AUTOMATED SOLAR PANEL CLEANING

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Bachelor of Science, School of Engineering

By

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

The goal of this capstone design project is to design an automated cleaning mechanism that can stay attached to the roof-mounted solar panel. Having clean solar panels is important so the solar cells can collect as much sunlight as possible. The design as shown in Figure 1 aims to eliminate the need for climbing onto the roof every time a solar panel requires cleaning, and to reduce the cost of cleaning solar panels. The team's mission statement is to design and build a prototype of an automated solar panel cleaning system for residences.

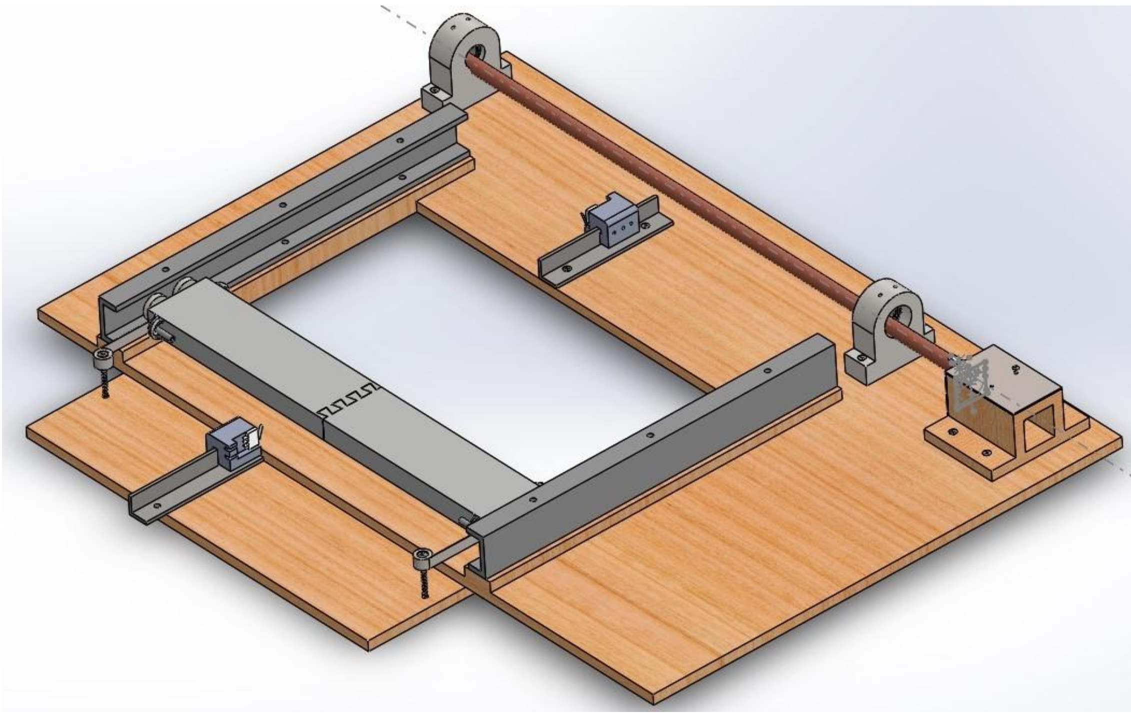

Figure 1: Proposed Design

Background

Research

Solar photovoltaic (PV) systems convert sunlight into electricity using solar cells. The cost for these systems have decreased since 2014 and are becoming a cost competitive energy source. It is projected that more than one in seven U.S. homes will have a rooftop solar PV system by 2030 (*Solar Energy in the United States*, n.d.). Dust and debris on the solar panel can increase energy loss by up to 7% in parts of the United States or as high as 50% in the Middle East (Hicks, n.d.). Leaves, bird droppings, and other debris left on the solar panel can impact the efficiency of the solar panel as well. The most common method to clean solar panels is using water and brushes to scrub the dirt which requires manual labor and solar panel cleaning experts (*Cleaning Solar Panels*, 2022). An annual solar panel inspection and cleaning costs ranges from $450 to $780 (*Learn How Much It Costs to Clean and Maintain Solar Panels.*, n.d.).

Constraints and Specifications

The design must be built to the specification of a 12”x20” solar panel model, which is 1:3.25 to scale of a typical solar panel size of 39”x65”. The solar panel model would be mounted on a plywood platform. There are many requirements to successfully build an automated solar panel cleaning mechanism. When not in use the device must stay away from the occlusion zone, which is defined as on top of the panel and the area not included from a measurement by a 45° angle from the edge of the panel. The device must cost less than $600 to make and be built to last against weather conditions such as sun, water, and snow. The safety of the attachment to the roof is important and must last against wind conditions. The goal of the automated solar panel cleaning mechanism design is to have a low cost, safe, durable, and efficient cleaning device.

Design Process

Considerations and Alternatives

Creating a final design idea involved an ideation phase, a concept screening phase, and a concept selection phase. In the ideation phase, each group member came up with five unique designs for a solar panel cleaner. In the concept screening phase, every member's five ideas were looked at to group together and narrow down similar ideas. It was decided to separately judge the cleaning method from the system mechanism. This meant that methods of cleaning the solar panel for example static, brushes, or water jets were compared to each other separately from the way the design would move to accomplish that cleaning such as rolling on tracks, rotations, or robotically. Each concept was rated with a -1, 0, or 1 for each factor where -1 was a negative rating of the factor, 0 was neutral, and 1 was positive. The team considered factors such as cost, cleaning efficiency, user friendliness, and manufacturability. At the end the ratings were added up to see which concepts had the highest positive number. The methods with higher ratings were then combined with the mechanisms with higher ratings to finalize the concept screening. Table I shows the method concept screening and Table II shows the mechanism screening. Appendix L contains the final concept screening with the relevant figures.

Concept scoring selection started with choosing five of the concept screened ideas that the group agreed were the better ideas. These five were rated again. In this rating each factor had a weighting for how important they were to the design; ratings were on a one to five scale, where one was negative performance and five was positive performance. A weighted rating for each concept was formed, summed together, and compared. Table III contains the concept scoring selection; concept scoring selection figures can be found in Appendix O.

Method concept screening

Table I: Cleaning Concept Screening Chart

Concept	Static	Squeegee	Comp. Air	Water Jet	Brush
Factor					
User Friendly	1	1	1	1	1
Weather durability	0	-1	0	0	-1
Snow, ice, and wind operation	-1	0	-1	-1	0
Cost	-1	0	1	-1	0
Safety - Roof Attachment	-1	1	0	0	0
Non abrasive	1	-1	0	0	-1
Cleaning efficiency	0	1	0	0	1
Low Maintenance	1	0	1	0	-1
Big Debris	-1	1	-1	1	1
Manufacturability	0	1	1	1	1
Environmental Degradation	1	-1	1	0	-1
Total	**0**	**2**	**3**	**1**	**0**

Mechanism concept screening

Table II: Mechanism Concept Screening Chart

Concept	Roller on tracks	Rotation	Robot	Portable Assembly	CNC
Factor					
User Friendly	0	0	0	-1	0
Ease of operation	1	1	-1	-1	1
Retractability	1	1	1	1	1
Weather durability	-1	1	0	1	-1
Harsh weather operation	0	0	0	0	0
Cost	0	0	-1	1	-1
Safety - Roof Attachment	1	1	-1	0	0
Coverage	1	-1	1	0	1
Cleaning efficiency	0	0	1	0	0
Low Maintenance	0	0	-1	0	-1
Big Debris	0	0	1	1	1
Manufacturability	1	1	-1	1	-1
Total	**4**	**4**	**-1**	**3**	**0**

Overall concept scoring

A "squeegee on rollers" design was selected as the best design. Given that previous screening was done using separate judgments of the mechanisms and the cleaning methods, the team scored the best combinations thus yielding the five concepts scored in this document.

