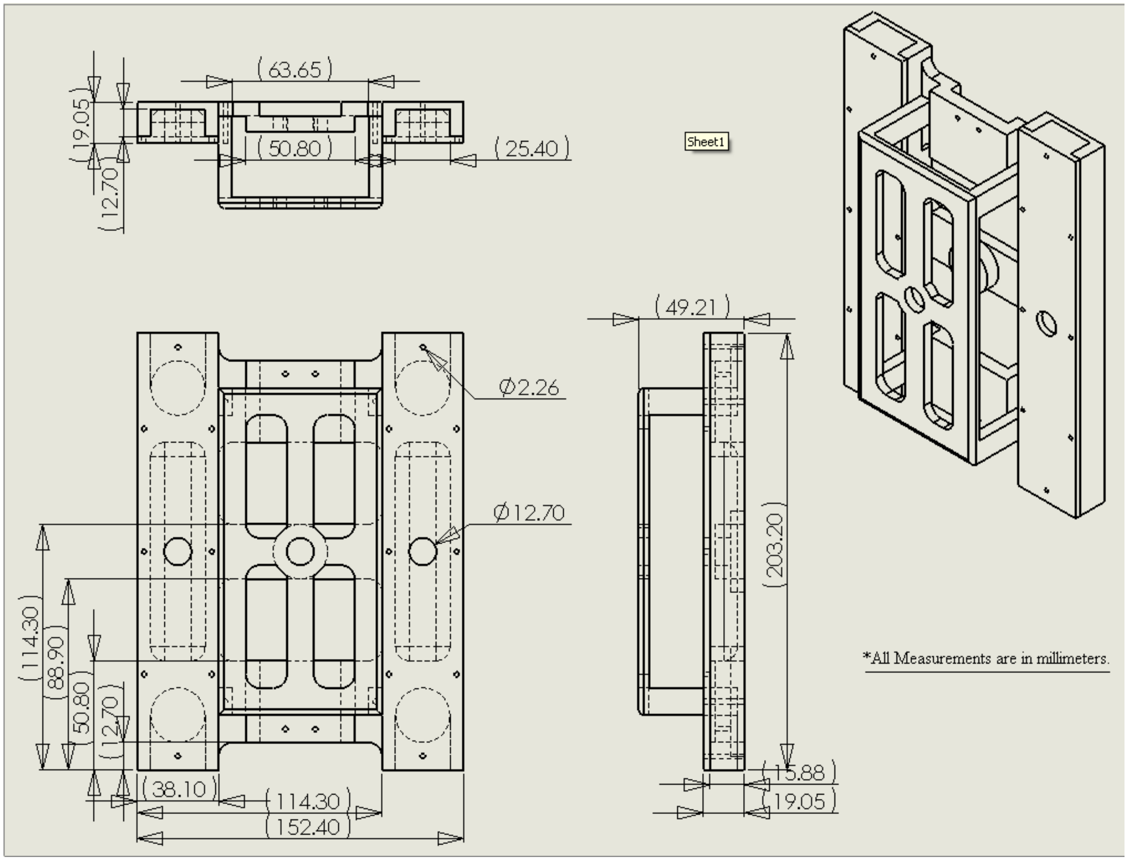


FIGURE 8.2: Dimensioned engineering drawing



8.2 Bill of Materials

The overall cost of our project as of December 10 is approximately $360 (See Table 8.1). Since this project needed parts which the University of Michigan was unable to provide, many parts had to be purchased. Therefore the addition of the delivery charges increased the overall cost by around 22%. The cost of materials only was about $280 with a total delivery charge of around $80. Most of our parts came from Solarbotics, which also is the parent company of HVW Technologies. They provided all of our motor control devices, motors, and wheels costing about $80, not including shipping. The only parts used from the University of Michigan were some of our screws, magnets, PVC, wire, resistors, and diodes.

TABLE 8.1: Bill of Materials – BOM

Quantity	Part Description	Purchased From	Part #	Price	Shipping
1	Acrylic Sheet, 3/8" X 24" X 24"	Pierce-Ohio Companies[1]	AC382424	$25.07	$2.58
1	PVC Sheet, 1/8" X 12" X 12"	Pierce-Ohio Companies[1]	PVC121212	$3.66	$2.58
1	PVC Sheet, 1/4" X 12" X 12"	Pierce-Ohio Companies[1]	PVC251212	$3.88	$2.58
2	PVC Sheet, 5/8" X 12" X 12"	Pierce-Ohio Companies[1]	PVC621212	$28.24	$7.54
1	Joystick, Digital, 8-way	HVW Technologies[2]	17670	$18.95	$4.50
1	PICAXE-18X IC	HVW Technologies[2]	28450	$8.50	$4.50
1	PICAXE-18 Project Board	HVW Technologies[2]	28460	$9.95	$4.50
1	Solarbotics L298 Compact Motor Driver Kit	HVW Technologies[2]	K CMD	$18.95	$4.50
2	GM2/3/8/9 series Plastic Wheel - Blue	Solarbotics[3]	GMPW-LB	$6.50	$5.46
4	Sintra - 8" X 12" x 2mm - White	Solarbotics[3]	SIN2mm-W	$11.40	$5.46
2	224: 1 Gear Motor - 180 deg	Solarbotics[3]	GM2	$11.50	$5.46
4	GM2/GM8 Steel Motor Mount	Solarbotics[3]	GMB28	$5.40	$5.46
1	Tap and Die Set for #4-40 Screws	The Home Depot	42526802096	$4.50	$0.00
2	#4-40 Wood Screws	The Home Depot	30699264810	$2.07	$0.00
2	#4-40 Metal Screws	The Home Depot	30699231010	$2.02	$0.00
1	2' x 4' x 1/2" Plywood	The Home Depot	99167733357	$6.56	$0.00
8	1-1/2" Angle Metal Brackets	The Home Depot	707392916604	$3.12	$0.00
10	Magnets, 1" X 1/4" Disc, N50, Black NI	K&J Magnetics, Inc.[4]	DX04B	$46.30	$6.36
4	Magnets, 1" X 1/8" Disc, N50, Black NI	Magnet 4 Sale[5]	ND0505-50NM	$13.92	$9.10
1	PICAXE Programming Cable (Serial)	Sparkfun Electronics[6]	PGM-08313	$6.95	$6.60
1	7.2V Ni-Cd Battery Pack and Charger Combo Pack	Radio Shack	230-0322	$25.00	$0.00
4	Cleaning Material Brush	Meijer	N/A	$13.53	$0.00
1	Sponge	Meijer	N/A	$5.00	$0.00
20	#4-40 Screws	University of Michigan	N/A	$0.00	$0.00
8	270Ω Resistors	University of Michigan	N/A	$0.00	$0.00
8	Diodes	University of Michigan	N/A	$0.00	$0.00
10	Magnets, 1/2" Dia., 1/2" Thick, Neodymium	University of Michigan	N/A	$0.00	$0.00
1	PVC Block, 1" X 6" X 9"	University of Michigan	N/A	$0.00	$0.00
N/A	Electrical Wire	University of Michigan	N/A	$0.00	$0.00
			Subtotal	$280.97	$77.18
			Total	$358.15	

[1]www.freckleface.com
[2]www.hvwtech.com
[3]www.solarbotics.com
[4]www.kjmagnetics.com
[5]www.maget4sale.com
[6]www.sparkfun.com

9. Manufacturing

9.1 Overview

The entire prototype body has been manufactured by our team out of PVC. Most pieces were hand-milled, with the exception of the driver base and top piece, which are more complex and were CNC milled. SolidWorks was used to model our prototype, and the necessary files were imported into Unigraphics to generate tool paths for the CNC programs. Process plan sheets are located in Appendix C.

Ordered parts include the motor driver and microcontroller, the joystick, the battery pack, and the motors.

For large-scale manufacturing, we would likely use injection molding. While our prototype has many small pieces, these could be combined into two injection-molded pieces, which could then snap together, replacing the many screws used to hold together our prototype. This would lower the amount of parts needed, the assembly time required, and ultimately the cost of the mass-produced product.

9.2 Prototype Manufacturing

The Winrobo prototype that was produced for the Design Expo consisted of the main driver machine, a follower, and a controller box (with the joystick). All parts were manufactured by hand (or through CNC code) or were purchased from hobby websites such as Solarbotics.com.

9.2.1 Body & mechanical assembly

The items that were purchased included the joystick itself, a motor driver circuit board (which came unassembled and unsoldered), the power source, the two motors, and the wheels. The joystick, power source and driver were held in the controller box, and the motors were fastened to the main driver base using metal brackets that were provided by the company.

The driver base was cut from a large block of PVC using a CNC mill. The other parts that were milled included the two cover pieces for the base, the top cover, and the follower base (with four magnet mounts). These were all milled by hand using a variety of ball and end mills most of which were either 1 or ½ inch diameter, and all of the pieces were fastened together using #4-40 screws, either ½ inch in length.

The controller box was cut from a large piece of plywood and held together with metal brackets. Once these pieces were all constructed, the wires and circuitry were attached and soldered, finishing the final prototype design.

9.2.2 Electronics Assembly

In order to show the capabilities of the final design concept at the design expo, it was necessary to have a functioning joystick able to control the robot's movements. It was necessary to show that the robot could go forwards and backwards, as well as rotate both clockwise and counterclockwise. It was assumed that this had to be done without having someone pushing the wires together on the base as had been the primary method throughout the semester.

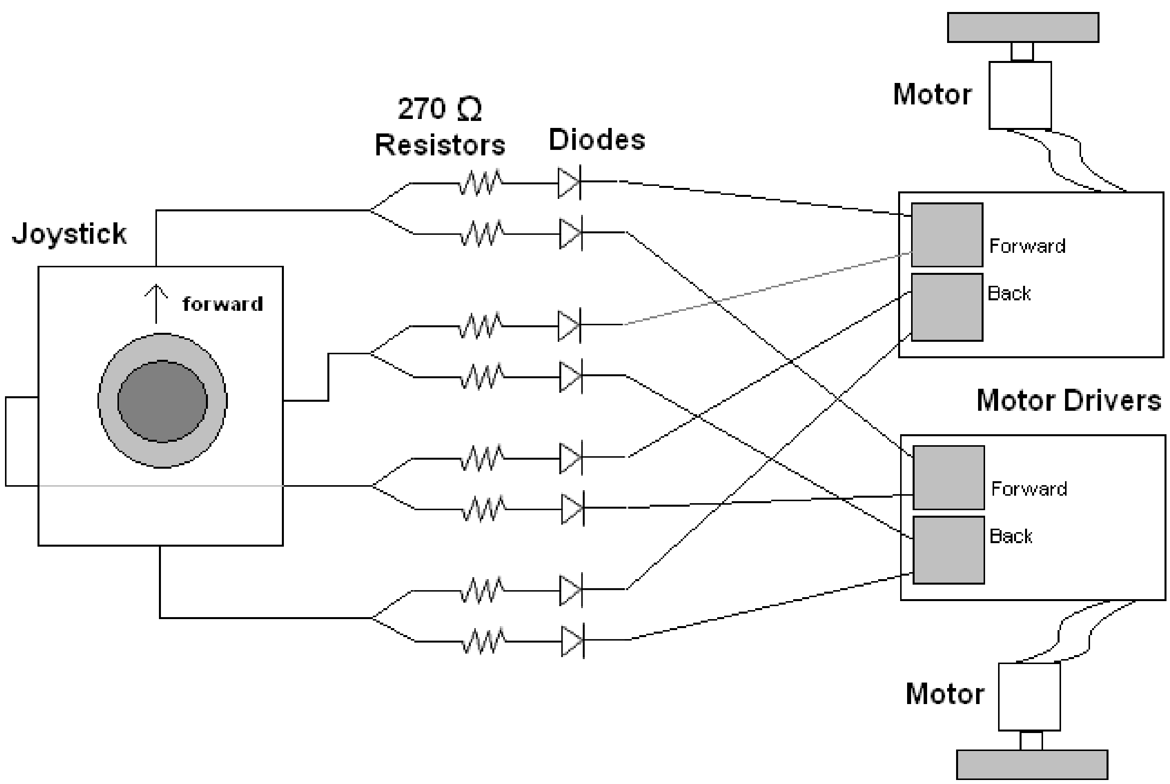
Using the L298 Motor Drivers that were purchased from Solarbotics, it was possible to make the motors go forward and backward, and with the four directions on the joystick that was provided, it would be possible to achieve the different motions necessary. Connecting the joystick to the drivers, however was not an easy thing to do, and in the end, this became the biggest problem that was encountered in building the final product.

A "PICAXE" chip was purchased with the joystick and motor drivers from Solarbotics. This chip could be programmed to translate the joystick's signals into output signals which could be sent to the drivers to perform the intended task. There was an issue with the chip, in that it provided a constant voltage to all parts of the circuits, which could not be interrupted, resulting in the ground voltage level being the same as the voltage provided. Without a voltage difference between the provided signal and the ground, no current would flow and the motor drivers wouldn't work.

After spending a significant amount of time trying to repair this problem, the decision was reached to abandon the PICAXE and try to connect the joystick directly to the drivers. This would not be easy because each of the four driver input ports (forward and backward for each of the 2 drivers) would be connected to two different positions on the joystick. It turned out that the circuits all became interconnected and could not be isolated.

Using what had been learned in an introductory circuits course, a collection of resistors and diodes were connected to each of the output ports on the joystick preventing any current from flowing backwards through the circuits, isolating the desired circuits for each of the four directional outputs. A model of this setup can be seen in Figure 9.1.

FIGURE 9.1: Electrical schematic for motor direction control



Once this system was put together, the connections were all soldered and then covered with electrical tape to protect the circuitry, and prevent unintentional connections. This was constructed and tested, and when it was clear that this would effectively control the machine, everything except for the motors in Figure 9.1 was placed into a wooden box as a protective housing, with the joystick fastened on top.

9.3 Manufacturing Logistics

For a starting point, we will begin estimating the total number of units required for production by assuming our target market will be the paraplegic peoples with a minimum income of $35,000. According to the University of California at San Francisco's Disability Statistics Center (DSC) findings, 0.3% of the US population meets this demographic. Therefore our total potential market comes to be around 850,000 individuals. Based on the same DSC findings, a conservative estimate concludes that 65% of these people require aide in doing housework. For this reason, we have reduced our market estimate by the same amount. The readjusted market total comes to about 550,000.

Assuming we purchase 4 injection molding machines, we use the following determined constants to help us calculate our total injection molding cost per unit.

Density: 1.37 g/cc
Volume, V = 400 cc/unit
Mass, M = 0.548 kg/unit
Material cost, C_{mat} = 1.764 $/kg * M = 0.9665 $/unit
Molding cost, C_{mold} = 40 $/hr
Thermal diffusivity, α = 0.182E-6 m^2/s
Mold cavities, N = 3
Nominal wall thickness, h = 1.59 cm
Assembly time, t_{assem} = 0.0083 hr
Assembly Cost, C_{assem} = 9 $/hr
Equipment Cost, C_{equip} = $20,000
Production quantity, N = 550000

Using the following relationships, we are then able to determine the total time to produce a single unit as well as the cost to produce each unit.

$$t_{mold} = \frac{5 + h^2/\alpha}{N} = 0.129\ hr \quad \text{(Eq. 9.1)}$$

$$t = t_{assem} + t_{mold} = 0.137\ hr/unit \quad \text{(Eq. 9.2)}$$

$$C_{labor} = t_{assem} \times C_{assem} + C_{mold} \times t_{mold} = 5.235\ \$/unit \quad \text{(Eq. 9.3)}$$

$$C_{tot} = C_{mat} + \frac{C_{equip}}{n} + \frac{C_{labor}}{n/t} \approx 1.00\ \$/unit \quad \text{(Eq. 9.4)}$$

We therefore conclude that we will be able to injection mold all 550,000 units in 42 working days (10 hour days) at a cost of $1 per unit. Adding this to our manufacturer's rates on purchased items, we have the following table. The final total per unit produced comes out to be $61.22.

TABLE 9.1: Manufacturing Cost Breakdown

Item/Process	*Cost per item ($)*	*Cost per unit produced ($)*
Injection molding	1.00	1.00
Gear motor	3.00	6.00
Magnets	2.50	12.50
Motor brackets	0.06	0.12
Joystick	10.00	10.00
Diodes	0.10	0.80
Resistors	0.10	0.80
L298 Motor Driver	10.00	10.00
Wheels	1.00	2.00
Battery	8.00	8.00
Wiring	1.00	1.00
Final Assembly (labor)	9.00	9.00
TOTAL		61.22

The above is an overestimate since some parts may actually be manufactured as opposed to bought. These items include the wheels, circuit boards, and joystick. Also, we have the option of upgrading to electromagnets instead of permanent magnets which would further reduce costs.

10. Testing

Several tests were conducted to validate and optimize our design. First of all, after building the prototype, the device was attached to the window to verify that it would remain on the window without slipping. When it held, we moved on to more strenuous tests.

Our cleaning material had been previously selected due to its low coefficient of friction and seeming ease of wiping off dry erase dots. In a series of tests, we attached several different cleaning surfaces to our prototype to examine its ease of motion versus ease of cleaning. After testing our original cleaning materials, various sponges, and paper towels, we settled on the original cleaning material, again due to the ease with which the robot navigated the window while it was attached (in other words, its low drag), and yet it easily cleaned the dots off of a glass window.

Another interesting fact we encountered is that acrylic is much harder to clean than glass. Our original testing plan was to create a window on which we could both test our window and present it at the design expo. We ordered an acrylic sheet for this window due to its lower weight, lower cost, and its greater strength – we wanted to make sure our window wouldn't shatter on the way to Lansing. While testing our device on the window we created, we noticed that dry-erase dots on the acrylic sheet did not clean very well. Further testing on glass proved that acrylic is much harder to clean than glass, at least as far as dry-erase dots are concerned. This prevented us from demonstrating the cleaning power of the prototype at the design expo.