Table III: Overall Concept Scoring Chart

		Compressed air on rollers		**Squeegee on rollers**		**Squeegee on rotation**		**Static**		**Compressed air rotation**	
Concept	**Weights**	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Weather durability	10%		0.30	2	0.20	2	0.20	4	0.40	1	0.10
Snow, ice, and wind operation	3%		0.03	3	0.09	3	0.09	1	0.03	1	0.03
Cost	7%		0.21	3	0.21	3	0.21	1	0.07	1	0.07
Abrasiveness	15%		0.60	2	0.30	2	0.30	5	0.75	1	0.15
Cleaning efficiency	20%		0.40	5	1.00	4	0.80	2	0.40	1	0.20
Low Maintenance	5%		0.10	2	0.10	2	0.10	4	0.20	1	0.05
Big Debris	10%		0.20	4	0.40	4	0.40	1	0.10	1	0.10
Manufacturability	5%		0.10	3	0.15	4	0.20	2	0.10	1	0.05
Environmental Degradation	10%		0.40	1	0.10	1	0.10	5	0.50	1	0.10
Safety	10%		0.30	3	0.30	4	0.40	1	0.10	1	0.10
Coverage	5%		0.10	4	0.20	2	0.10	4	0.20	1	0.05
Total Score	100%	2.74		3.05		2.90		2.85		1.00	
Rank		4		1		2		3		5	
Continue?		No		Yes		No		No		No	

Chosen Design

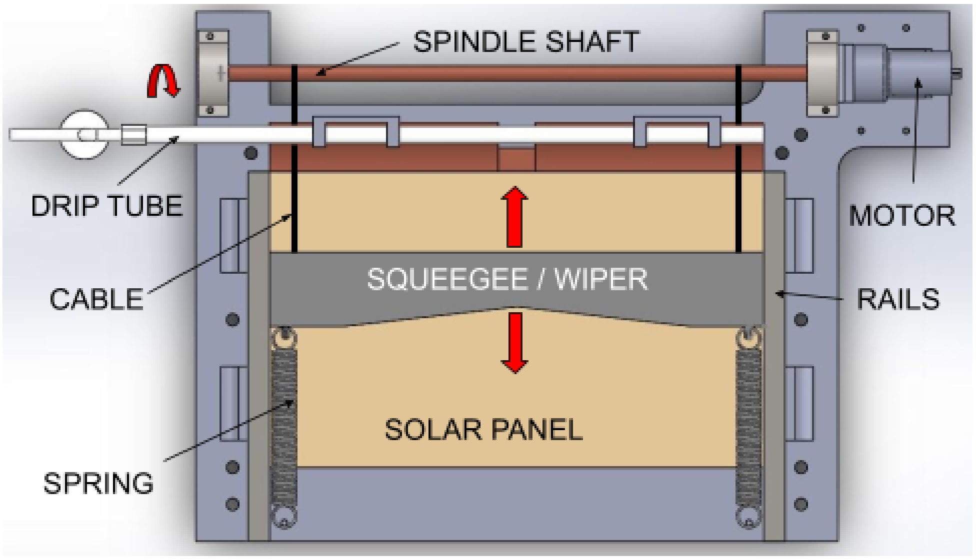

Figure 2: Top-down View of Key Intended Design Components

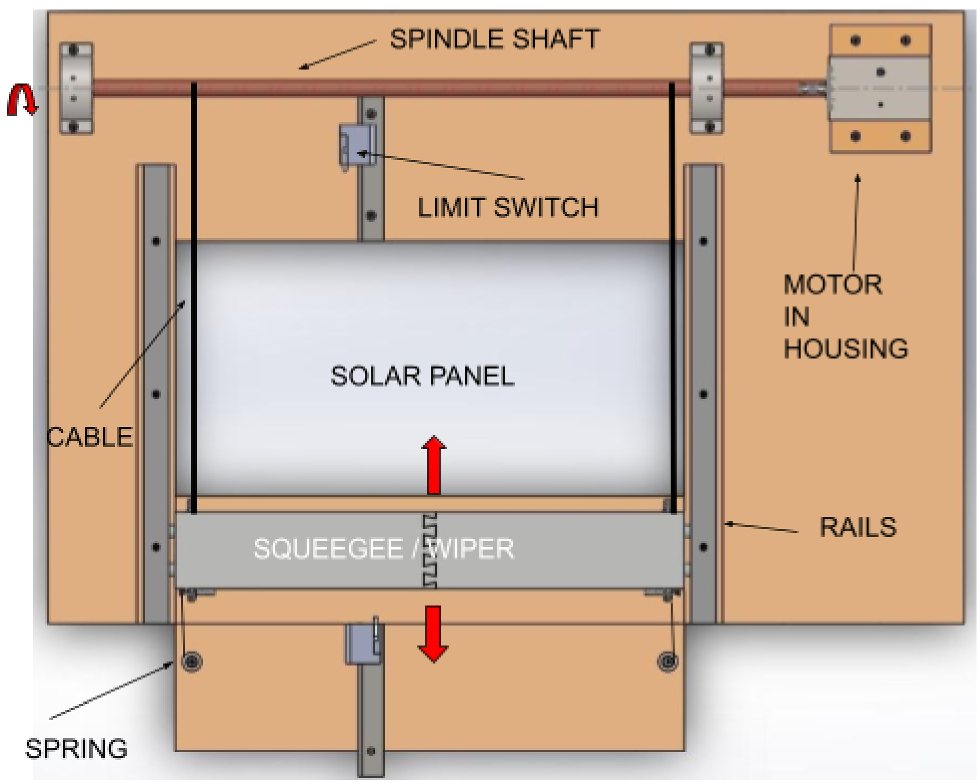

Figure 3: Top Down View of the Final Chosen Design

The chosen design comprises a horizontal squeegee that moves up and down the length of the solar panel along tracks that span the panel vertically. The horizontal squeegee has wheels on both ends that allow it to roll along the tracks easily. The squeegee is driven by a winch system that operates along the top of the system. A high torque, low RPM motor is connected to a horizontal shaft that runs through two bearings along the top of the solar panel. This shaft is connected to the squeegee by two steel cables. Rotating the motor one way will result in the shaft winding up the cables, pulling the squeegee to the top of the solar panels. Rotating it the other way will unwind the cables allowing the squeegee to move back to the bottom of the solar panel. The direction of the motor is provided by an H-bridge control board connected to the motor and an Arduino microcontroller. The motor reverses its direction according to a pre-programmed sequence using two limit switches.

To provide force to reliably pull the wiper blade to the bottom of the solar panel, two negator springs are placed on either end of the squeegee opposite the winch. When the squeegee is brought to the top of the panel, the springs are put into a constant tension, allowing them to pull the squeegee back to the bottom of the solar panel when the winch is unwound. This winch method was chosen over several other considered driving mechanisms due to its practicality and cost. Initially a linear actuator was considered to drive the squeegee arm but linear actuators were deemed too bulky and expensive for the envisioned system. Another method considered was to have the motor mounted on the squeegee, and have it drive the wheels on the squeegee arm directly. However, the added weight to the squeegee arm and the necessity to design for a moving power supply added too much instability to the system. The winch method allows for the solar panel to be unobstructed while not cleaning and is simple enough to minimize unforeseen problems.

To affix the mechanism onto the roof, a mounting plate with a rectangular cut-out is first attached around the solar panel. This mounting plate will ideally be made of sheet metal and will have holes punched out for locating screws. This plate will have custom-made fixtures for mounting the rails, motor, bearing mounts, and planned subsystems like the drip-guard and drip-irrigation systems. The number of screws and their sizes were found using Equations 2 and 4 from Appendix N. These calculate the stress exerted on each bolt by the wind load and the weight of the assembly. Meanwhile, the necessary torque on the motor was found using Equation 1 from Appendix N, which considers the force needed to overcome that exerted by the wiper weight and the tension springs.

Design for Manufacture

This design was constructed for easy manufacturing through ease of access to various important parts, distinct sub-assemblies, and integrated functionality for these sub-assemblies/parts. This design contains a good balance between simplicity and multifunctional capabilities. The sub-assemblies - frame/rails, motor/shaft, and wiper assembly - each have clearly demarcated parts and forms of assembly. Since each sub-assembly is clearly demarcated, each one can be easily put together and sent along for final construction. Attached parts like the motor, motor mounts, and rails are connected to the frame with screws and other easier attachment methods. This system allows for a limited modularity based on any custom-ordered spacing between rails and future panels. It also allows for the easy removal of the planned solution distribution system if necessary.

For the parts orientation and placement, the parts involved will either be symmetrical or clearly marked for proper orientation. For example, the wiper assembly can be placed with the blade facing either way. If the wiper bar is 3D printed, it has been built to be printed best with the sun-facing side as the base when printed. This not only reduces the usage of expensive dissolvable support material necessary for the blade slot, but it also keeps the surface of the panel-facing side smooth. This is because the base layers of 3D printed parts can be rougher than the top layers. Since the sun-facing layer will be the "rough" layer, the panel-facing side will be the smoother top layers of the print.

The current prototype design utilizes many off-the-shelf parts. If the team decides to continue with using certain off-the-shelf parts, then the team will optimize selection so that costs can be reduced. For example, parts like the bearing wheels, screws and nuts, springs, and motors can be had cheaply and great amounts can be stockpiled easily in case of disruption. Any future production facility would be built to prioritize reduced inventory costs with supply chain resilience. Parts made within the facility's nation would be considered with other factors when constructing supply chains.

Design for Sustainability

This project's design is inherently tied to sustainability due to its use cases. As such, the team aspired to make the best possible use of resources while maintaining unit performance. Better unit performance will mean increased solar panel efficiency for the home and ultimately for the wider power grid. Although this design is made from multiple materials, each part is able ultimately to be separated without much difficulty due to manufacturing methods. The team expects that at least the railing and the frame can be recycled. The motor as well can be easily salvaged.