We had planned to complete further testing on whether the magnetic strength significantly affected the cleaning power, as our prototype had space for larger magnets than were used in the final design, but due to the inability to clean the acrylic, this testing was shelved.

11. Discussion for Future Improvements

In evaluating our window washing robot there are certain aspects that could be improved upon. The first would be fixing the follower. The follower had to have its cleaning material removed so the device wouldn't slip. Since it did not have its soft cleaning material pressing against the window but instead PVC and duct tape-covered screws the window became scratched. A better solution would be to install a couple of ball bearings that would allow the follower to move in any direction without damaging the window, or cover the screws with a thinner, softer material such as felt.

Other areas to improve on are including making our design automatically detect the edges of the window. This could be done by using either optical sensors or bumpers. The base would need to be redesigned in order to accommodate these sensors. This would also make it necessary for the device to carry its own power source with it. Our battery is currently too large and heavy so we would need a smaller one and redesign the base to accommodate it.

Another problem is the amount of force applied to the shaft of the wheels. During operation we observed the top wheel's shaft started to bend. This bending caused the device to start turning at unexpected times. It is also possible that with continued use this part could become fatigued and eventually break. There are a few possible solutions that could be done to help elevate the stress on this shaft. One could be to reduce the magnetic force near the shaft or another could be to increase the strength of the shaft. These are some of the improvements possible for our automatic robot.

12. Conclusions

The Winrobo window washing robot is an innovative design geared toward helping the disabled, but also attractive as a method of reducing physical strain for its consumers. The design is a proof of concept and therefore the actual cleanliness of the window is less of a concern than the ease of use, and controllability of the final product. On the basis of proving this concept, it is apparent that this design was a complete success and is obviously applicable for the desired functionality. This design incorporates traditional items and systems (magnets, motors and wheels) and transforms them into a product unlike anything else available, creating a final product that is reliable, innovative, and practical.

13. Acknowledgements

Dr. Yoram Koran of the University of Michigan Department of Mechanical Engineering, and April Bryan, Graduate Student Instructor, were very helpful throughout concept generation phase, in referring us to appropriate contacts for motor information, and meeting with us to iron out additional issues with our project.

Professor Shorya Awtar of the University of Michigan Department of Mechanical Engineering was consulted as a first-hand resource on electromechanical devices. With his help, it was concluded that our system should not be automated, and that operation by remote would be the easiest and most time effective way for us to control our prototype. Professor Awtar also provided us with several resources on motor control and locations from which to order motors. This information was very useful when searching for motors and motor controllers.

We were also given Professor Brent Gillespie's name in association with electro-mechanical design. Upon e-mailing him, we found out that he is currently on sabbatical in California, but he provided us with information on motors through e-mail and urged us to ask him additional questions.

For general robotics questions, we contacted Professor Jason Daida of the University of Michigan Department of Oceanic, Atmospheric, and Space Sciences, a robotics enthusiast. He gave us very good references in the websites Solarbotics.com and HVWTech.com, which had several useful robotics components and an excellent technical support staff to answer our many questions about robotics and motor control.

For questions about magnets, we consulted with Professor Greg Tarle of the University of Michigan Physics Department. While we initially were hoping to calculate the magnetic force provided by a set of magnets so we could order the ideal magnets, he suggested that we empirically determine the force we needed and the magnetic force provided by sets of magnets. In addition, he provided us with some high-strength neodymium iron boride magnets and additional resources on electronic components.

For help with stepper motor control, we contacted Mr. Steve Culp of the University of Michigan Department of Mechanical Engineering. He provided us with stepper motor controllers built in the past for a former Mechanical Engineering technical elective course (ME 488) and gave us additional information about motor control.

Dr. Jon Luntz of the University of Michigan Department of Mechanical Engineering was very helpful in interfacing our motor controller and PICAXE microcontroller once we had ordered appropriate controllers and geared motors on the solarbotics.com website for testing for our proposed magnet-attached concept.

Finally, we would like to acknowledge Steve Erskine and Bob Coury for their expert advice on machining and design for manufacturing, used during the manufacturing of our prototype.

14. References

[1] http://klearviewsystems.com, access: 16 September 2007, page update: 11 July 2007.

[2] http://www.uspto.gov, access: 23 September 2007, page update: 23 September 2007.

[3] http://www.freepatentsonline.com, access: 23 September 2007, page update: 23 September 2007.

[4] http://www.solarbotics.com, access: 23 October 2007, page update: 8 October 2007.

[5] http://www.hvwtech.com, access: 23 October 2007, page update: 4 November 2007.

[6] Kaye, Stephen H., Kang, Taewoon and LaPlante, Mitchell P., http://dsc.ucsf.edu/publication.php, access: 18 November 2007, page update: May 2003.

[6] Personal conversation, Dr. Greg Tarle, Professor, University of Michigan Physics Department, 3 October 2007.

[7] Personal conversation, Dr. Jon Luntz, Assistant Research Scientist, University of Michigan Department of Mechanical Engineering, 25 October 2007.

[8] Personal conversation, Dr. Shorya Awtar, Assistant Professor, University of Michigan Department of Mechanical Engineering, 25 October 2007.

[9] Personal conversation, Dr. Yoram Koren, Professor, University of Michigan Department of Mechanical Engineering, multiple dates.

[10] Personal conversation, Dr. Jason Daida, Associate Research Scientist, University of Michigan Department of Atmospheric, Oceanic, and Space Sciences.

[11] Personal conversation, Mr. Steve Culp, Audio-Visual Technician, University of Michigan Department of Mechanical Engineering, 23 October 2007.

[12] Personal conversation, Dr. Brent Gillespie, Professor, University of Michigan Department of Mechanical Engineering, 11 October 2007.

[13] http://solarbotics.com/products/gmpw/ *(Rubber Wheels)*

[14] http://solarbotics.com/products/k_cmd/ *(L298 Motor Controller)*

[15] http://solarbotics.com/products/gm2/ *(Plastic Gear Motors)*

[16] http://www.hvwtech.com/products_view.asp?ProductID=338 *(Joystick)*

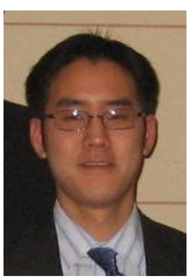
[17] *Wheelchair Use in the United States*, Kaye, Stephen H., Kang, Taewoon, and LaPlante, Michell P., May 2002 <http://dsc.ucsf.edu/publication.php>

15. Biographies

Eric Alexander

My name is Eric Alexander and I am from a small town near Akron, Ohio. My parents are both originally from Mt. Pleasant, Michigan and therefore I've made many trips into Michigan. My dad attended the University of Michigan and also majored in Mechanical Engineering. My first experience at this university was when I was nine years old and attended my first Michigan football game. Since then I have been a big Michigan fan where I have endured nine years of persecution in the buckeye state. Once I graduated from high school I decided it was an easy choice to come to Michigan. I found choosing Michigan fairly easy but choosing a major was a different story. I enjoyed my math and science classes in high school and enjoyed taking things apart therefore engineering seemed like a logical choice. Mechanical engineering really appealed to me because it's a broad major which covers many industries. After three years studying at Michigan I come into my senior year with only one year to go. I'm looking forward to graduate and move on into the working world preferably in the manufacturing or defense industry. I eventually plan on getting my Professional Engineering license and my MBA. Those are a few years away and for now I just try to get by day by day, inch by inch.

Yi-Lei Chow



I am a University of Michigan senior who will be graduating with a B.S.E. in Mechanical Engineering in December 2007. I was born and raised in Los Altos, California which is about thirty minutes south of San Francisco. Both my parents were twice immigrants. The first when they escaped the communist revolution in China during their childhood and second when they came to the United States under academic scholarships. Since then my father has "retired" as an industrial operations consultant and my mother works as a biochemist. My interest in the field of mechanical engineering actually stems from two major influences in my life. The first was my fascination with physics. From quanta to kinematics, I have been entertained by physics' promise of allowing me the comprehension of the Universe's methods. Secondly, I have from a young age enjoyed manual labor. As a child I grew vegetables and various other plants in our backyard. In the past decade I have graduated to hands-on work of lager scales such as automotive repair and household construction. These two aspects seemed to fit well with majoring in mechanical engineering.

After graduation, I hope to seek employment in the field of mechanical engineering. Ideally, I would be able to focus on my thermodynamics and heat transfer knowledge. I have no particular interest in any specific industry, but I lean towards aerospace because I am interested in gaining a grasp of modern propulsion methods.

Jared Cohen

My name is Jared Cohen, I am 22 years old and I am from Potomac, MD which is a suburb of Washington, DC. In high school, I took every level of physics my school offered (at least once) as well as any pre-engineering, computer programming, or technology class I could fit into my schedule. I applied to the engineering school knowing I had an interest in the general field, but without any idea of the particular type of engineering I would like to study. Sophomore year, I took ME 240 and thought that it was one of the most well-coordinated classes I'd ever taken. The subject matter, solid mechanics, seemed to be the sort of thing I'd want to understand, as opposed to something I had to learn in order to get good grades, and it was this class that convinced me to continue studying mechanical engineering. In the future, I plan to broaden my field of work, with less of a focus on engineering as a career. If possible, I would be interested in a business oriented field of work that would still allow me take advantage of what I learned as mechanical engineering major, but graduate studies are not out of the question.

Stephen Jeske

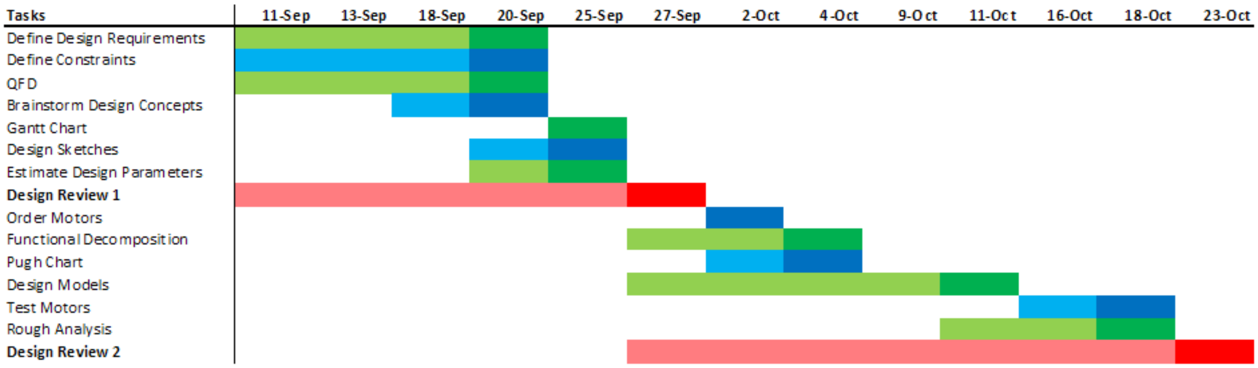
I am a 4th-year student in Mechanical Engineering from St. Joseph, Michigan, which is in the southwest corner of Michigan, about 20 miles north of the Indiana border and right on Lake Michigan. I worked in a trim die manufacturing plant during high school and learned an appreciation for mechanical devices, which is one reason I decided to study mechanical engineering. I also was a part of an electrical race car team in high school, helping maintain, test, improve, and drive the vehicle. This experience in design, testing, and building components further drove my interest in mechanical engineering.

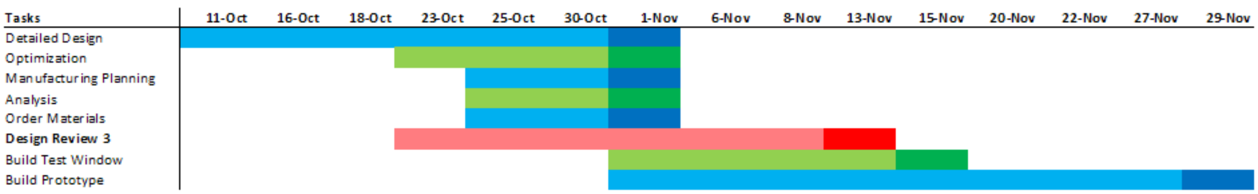
I have always had a fascination with how things work and an affinity for math and science related courses, and always assumed engineering would be a natural fit. I declared into mechanical engineering the second semester of his freshman year in college and never looked back.

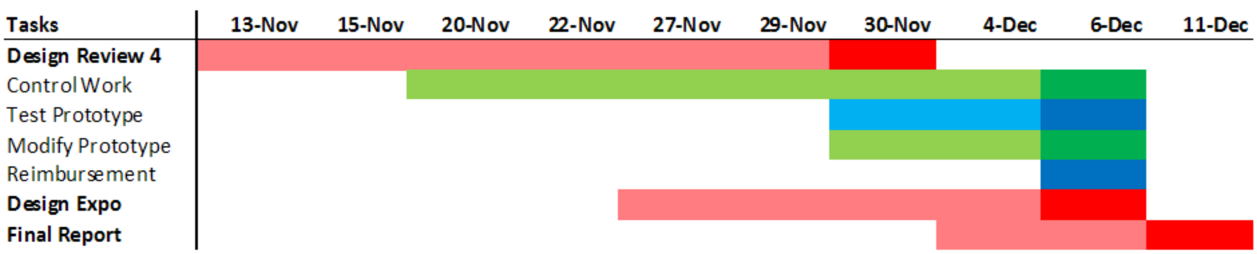
In the future I plan to pursue product development, as I am interested heavily in design and analysis. I also am interested in space and would eventually like to work for a space sciences company, getting involved into developing rockets and delivery vehicles for extraterrestrial missions.

16. Appendices

Appendix A: Gantt Chart







Appendix B: Magnet Concept Motor Torque Calculations

B.1 Static Frictional Force

To find the force of static friction, we began by determining the normal force applied by the magnets. The magnetic force of each of our selected magnets was experimentally determined with an analogue force gauge. The following values were found for the force of the ½" thick, ½" diameter cylindrical magnet (F_{M1}) and the ¼" thick, 1" diameter flat magnet (F_{M2}). Note: the gauge used gave units of kg, hence the F/g measurements given below.

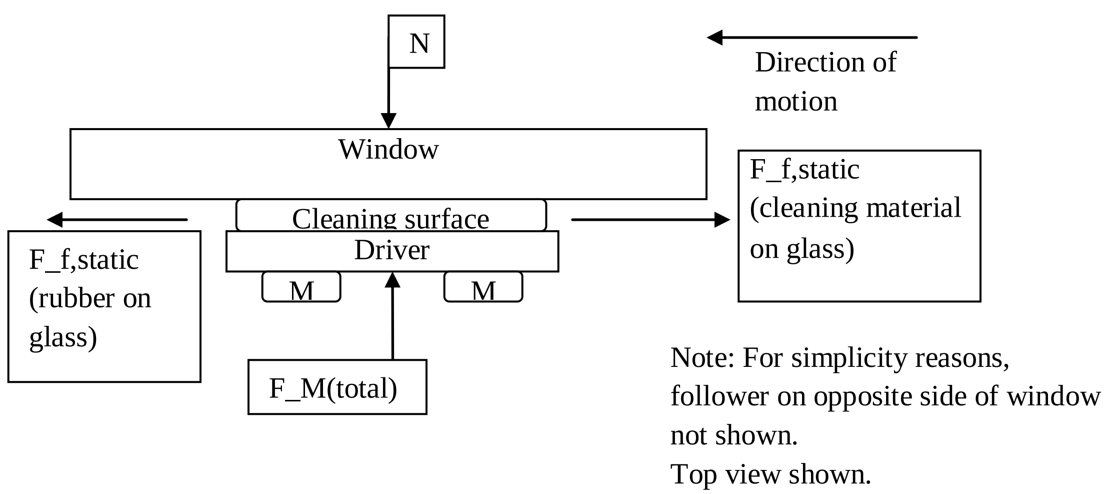
$$F_{M1}/g = 0.17 \pm 0.03\,[kg]$$

$$F_{M2}/g = 1.18 \pm 0.10\,[kg]$$

Therefore, the total magnetic force of our device can be estimated with Equation B.1 below. We multiply F_{M2} by four because we utilize a total of four of this type of magnet.

$$F_{M\_Total} = \left(F_{M2}/g \times 4 + F_{M1}/g \right) \cdot g = (4.89 \pm 0.10) \cdot (9.81) = 47.97 \pm 0.98\,[N] \qquad \text{(Eq. B.1)}$$

FIGURE B.1: Free body diagram of robot in motion



We experimentally determined that the coefficient of static friction between our cleaning surface and glass can be approximated as $\mu_{f,c/g} = 0.4$. From this, we then derive the value of cleaning static frictional force with the following relation:

$$F_{f,c/g}/g = \mu_f \times F_{M\_Total}/g = 1.96 \pm 0.10\,[kg] \qquad \text{(Eq. B.2)}$$

According to Figure B.1, as long as the force of static friction from the wheel rubber on the glass is greater than the static friction of the cleaning material on the glass, the robot will move.
With a static coefficient of friction of rubber on glass of $\mu_{f,r/g}$ = 2.0,

$$F_{f,r/g} = \mu_{f,r/g} \cdot F_{M\_Total} = (2.0) \cdot (4.89) \cdot (9.81) = 95.94\,[N] \qquad \text{(Eq. B.3)}$$

$$(F_{f,r/g} = (95.94\,[N]) > (F_{f,c/g} = (3.91) \cdot (9.81) = 38.38\,[N]) \qquad \text{(Eq. B.4)}$$

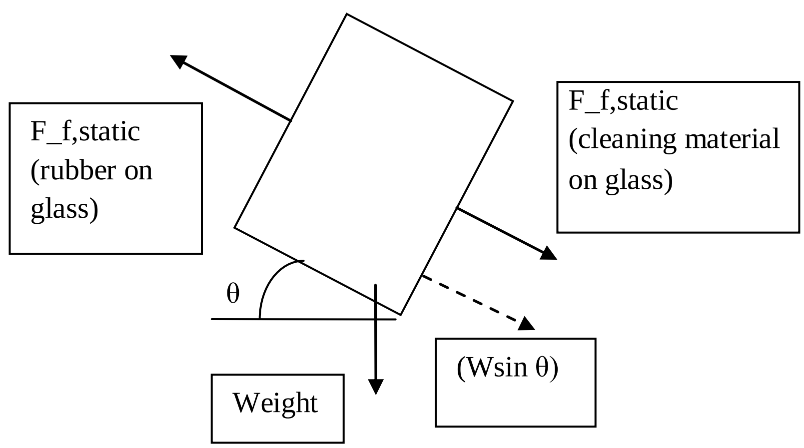
Since this condition is met, the robot will move side-to-side along the window.