For long-term maintenance, the usage of off-the-shelf parts for high-wear areas (i.e. bearings, the wiper blade, etc.) mean that this product can be maintained with only minor trouble. The most involved regular expected maintenance would be to replace the wiper blade. In this case the wiper assembly would need to be removed from the railing and the wiper blade slid out and replaced. For energy considerations, it is expected that the wiper would be connected to the house's energy system. Since by definition there would be solar panels on the roof, this means that the motor could draw energy from renewable sources. The motor's electricity consumption is believed to be insignificant compared to the energy gained through gained panel efficiency.

Standards

The project used off-the-shelf parts in standards using both metric and imperial measuring systems. For example, the R8 and R10 bearings use the ABEC 1 standards; the U channel abides by ASTM B221 regulations. The screws held to SAE standards. The Arduino and other electronics parts held to their own relevant standards and certifications. The Arduino and cables hold to Universal Serial Bus (USB) standard. The Arduino itself has numerous compliance controls and applied electronics standards which will not be elaborated here. All the custom parts like the wiper bar were designed to interface with these off-the-shelf parts. Relevant safety and roofing codes were viewed at various points in the project. International Building Code (IBC) Section 3403 was looked at when considering the weight of the system on the roof trusses (*Know your codes for solar mounting*, 2018). Fire codes like the International Fire Code (IFC) 605.11.3.2.1 and IBC 1503.2 were considered but were not deemed immediately relevant for the proof of concept/prototype stage.

Construction of the Cleaner

The creation of an automated solar panel cleaning mechanism aims to decrease the cost of cleaning solar panels since manual labor is expensive. The design goals include being low cost, being safely attached to the roof, and having good durability to weather conditions. The ideation, concept screening, and concept scoring was completed and the mechanical wiper blade mechanism was chosen as the final design. The initial design was completed and modeled in a 3D software.

The components were then purchased and assembled during the spring semester. This assembly was done using resources found at the MAE MILL (B005), the MAE Machine Shop, and the Architecture School's FabLab. The team made the mounting plate from a 3'x2' piece of ½" MDF board. This was cut to size, with a 20.5" x 10.5" rectangular cut-out provided for the solar panel. An additional 10" x 10.5" strip of balsa was affixed to the bottom of the mounting plate to provide enough space for the negator spring attachments, as well as the limit switches. The limit switches were glued into 3D printed limit switch mounts. These limit switch mounts were subsequently mounted onto steel rails cut from scrap; the mounts were affixed onto the rails via a set screw. Holes were drilled into the MDF mounting plate to attach to the aluminum U-channel rails. The motor mounts, pillow blocks, and the plinths on which the rails stand were made from the scraps of leftover MDF and were screwed into the MDF mounting plate using #8 1-¼" wood screws..

The wiper blade assembly was printed using the Lulzbot Taz 6 FDM (Fusion Deposition Modeling) 3D printer at the Clemons library 3D Printing Lab. This assembly involved rapid testing and prototyping to achieve the final product. The wiper blade insert was procured beforehand and intensely measured due to its curved cross-sectional outline. During this design stage the part had to be split into two halves since there were no 3D printers capable of printing such a long (20 inch) part. A dovetail was added in the middle since the insert's metal outer layer would reinforce the intersection. The team's 3D Printing Lead made multiple section prints of the dovetailing and of the assembly ends to test tolerances and functionality before the final prints were made. To save manufacturing costs while meeting project requirements, the lead sliced the final assembly on Lulzbot Cura 3.6.37 for PLA (Poly-Lactic Acid), a 0.2mm layer height, two outer walls, a 10% gyroid infill, and with support structures used. Support structures were only needed in a few small sections. A 10% gyroid infill was deemed sufficient for unit strength while maximizing weight savings and reducing potential motor load. At the time the motor specifications had not been determined.

Other parts such as the motor shaft coupling, limit switch mounts, and shaft bearing mounts were 3D printed in PLA to various adapted settings. The motor shaft coupling was printed at a fine quality 0.1mm layer height and a stronger 60% gyroid infill; the mounts were printed at a normal quality 0.15mm layer height and a 10% gyroid infill. The motor shaft coupling and shaft bearing mounts were printed on an Ultimaker S3 FDM printer in the Clemons library 3D Printing lab. The limit switch mounts were printed on a Prusa MK2.5 FDM printer in the MAE MILL belonging to the UVA 3D Printing Club (Matthew Kim, the 3D Printing Lead, is an officer in the club). All were sliced in Ultimaker Cura 5.2.2/5.3; for the shaft bearing mounts a third-party support structures blocker extension was used in certain sections to ease in post-processing.

The goal of the electronics system was to create a simple program that would run a cleaning trip after a user prompts it to turn on. A limit switch at the top and bottom of the board was necessary, and two buttons. One button would be a designated On/Off button, the other button would be a Reset button, which would allow the user to return the wiper to start if it had been prompted to stop in the middle of a cleaning cycle. A L298N motor driver controller was used because it was capable of managing 30 volts. The motor was a 24 volt powered motor and needed at least 15 to 18 volts to run at a reasonable speed., The L298N also functioned as an H-bridge which allowed for the code to designate which direction the motor should spin. An Arduino Uno R3 was used to manage these interactions between switches, the motor driver controller, and the motor. Appendix C has a wiring diagram of all the electrical components used. The code used on the arduino can be referenced as a flowchart and writing code in Appendix D. The code creates variables to keep track of if the motor is running or not, or if the wiper blade is returning or not, and then checks if certain buttons have been pressed that would change the next instruction.

Final Solution

Final Design

The final design of the device is a wiper supported in a mount that rolls up and down aluminum rails by means of cables rotating around a copper shaft powered by a DC motor and controlled by an Arduino microcontroller. This design has several benefits over potential alternatives. The device requires only one motor. The cable system has the potential to allow for the design to be expanded to span across multiple panels without significantly increasing the cost of the device. All of the parts can readily be waterproofed or are already corrosion resistant. No open slots with lubricants present are required. There also aren't any large lubricated surfaces such as with a lead screw type design.

The device did meet the dimensional specification, occlusion specification, and was less than $600. In terms of being built to last against weather conditions such as sun, water, and snow, the prototype device did not meet the specification. Some materials chosen for the prototype are not weather resistant, such as the MDF used for the mounting plate. The original design called for an aluminum mounting plate, but for ease of fabrication, modification, and cost an MDF board was substituted in its place. The PLA plastic used in the 3D printed parts is not suitable for outdoor use due to likely deformation that would occur from prolonged exposure to the sun. In a commercial product these parts would need to be made from a plastic suitable for outdoor use. The electronics would also need to be weatherproofed, as well as the motor housing and bearing mounts.

Global, Social, Cultural, and Environmental (GSCE) factors and Public Health and Safety:

Public health and safety concerns were taken into account during the design process. The prototype was designed so that it would be light enough to not burden the roof trusses but heavy enough to not blow away in the wind. With regards to Global, Social, Cultural, and Environmental factors, this product is sustainable since it helps improve a renewable energy source over its lifetime. Even compared to the panels, the manufacturing inputs are comparatively low. The materials planned for product usage are expected to be easily recycled once separated. Those who will benefit most are those who own single-family homes and who can afford residential solar systems. It stands to reason that homeowners in developed countries will benefit more from this product than those in other nations.

Cost Analysis

In order to be marketable, the lifetime cost of the device must be cheaper per a given number of solar panels than the lifetime cost of manual cleaning the same number of solar panels. If the device is not cheaper for a consumer than manual cleaning, they won't buy it. The lifetime cost of manual cleaning depends on labor costs, the number of installed panels, the number of cleanings per year, and the total number of years. The lifetime cost of the automated solar panel cleaner solution depends on the ability of the system to span multiple panels in a single row and roof geometry permitting this span in order to reduce the total number of devices needed for one solar panel array (represented as number of devices), the cost per device, the annual inspection cost, the annual maintenance cost, and the number of years the system will be in operation. Below is a cost analysis of a hypothetical 24 panel solar array.

The cost of manual cleaning is highly dependent on the cost of labor, which varies greatly by region. For a 24 panel array the cost of manual cleaning is in the range of $15,600 - $30,000 over the course of 25 years, as shown in Table IV. As seen in Table V, The lifetime cost of the automated solar panel cleaning system for this array is below that range, but only when the number of devices can be reduced by having one device span across a row of solar panels and service multiple panels. Reducing the number of devices also keeps the initial cost lower.

Table IV: Estimated Manual Cleaning Lifetime Costs

Manual cleaning		Cost per cleaning	Average annual cost	Total lifetime cost
Number of panels	24			
Times per year	2			
Years	25			
Low cost per panel	$ 13.00	$ 312.00	$ 624.00	**$ 15,600.00**
High cost per panel	$ 25.00	$ 600.00	$ 1,200.00	**$ 30,000.00**

Table V: Estimated Automated Cleaning Lifetime Costs

Automated device		Initial cost	Average annual cost	Total lifetime cost
Number of panels	24			
Years	25			
Initial cost per device	$ 500.00			
Annual inspection cost	$ 225.00			
Average annual maintenance cost per device	$ 16.00			
Number of devices	1	$ 500.00	$ 245.00	**$ 6,625.00**
Number of devices	4	$ 2,000.00	$ 305.00	**$ 9,625.00**
Number of devices	6	$ 3,000.00	$ 345.00	**$ 11,625.00**
Number of devices	24	$ 12,000.00	$ 705.00	**$ 29,625.00**

Conclusion

Having constructed our device, we learned that it is able to perform the basic tasks required. It can traverse the span of a 20”x10” solar panel, with enough applied pressure to wipe the surface. It can do so using only one motor, and can be constructed fairly cheaply. To improve the device as it currently stands, the team can first replace the motor with a lower torque and higher speed motor. Doing so will speed up the cleaning process while also vastly reducing the cost of the motor. The system takes around nine minutes to complete a full cycle. The current motor is overpowered because its specifications were selected for use with tension springs which experience strain hardening, a problem which our constant-force negator springs do not suffer from. Another improvement that can be made is to reduce the weight and strength of our components.

The final assembly is currently overbuilt and far exceeds the strength requirements needed given our use of off-the-shelf components rather than custom parts. Therefore, in later iterations, we can focus on creating more custom components which lower material costs and sacrifice unnecessary robustness for weight saving. With these improvements, the team can expand the current idea — a wiper blade driven by a cable and winch — into something that can accommodate a larger panel array and range of customer conditions.

Future Work

The design can be consolidated into integral units. This will optimize the design for mass production and installation. Choosing weatherproof materials for implementation on actual solar arrays needs to be done, as well as developing methods for more cost efficient production of parts. Transitioning some of the off-the-shelf components into integrated custom parts is a next step. Additionally, work needs to be done to make the system modular and expandable such that it may be used on arrays of solar panels rather than a single one. The team will also brainstorm designs for a supplemental cleaning solution drip sub-system to assist in cleaning if requested by the customer.

Testing should be done to determine the efficiency of the device at cleaning different types of debris including dirt, pollutants, organic debris, and pollen. Any future improved device closer to a production model would also need to be tested for endurance and weather resistance. A closed loop feedback system may also be added. This system would ensure that debris is effectively removed from the panel surface, providing feedback on cleaning efficiency.

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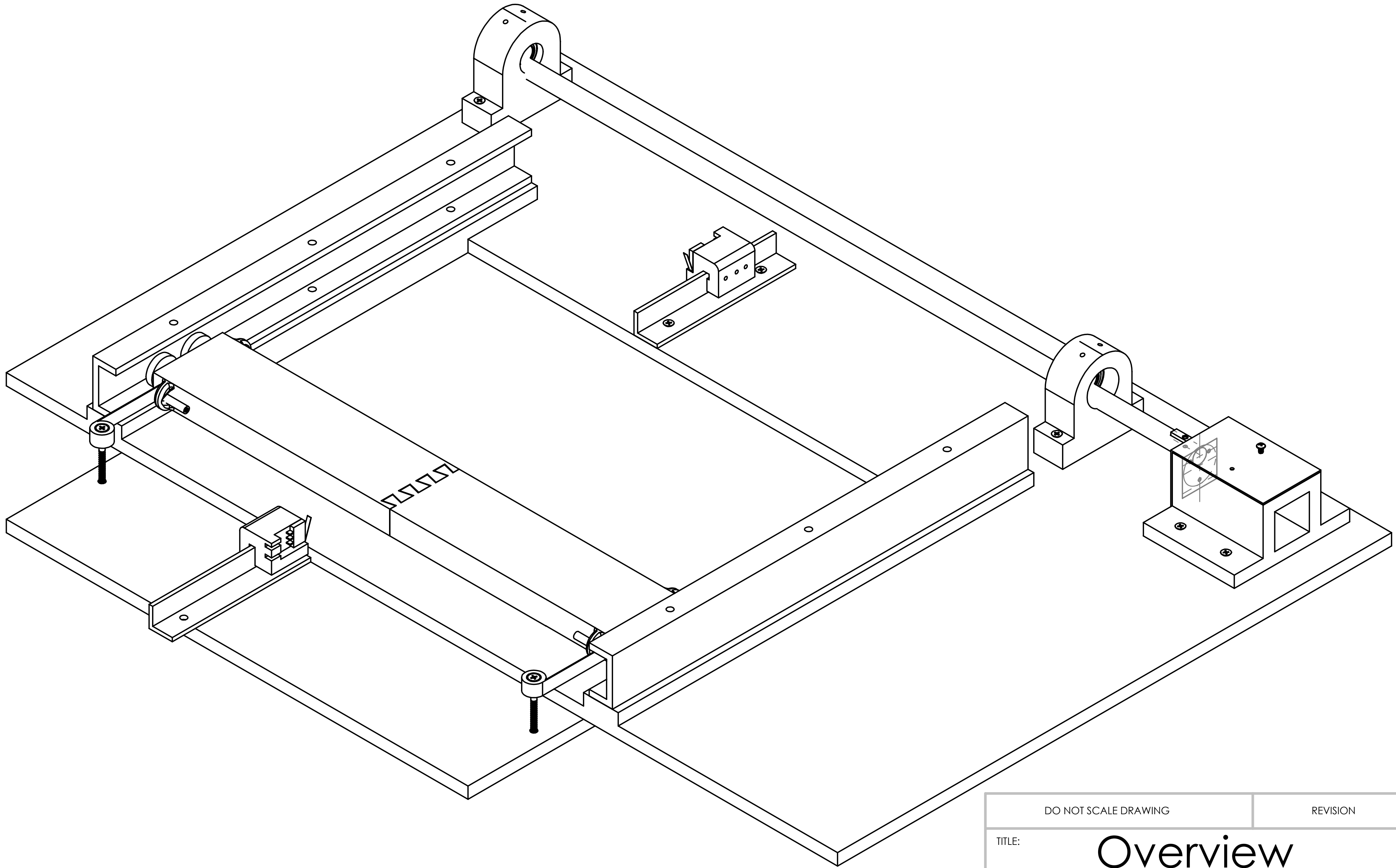
Appendix

Note: Appendices A-B are inserted sequentially.



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GROUP Hoos Wiping	A4
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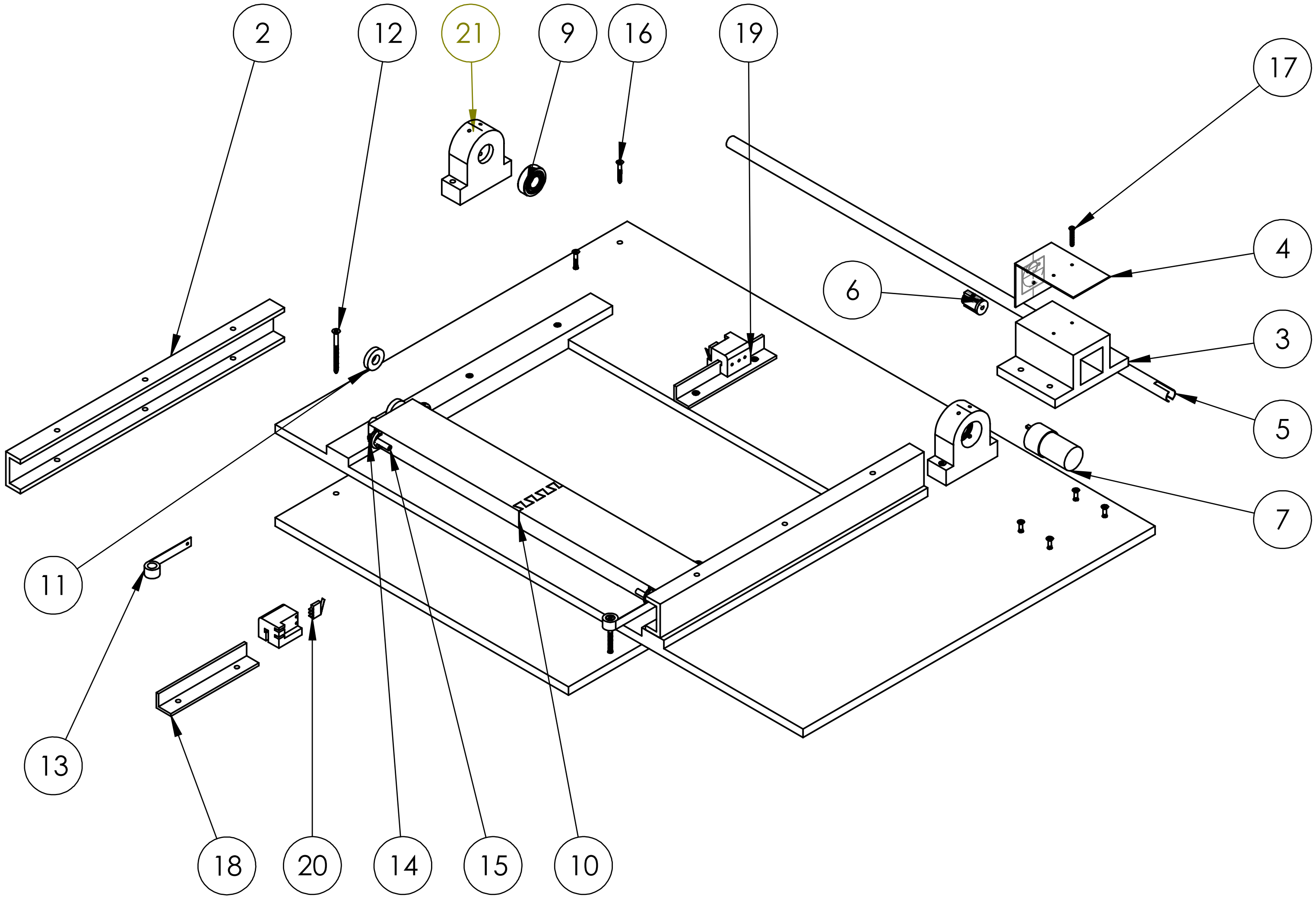
ITEM NO.	PART NUMBER	QTY.
1	Mounting Plate	1
2	Aluminum U-Channel	2
3	Motor Mount Body	1
4	Motor Mount Plate	1
5	Copper Pipe	1
6	Shaft Coupling	1
7	DC Motor	1
9	R10 Bearing	2
10	Wiper Assembly	1
11	R8 Bearing	4
12	#10 2-1/2 wood screw	2
13	NegatorSprings	2
14	#6 1/2 in bolt	2
15	#6 1 in standoff	2
16	#8 1-1/4 wood screw	16
17	#6 1-1/2 in screw	1
18	Limit Switch Rails	2
19	Limit Switch Mount (includes M3 Hex nut and screw)	2
20	Limit Switch	2
21	Bearing Mount	2