The next step is to explore what will happen when the robot tries to move vertically up the window.

We assumed a total mass of the equipped master and follower units to be M = 1.0 kg, as the max per competition rules, even though our prototype would likely have a lower mass. This gives us a total weight force of:

$$F_g / g = 1.0 \sin(\theta)\,[kg] \text{ (where } \theta \text{ is the angle of incline of the device)} \qquad \text{(Eq. B.5)}$$

FIGURE B.2: Free body diagram for upwards motion



As shown in Figure B.2 above, the force of static friction from the wheels on the glass must overcome the static friction force of the cleaning surface on the glass (since that material is sliding on the glass, normally a kinetic friction force would be used, but the static friction force will be greater and may have to be overcome if the robot stops in this position), as well as the component of weight along that direction.

With a static coefficient of friction of rubber on glass of $\mu_{f,r/g} = 2.0$,

$$F_{f,r/g} = \mu_{f,r/g} \cdot F_{M\_Total} = (2.0)\cdot(4.89)\cdot(9.81) = 95.94\,[N] \quad \text{(Eq. B.6)}$$

$$F_{f,r/g} \geq F_{f,c/g} + F_g \sin(\theta) \quad \text{(Eq. B.7)}$$

$$95.94\,[N] \geq \{(1.96)\cdot(9.81) + (1.0\sin(\theta))\cdot(9.81)\} = \{19.23 + 9.81\sin(\theta)\,[N]\})$$

Since this condition is met regardless of the angle to the horizontal, the robot will also move vertically up the window, provided the motors supply the required torque. This is further investigated in the next subsection of this appendix.

Note that earlier in the semester we believed there to be a critical angle beyond which the robot would slip rather than move across the window. This restriction was based on earlier calculations that used a much weaker magnetic force; the stronger magnets used for the final design allow for vertical travel.

B.2 Torque Calculation

The distance from the center of rotation of our motor to the contact surface of the wheel is provided by the manufacturer as R=34.5 mm. Using this, we can determine the torque required to move the robot:

$$T = \left(F_{f,c/g} + F_g\right) \times R = 0.66 + 0.34\sin(\theta)\,[Nm] \quad \text{(Eq. B.8)}$$

This means that a maximum torque of approximately 1 Nm will be required to move the robot vertically up the window. The motors used have a stall torque of 72 oz-in each, which corresponds to a total torque (with two motors) of 1.02 Nm. Thus, it moves very slowly, but it can move vertically up the window, which has been verified with testing. At smaller angles to the horizontal, the robot then moves faster because less torque is required.