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Appendix C: Wiring Diagram

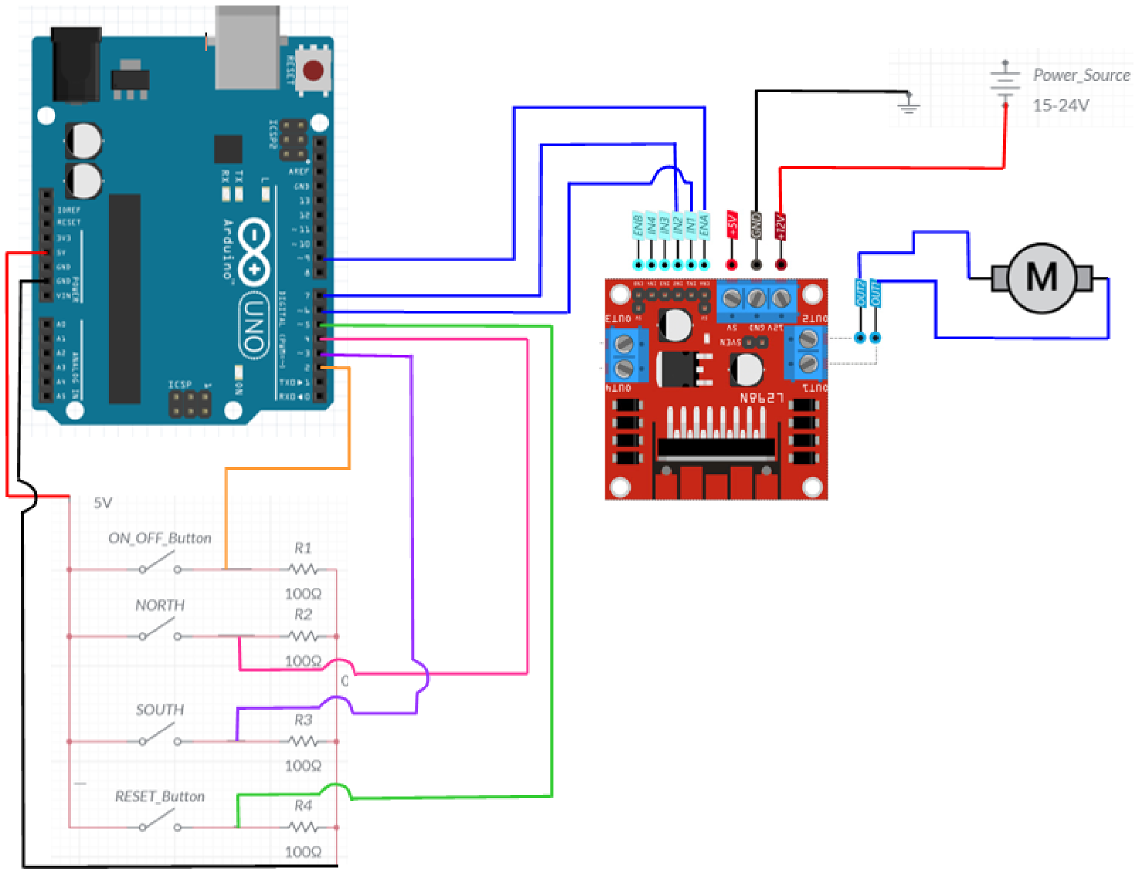


Figure C1. A wiring diagram of the Arduino, four switches, L298N, power supply, and motor.

Appendix D: Arduino Code

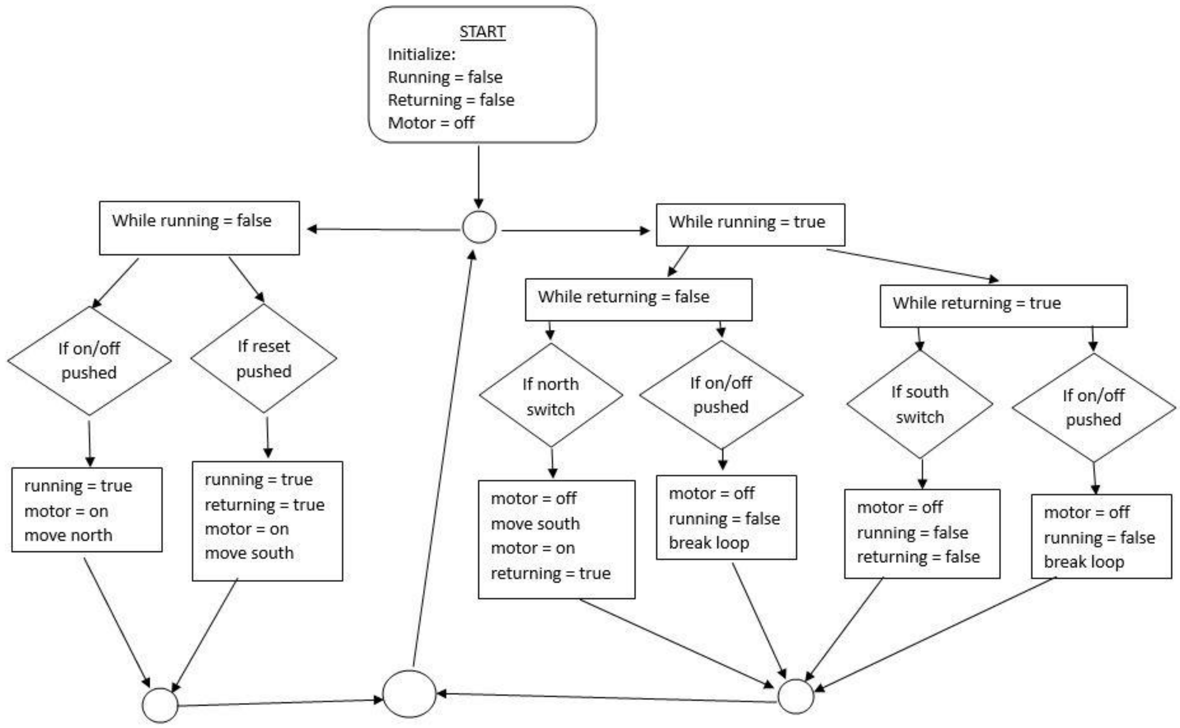


Figure D1. Flow chart of the arduino code logic.