Appendix C: Supplemental Engineering Drawings

FIGURE C.1: Base

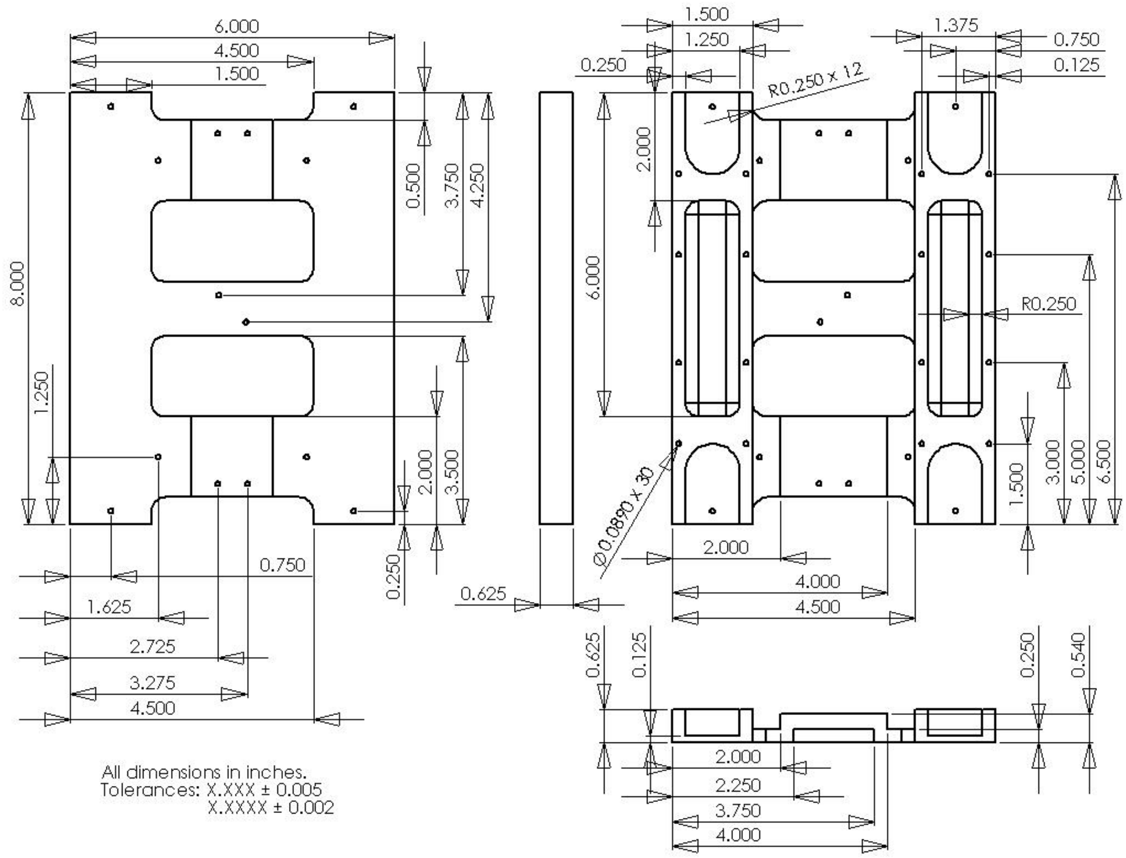


FIGURE C.2: Driver magnet stopper

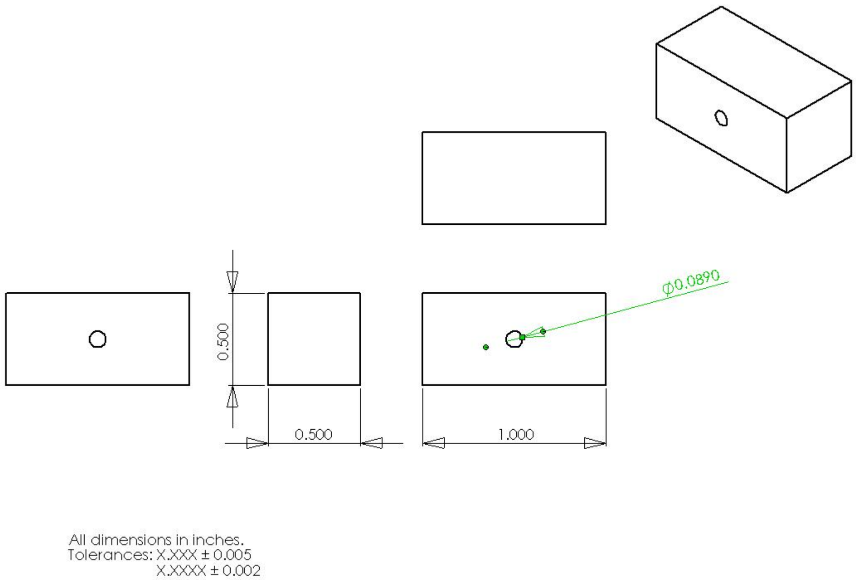


FIGURE C.3: Follower magnet holder

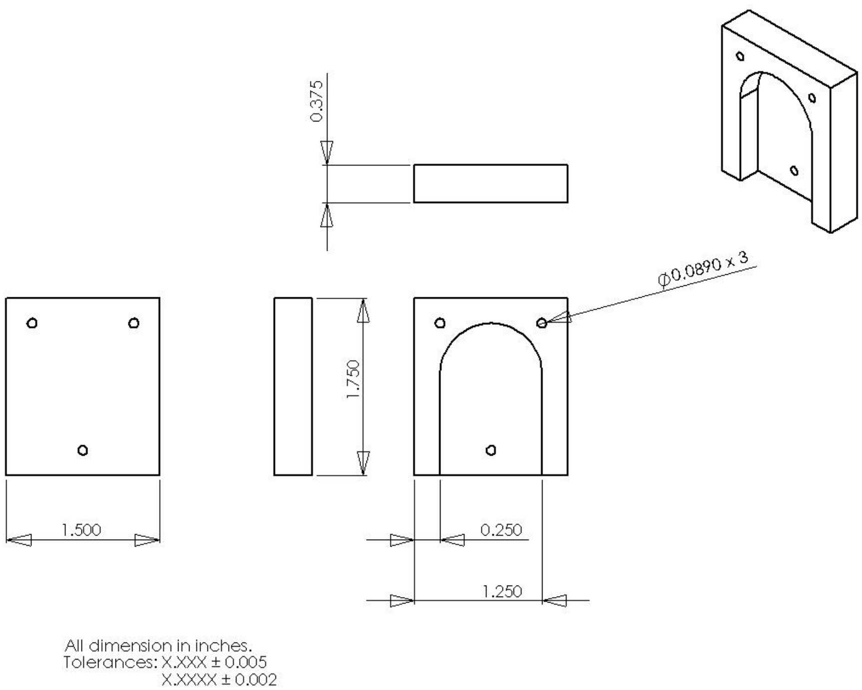
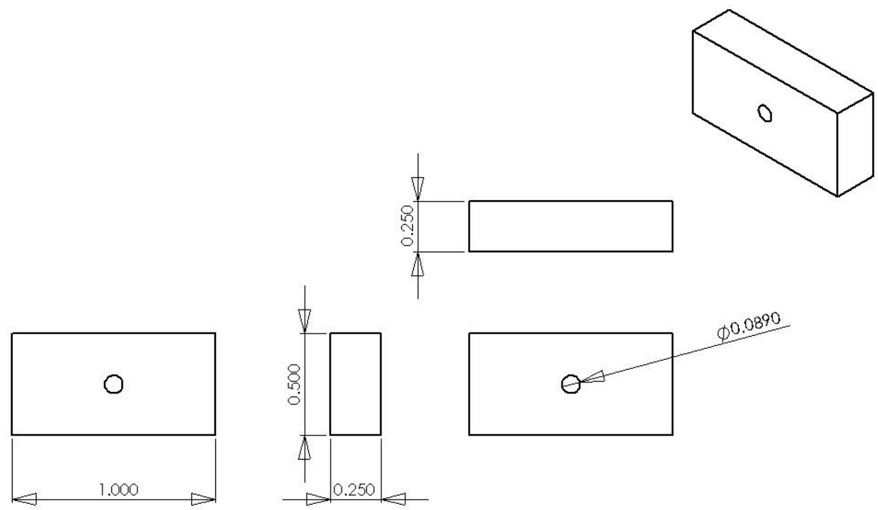
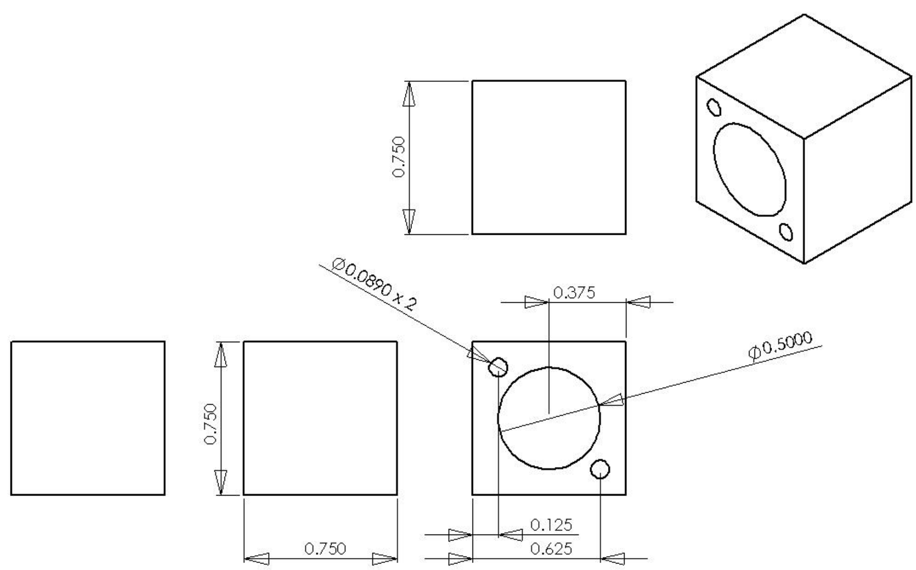


FIGURE C.4: Follower magnet stopper



All dimensions in inches.
Tolerances: X.XXX ± 0.005
X.XXXX ± 0.002

FIGURE C.5: Follower middle magnet mount



All dimensions in inches.
Tolerances: X.XXX ± 0.005
X.XXXX ± 0.002

FIGURE C.6: Side magnet mount

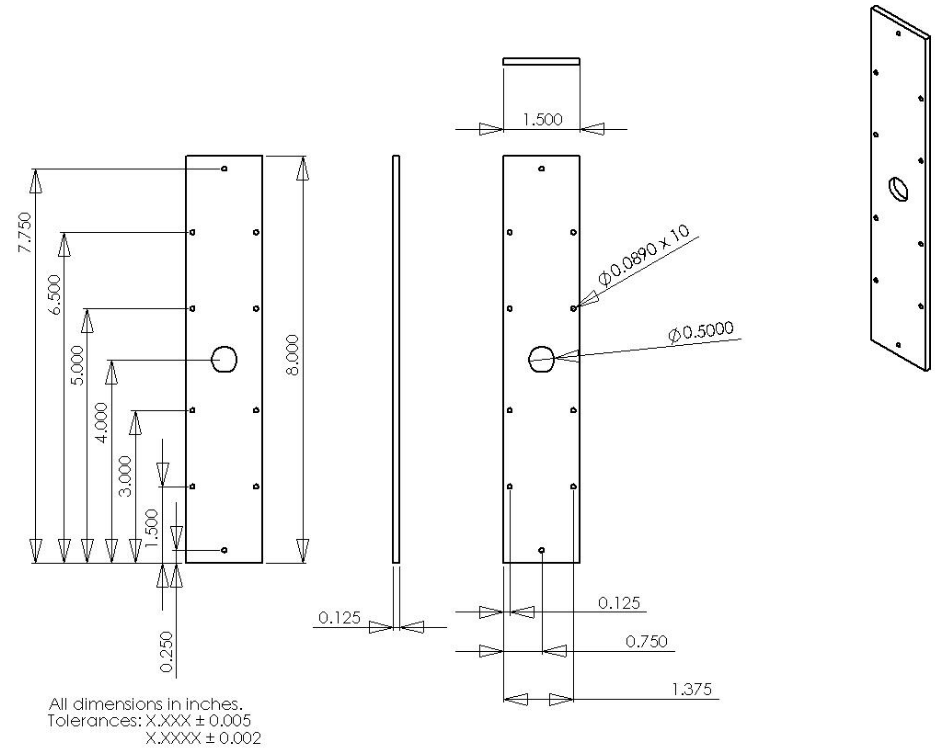


FIGURE C.7: Top cover leg

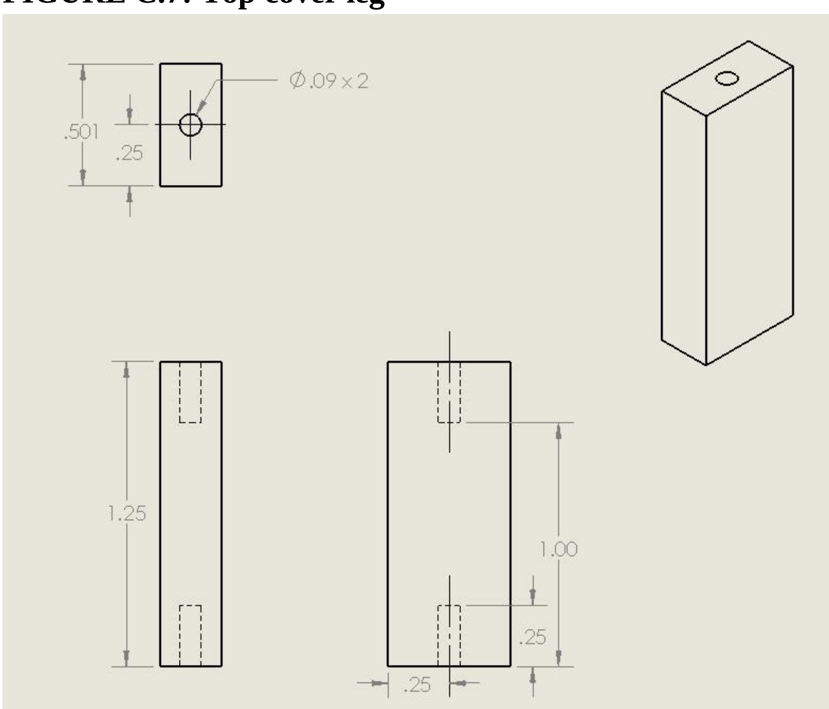
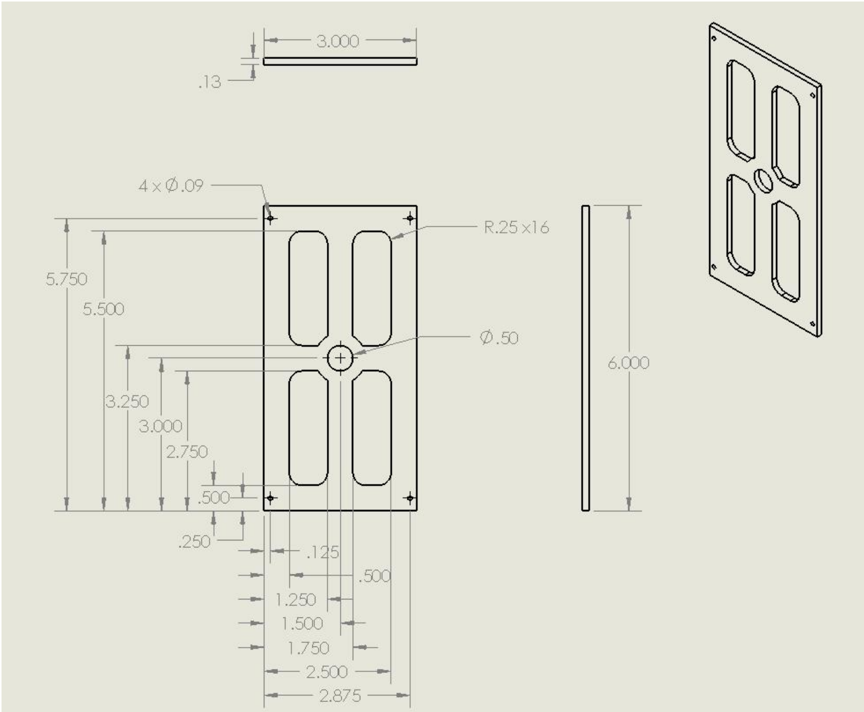