D2: Arduino Code:

```
#define enA 9
#define in1 6
#define in2 7
#define reset_button 5
#define switch_north 4
#define switch_south 3
#define on_off_button 2

bool running = false;
bool returning = false;

void setup() {
  pinMode(enA, OUTPUT);
  pinMode(in1, OUTPUT);
  pinMode(in2, OUTPUT);
  pinMode(reset_button, INPUT);
  pinMode(switch_north, INPUT);
  pinMode(switch_south, INPUT);
  pinMode(on_off_button, INPUT);
  // Set initial rotation direction
  digitalWrite(in1, LOW);
  digitalWrite(in2, LOW);
```

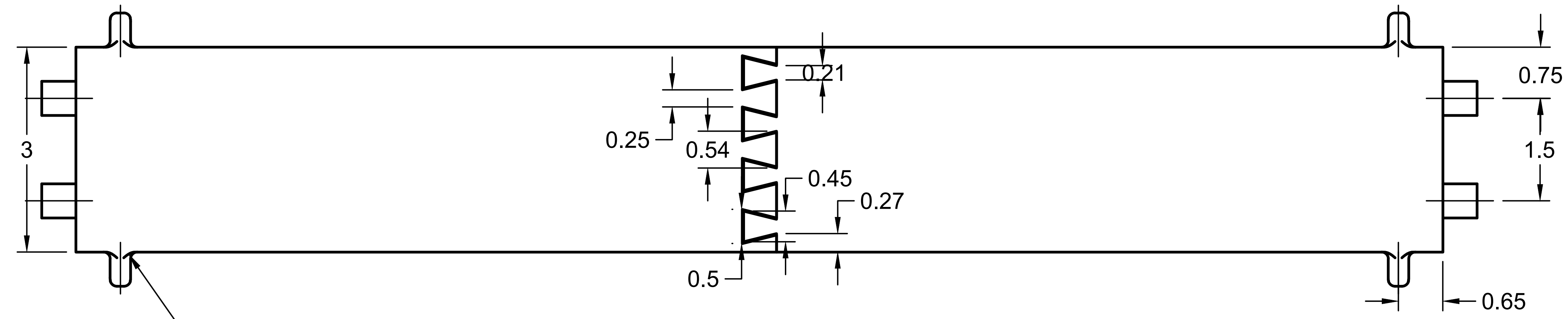
```
}

void loop() {
  // Send PWM signal to L298N Enable pin
  while (running == false) {
    if (digitalRead(on_off_button) == true) {
      digitalWrite(in1, LOW);
      digitalWrite(in2, HIGH);

      analogWrite(enA, 255);
      running = true;
      delay(400);
    }

    else if (digitalRead(reset_button) == true) {
      digitalWrite(in1, HIGH);
      digitalWrite(in2, LOW);

      analogWrite(enA, 255);
      running = true;
      returning = true;
      delay(400);
    }
  }
  while (running == true) {
    while (returning == false) {
      if (digitalRead(switch_north) == true) {
        digitalWrite(in1, LOW);
        digitalWrite(in2, LOW);

        analogWrite(enA, 0);
        delay(800);

        digitalWrite(in1, HIGH);
        digitalWrite(in2, LOW);

        analogWrite(enA, 255);
        returning = true;
        delay(100);
      }
      else if (digitalRead(on_off_button) == true) {
        digitalWrite(in1, LOW);
        digitalWrite(in2, LOW);

        analogWrite(enA, 0);
        running = false;
        delay(500);
        break;
      }
```

```
    }
    while (returning == true) {
      if (digitalRead(switch_south) == true) {
        digitalWrite(in1, LOW);
        digitalWrite(in2, LOW);

        analogWrite(enA, 0);
        returning = false;
        running = false;
        delay(500);
      }
      else if (digitalRead(on_off_button) == true) {
        digitalWrite(in1, LOW);
        digitalWrite(in2, LOW);

        analogWrite(enA, 0);
        running = false;
        delay(500);
        break;
      }
    }
  }
}
```

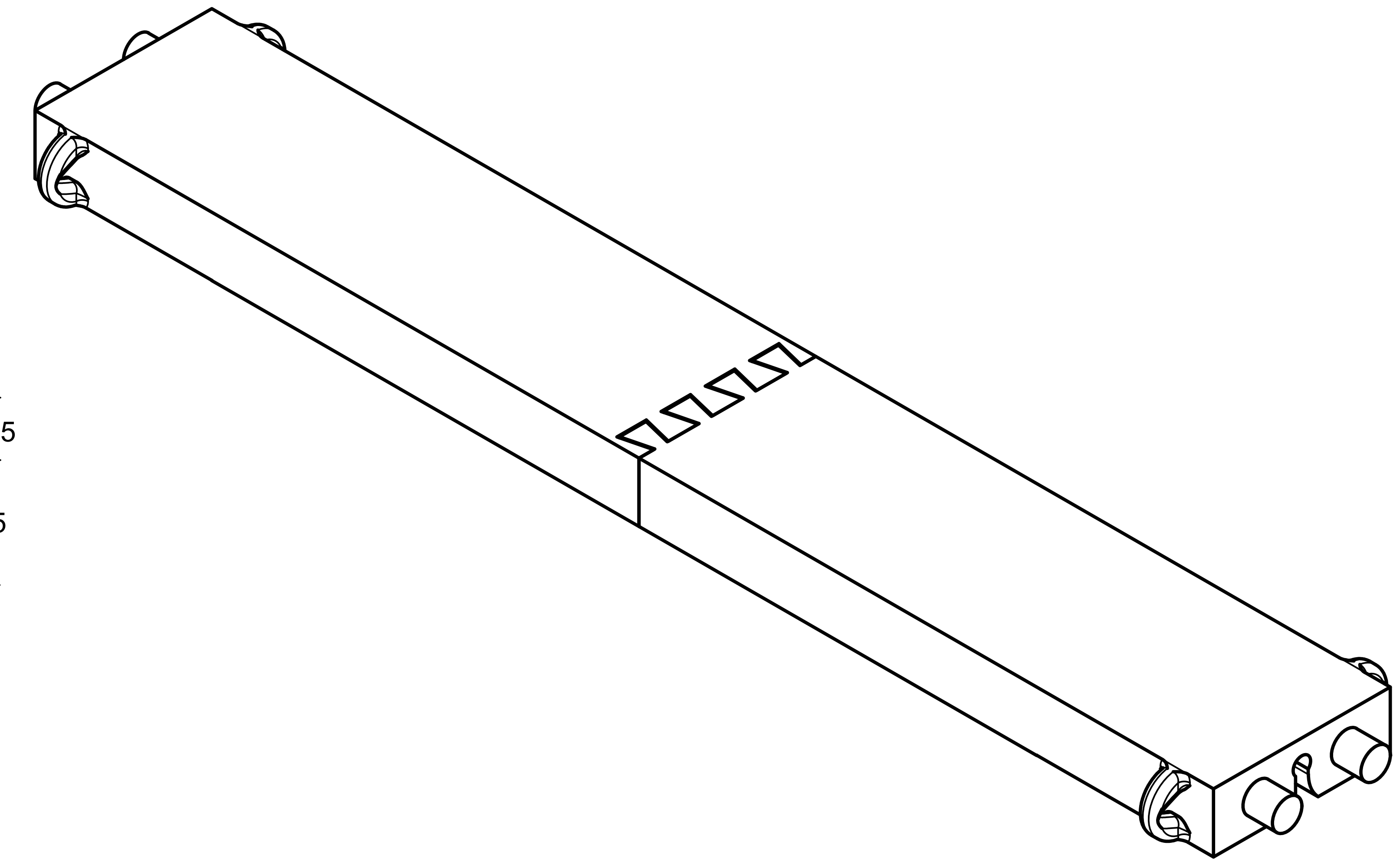
Note: Appendixes E-K Inserted Sequentially

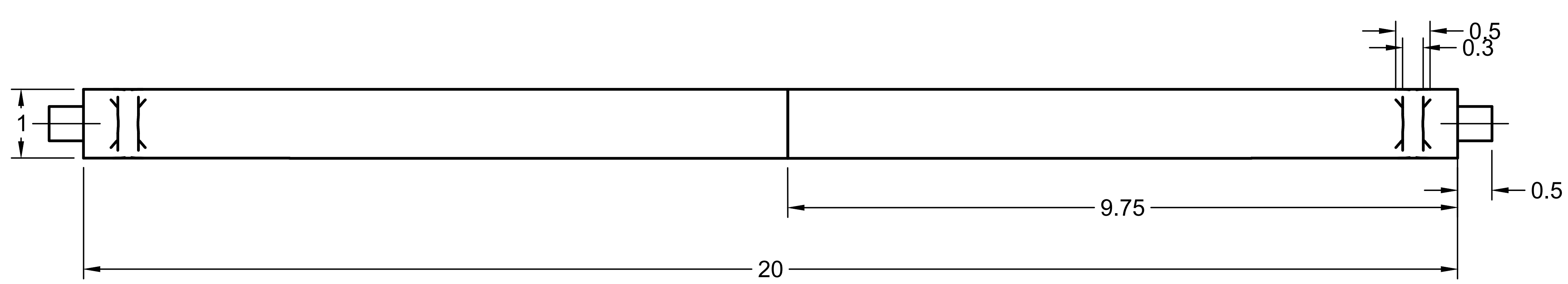
Appendix E: Wiper Assembly Detailed Drawing
Appendix F: Mounting Plate Detailed Drawing
Appendix G: Mounting Plate Face Details Drawing
Appendix H: Motor Mount Detailed Drawing
Appendix I: Limit Switch Mount Detailed Drawing
Appendix J: Shaft Coupling Detailed Drawing
Appendix K: Bearing Mount Detailed Drawing

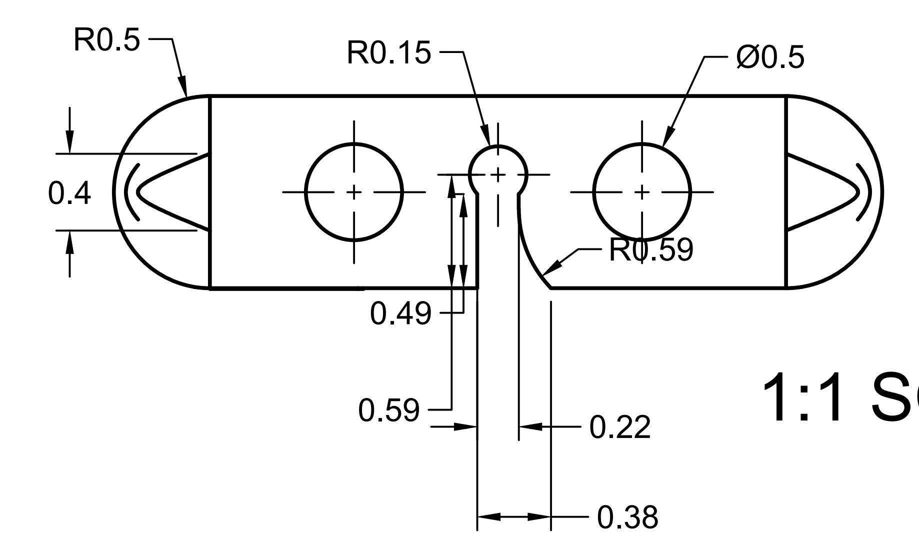
0.02 in/0.5mm gap on all three sides of dovetails. Left side has the smaller dovetails.



0.1 inch fillets for all holes

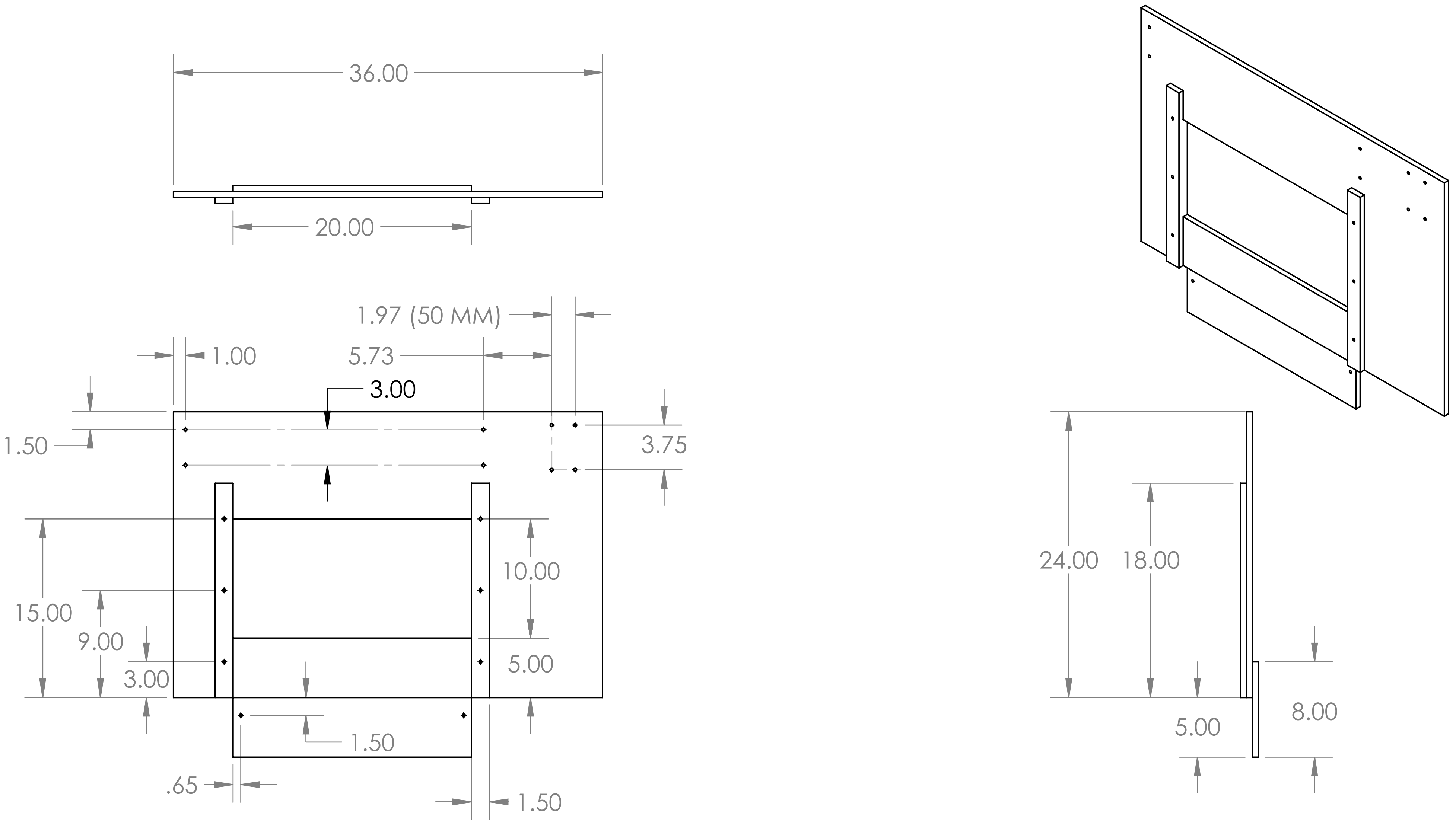






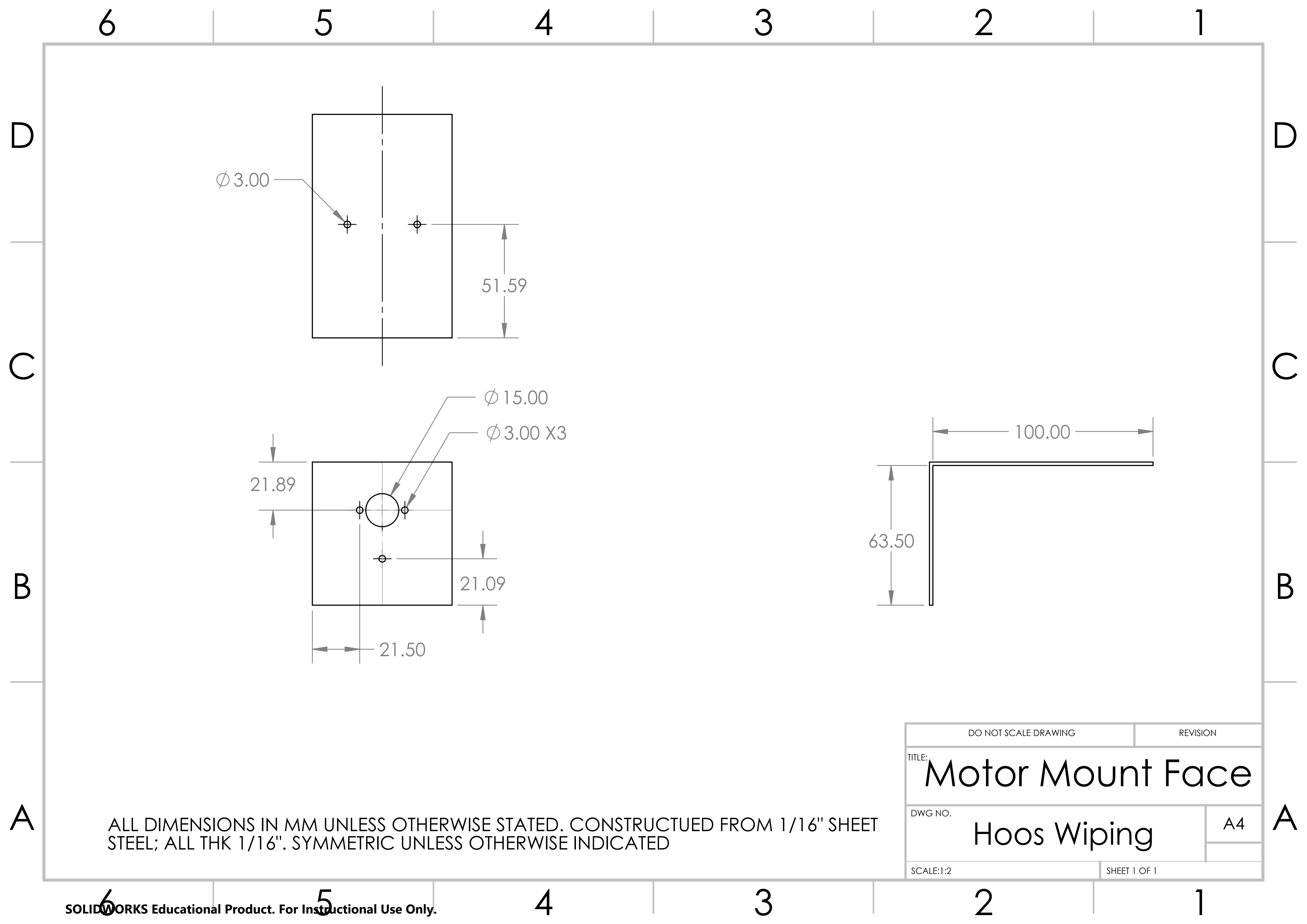
1:1 SCALE

PROJECT	Wiper Attachment		
TITLE	Wiper Attachment V19 No Wiper Blade ABS Plastic assuming 100% infill		
APPROVED	SIZE: C	CODE: MAE 4620	DWG NO	REV: 2
CHECKED			
DRAWN: Matt Kim, 02/18/2023	SCALE 1:2	WEIGHT 34.8 oz	SHEET 1/1