FIGURE C.8: Top cover



Appendix D: Process Planning Sheets

TABLE D.1: Base driver

Quantity: 1

Step	Machine	Tool	Fixture	Process
1	Mill	N/A	Vise	Load 8.00” x 6.000” x 0.625” block into vise with 1.000” dimension facing the tool, lock down.
				Index face along 8.000” dimension as [A], face along 6.000” dimension as [B], face along 0.625” dimension as [C]
2	Mill	1” end mill	Vise	Move part so that the cutting edge is 1.750” from [A], from 1.750” to 4.250” cut another 0.0847” into [C] ([C] should be 0.5403” between 1.750” and 4.250” from [A]). Cut entire length perpendicular to [B]
3	Mill	1” end mill	Vise	Center tool 0.750” from [A], cut 1.000” into block from [B] surface at a depth of 0.375” (may require multiple cuts at smaller cut depths; cut is parallel to [A] surface). CENTER of tool should go in 1.000”, so that end of cut has a radius of 0.500” and longest length of cut is 1.500”. Four (4) separate cuts will take place here, one at each corner at the end of [A] and the face parallel to [A].
4	Mill	½” end mill	Vise	Move part so that the cutting edge is 1.500” from [A] (center is 1.750” from [A]), cut to a length of 4.500” (EDGE is at 4.500” from [A], center is at 4.250” from [A], cutting inward from [B] 0.500” along entire height.
5	Mill	½” end mill	Vise	With center of tool 1.750” from [A] (cutting edge 1.500” from [A]), at a height of 0.250” from the bottom of the part (0.375” from tallest surface of part), cut along entire length.
6	Mill	½” end mill	Vise	With center of tool 4.000” from [A] (cutting edge 3.7500” from [A]), at a height of 0.250” from the bottom of the part (0.3750” from tallest surface of part), cut along entire length.
7	Mill	½” end mill	Vise	With center of tool at 1.750” from [A] and 3.500” from [B], cut with 1.750” dimension fixed until tool center is 4.500” from [B]. Now fix 4.500” dimension and cut until tool center is at 4.250” from [A]. Cut out middle material bordered by these cuts.
8	Mill	½” ball mill	Vise	With center of tool 0.5000” from [A] and 2.0000” from [A], cut from 0.5000” to 1.0000” from [A] and 2.0000” to 6.0000” from [B] at a total depth of 0.3750” (NOTE: cut will be 0.2500” to 2.2500” from [A] and 1.7500” to 6.2500” from [B]).
9	Mill	½” ball mill	Vise	Repeat #8 on opposite side of part (center of tool moves 5.0000” to 5.5000” from [A] and 2.0000” to 6.0000” from [B], total cut is 3.7500” to 5.7500” from [A] and 1.7500” to 6.2500” from [B]). Cut is also at total depth of 0.3750”.
10	Mill	1/2” ball mill	Vise	With center of tool 1.7500” from [A] and 2.2500” from [B], cut 2.0000” away from [A] (to 4.2500” from [A]) and 1.0000” away from [B] (to 3.2500” from [B]). Cut along

				entire height.
11	Mill	½" ball mill	Vise	Make cut symmetrical to #10. Cut with center of tool 1.7500" to 4.2500" from [A], 4.7500" to 5.7500" from [B]. Cut entire height. Now should have two symmetrical "holes" or "spaces" in the part.
12	Mill	#43 drill bit	Vise	With center of tool at 0.125" from [A], drill four (4) holes, one at each of 1.500", 3.000", 5.000", and 6.500" from [B]
13	Mill	#43 drill bit	Vise	With center of tool at 1.375" from [A], drill four (4) holes, one at each of 1.500", 3.000", 5.000", and 6.500" from [B]
14	Mill	#43 drill bit	Vise	With center of tool at 4.625" from [A], drill four (4) holes, one at each of 1.500", 3.000", 5.000", and 6.500" from [B]
15	Mill	#43 drill bit	Vise	With center of tool at 5.875" from [A], drill four (4) holes, one at each of 1.500", 3.000", 5.000", and 6.500" from [B]
16	Mill	#43 drill bit	Vise	With center of tool at 0.250" from [B], drill two (2) holes, one at each of 0.750" and 5.250" from [A].
17	Mill	#43 drill bit	Vise	With center of tool at 7.750" from [B], drill two (2) holes, one at each of 0.750" and 5.250" from [A].
18	Mill	#43 drill bit	Vise	With center of tool at 1.000" from [B], drill two (2) holes, one at each of 2.725" and 3.275" from [A].
19	Mill	#43 drill bit	Vise	With center of tool at 7.000" from [B], drill two (2) holes, one at each of 2.725" and 3.275" from [A].
20	Mill	#43 drill bit	Vise	With center of tool at 1.625" from [A], drill two holes, one at each of 1.250" and 6.750" from [B]
21	Mill	#43 drill bit	Vise	With center of tool at 4.375" from [A], drill two holes, one at each of 1.250" and 6.750" from [B]
22	Hand tap set	#4-40 tap	Vise	Thread all #43 holes

TABLE D.2: Follower base

Quantity: 1

Step	Machine	Tool	Fixture	Process
1	Mill	N/A	Vise	Load 8.000" x 6.000" x (2mm) block into vice with 8.000" x 6.000" face facing upwards
				Index face along 8.000" dimension as [A], face along 6.000" dimension as [B], large upwards face as [C]
2	Mill	#43 drill bit	Vise	With center of tool 0.250" from [A], drill two holes, one at each of 1.500" and 6.500" from [B]
3	Mill	#43 drill bit	Vise	With center of tool 1.250" from [A], drill two holes, one at each of 1.500" and 6.500" from [B]
4	Mill	#43 drill bit	Vise	With center of tool 4.750" from [A], drill two holes, one at each of 1.500" and 6.500" from [B]
5	Mill	#43 drill bit	Vise	With center of tool 5.750" from [A], drill two holes, one at each of 1.500" and 6.500" from [B]
6	Mill	#43 drill bit	Vise	With center of tool 0.750" from [A], drill two holes, one at each of 0.250" and 7.750" from [B]
7	Mill	#43 drill bit	Vise	With center of tool 5.250" from [A], drill two holes, one at east of 0.250" and 7.750" from [B]

TABLE D.3: Magnet holder base: follower

Quantity: 4

Step	Machine	Tool	Fixture	Process
1	Mill	N/A	Vise	Load 1.500” x 1.750” x 0.250” block into vice with 1.500” x 1.750” face facing upwards
				Index face along 1.500” dimension as [A], face along 1.750” dimension as [B], large upwards face as [C]
2	Mill	1” end mill	Vise	With center of tool 0.750” from [B] (halfway along [A]), cut so that center of tool moves 1.000” into piece (1.000” into 1.750” dimension). With radius of cut, largest cut depth will be 1.500”. Cut 0.250” deep into material (into [C]).
3	Mill	#43 drill bit	Vise	Drill 0.750” from [B] and 0.250” from [A] thru material.
4	Mill	#43 drill bit	Vise	Drill 0.250” from [B] and 1.500” from [A] thru material.
5	Mill	#43 drill bit	Vise	Drill 1.250” from [B] and 1.500” from [A] thru material.

TABLE D.4: Magnet holder top: driver

Quantity: 2

Step	Machine	Tool	Fixture	Process
1	Mill	N/A	Vise	Load 8.000” x 1.500” x 0.125” block into vice with 0.125” dimension facing downward
				Index face along 8.000” dimension as [A], face along 1.500” dimension as [B], and face along 0.125” dimension as [C]
2	Mill	#43 drill bit	Vise	With tool center at 0.125” from [A], drill holes at 1.500”, 3.000”, 5.000” and 6.500” from [B]
3	Mill	#43 drill bit	Vise	With tool center at 1.375” from [A] (0.125” from face parallel to [A]), drill holes at 1.500”, 3.000”, 5.000” and 6.500” from [B]
				8 total holes should now be drilled, 4 on each side. Part should be symmetric.
4	Mill	#43 drill bit	Vise	With tool center at 0.750” from [A] (in the middle of the piece), drill holes at 0.250” and 7.750” from [B]
				10 total holes should now be drilled. Part should still be symmetric.
5	Mill	½” drill bit	Vise	With tool center at 0.750” from [A] and 4.000” from [B] (in exact center of part on [C] face), drill hole.

TABLE D.5: Magnet holder top: follower

Quantity: 4

Step	Machine	Tool	Fixture	Process
1	Mill	N/A	Vise	Load 0.125" x 1.500" x 1.750" block into vice with 0.125" dimension facing downward
				Index face along 1.750" dimension as [A], face along 1.500" dimension as [B], and face along 0.125" dimension as [C]
2	Mill	#43 drill bit	Vise	With tool center at 0.125" from [A], drill hole at 1.500" from [B]
3	Mill	#43 drill bit	Vise	With tool center at 1.375" from [A] (0.125" from face parallel to [A]), drill hole at 1.500" from [B]
4	Mill	#43 drill bit	Vise	With tool center at 0.750" from [A], drill hole at 0.250" from [B]

TABLE D.6: Magnet stop: driver base

Quantity: 4

Step	Machine	Tool	Fixture	Process
1	Mill	N/A	Vise	Load 0.500" x 1.000" x 0.500" block into vice with 0.500" dimension facing downward
				Index face along 0.500" dimension as [A], index face along 1.000" dimension as [B], index face along 0.375" dimension (facing downward) as [C]
2	Mill	#43 drill	Vise	Drill hole 0.250" from [A] and 0.500" from [B] (in the middle of the piece) thru entire height.

TABLE D.7: Magnet stop: follower base

Quantity: 4

Step	Machine	Tool	Fixture	Process
1	Mill	N/A	Vise	Load 0.500" x 1.000" x 0.250" block into vice with 0.250" dimension facing downward
				Index face along 0.500" dimension as [A], index face along 1.000" dimension as [B], index face along 0.250" dimension (facing downward) as [C]
2	Mill	#43 drill	Vise	Drill hole 0.250" from [A] and 0.500" from [B] (in the middle of the piece) thru entire height.

TABLE D.8: Magnet holder: mid base

Quantity: 4

Step	Machine	Tool	Fixture	Process
1	Mill	N/A	Vise	Load 0.750” x 0.750” x 0.750” block into vice
				Index one side face as [A], one side face as [B], and top face as [C]
2	Mill	#43 drill bit	Vise	Move center of tool 0.125” from [A] and 0.125” from [B]; drill 0.500” into [C]
3	Mill	#43 drill bit	Vise	Move center of tool 0.625” from [A] and 0.625” from [B]; drill 0.500” into [C]
4	Mill	½” drill bit	Vise	Move center of tool 0.375” from [A] and 0.375” from [B] (in center of part); drill 0.500” into [C]

TABLE D.9: Top

Quantity: 1

Step	Machine	Tool	Fixture	Process
1	Mill	N/A	Vise	Load 6.000” x 3.000” x 0.125” block into vise with 0.125” dimension facing the tool, lock down.
				Index face along 6.000” dimension as [A], face along 3.000” dimension as [B], face along 0.125” dimension as [C]
2	Mill	½” ball mill	Vise	With center of tool 0.500” from [A] and 2.000” from [A], cut from 0.500” to 1.000” from [A] and 2.000” to 6.0000” from [B] at a total depth of 0.125” (NOTE: cut will be 0.250” to 2.250” from [A] and 1.750” to 6.250” from [B]).
3	Mill	½” ball mill	Vise	Repeat #8 on opposite side of part (center of tool moves 5.000” to 5.500” from [A] and 2.000” to 6.000” from [B], total cut is 3.750” to 5.750” from [A] and 1.750” to 6.250” from [B]). Cut is also at total depth of 0.125”.
4	Mill	1/2” ball mill	Vise	With center of tool 1.750” from [A] and 2.250” from [B], cut 2.000” away from [A] (to 4.250” from [A]) and 1.000” away from [B] (to 3.250” from [B]). Cut along entire height.
5	Mill	½” ball mill	Vise	Make cut symmetrical to #10. Cut with center of tool 1.750” to 4.250” from [A], 4.750” to 5.750” from [B]. Cut entire height. Now should have two symmetrical “holes” or “spaces” in the part.
6	Mill	½” drill bit	Vise	At center of part (3.000” from [A], 1.500” from [B]) drill thru material.

TABLE D.10: Top support

Quantity: 4

Step	Machine	Tool	Fixture	Process
1	Mill	N/A	Vise	Load 0.250” x 0.500” x 1.500” block into vice with line along 1.500” dimension pointing downward
				Index face along 0.250” dimension as [A], index face along 0.500” dimension as [B], index face along 1.500” dimension (facing downward) as [C]
2	Mill	#43 drill bit	Vise	Drill hole 0.125” from [A] and 0.250” from [B] (in the middle of the piece); drill 0.375” into face parallel to [C]
3	Mill	N/A	Vise	Rotate piece so that [C] is now facing upward (was previously facing downward)
4	Mill	#43 drill bit	Vise	Drill hole 0.125” from [A] and 0.250” from [B] (in the middle of the piece); drill 0.375” into [C]

TABLE D.11: Starting blocks

Qty.	Part	Dimensions
4	Magnet Stop: Driver Base	0.500” x 1.000” x 0.500”
4	Magnet Stop: Follower Base	0.500” x 1.000” x 0.250”
4	Top Support	0.250” x 0.500” x 1.500”
2	Magnet Holder: Mid Base	0.750” x 0.750” x 0.750”
4	Magnet Holder Top: Follower	0.125” x 1.500” x 1.750”
2	Magnet Holder Top: Driver	8.000” x 1.500” x 0.125”
1	Driver Base	8.000” x 6.000” x 0.375”
1	Follower Base	8.000” x 6.000” x 0.079”
1	Driver Top	6.000” x 3.000” x 0.125”
4	Magnet Holder Base: Follower	1.500” x 1.750” x 0.250”

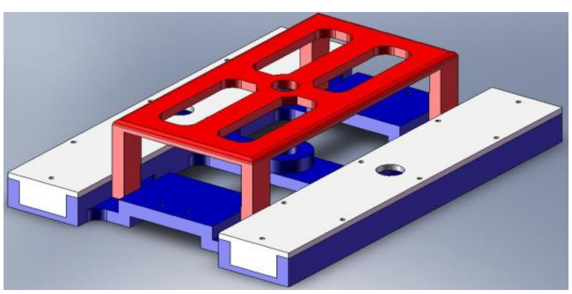
17. Engineering Change Notice

When actually building our final device a few changes were made. The major changes were located in the middle of the base. Our original design had a solid bridge between the two sides with a holder for one cylindrical magnet. We decided that this additional magnet was not needed and we partially cut out this bridge because of weight issues. Another change concerned the four legs needed to hold up the top. Once the motors were installed, they ended up blocking two of the legs in a way that made them impossible to use in their original location. Now, with only two legs supporting the top it became unstable and therefore we needed to add more legs. We put two legs in the middle of the base but near the edges of the two sides where the bridge was partially cut out. With the addition of these two legs the top became more stable.

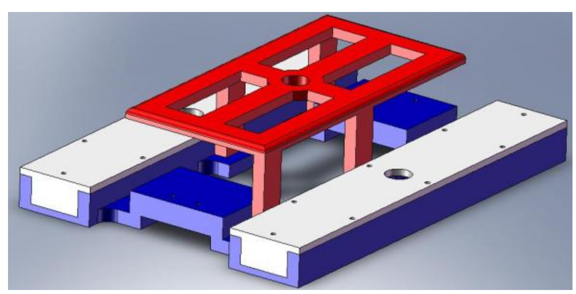
The next change to our design was additional PVC underneath both the motors to raise the height of the wheels. We needed another 0.125 inch to have the motors be at a perfect height where they allow the wheels and the cleaning material to touch the glass. Refer to Figure 17.1 for a before and after picture.

The final change made was on the follower. The follower was originally supposed to have cleaning material on it. However, this additional cleaning material caused the magnets to be too far apart and thus the device to slip. The cleaning material needed to be removed so the magnets could provide more force and prevent the slipping. In its place we used duct tape to help prevent screws from scratching the window.

FIGURE 17.1: Before and after pictures



Before



After