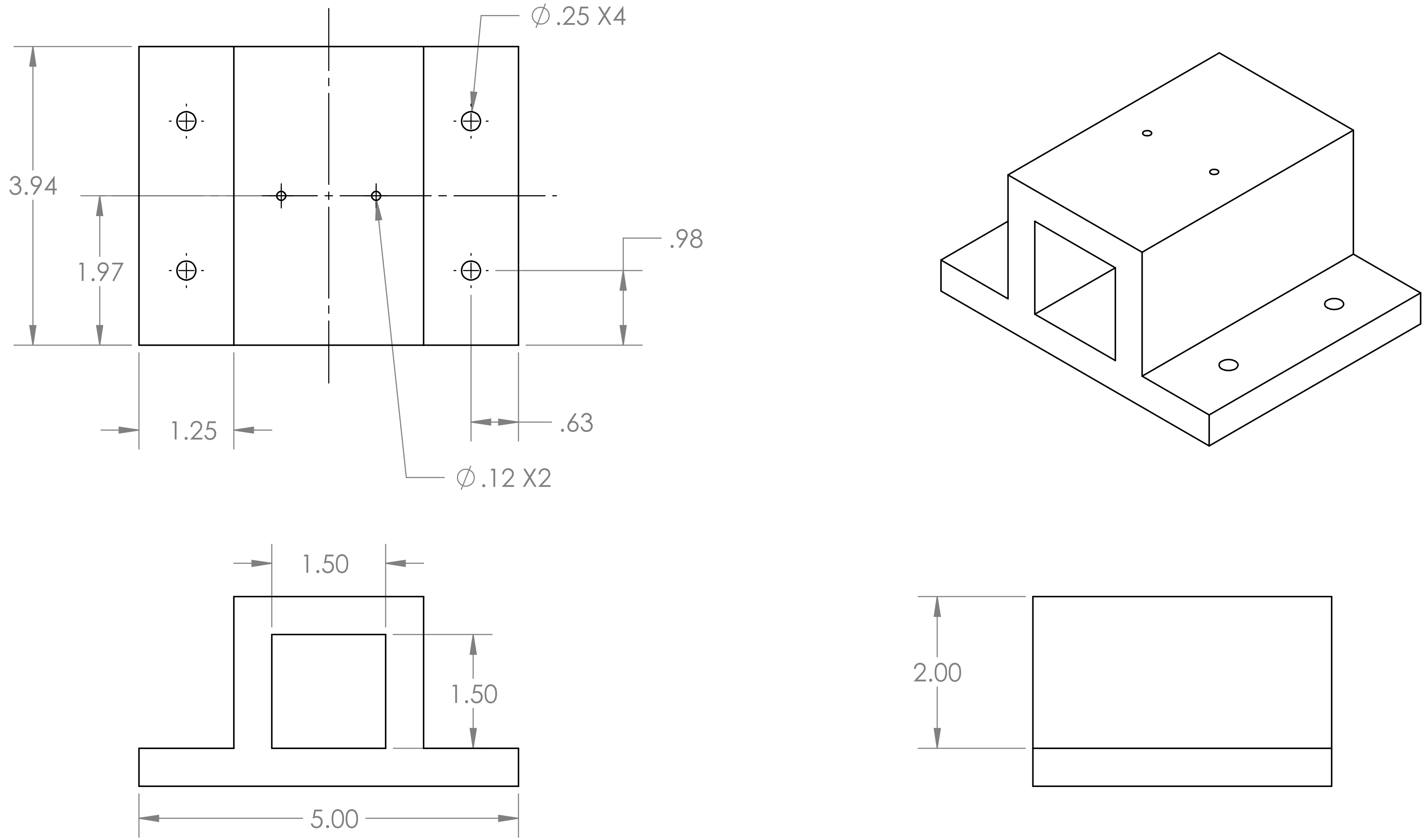
ALL THICKNESSES 1/2 IN MDF. ALL HOLES 0.25 IN. ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED

DO NOT SCALE DRAWING	REVISION
TITLE: Mounting Plate	
DWG NO. Hoos Wiping	A4
SCALE:1:12	SHEET 1 OF 1



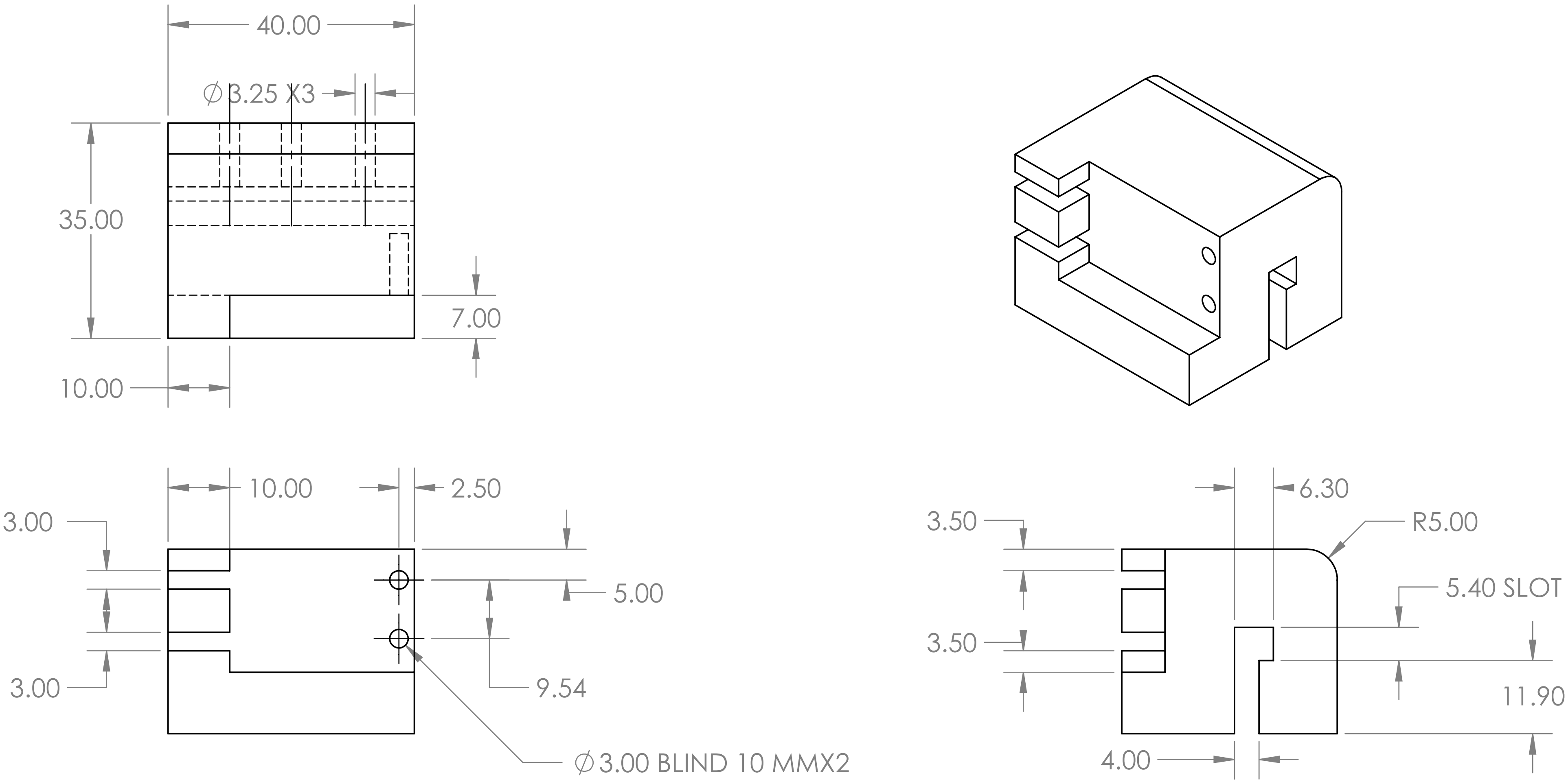
ALL DIMENSIONS IN MM UNLESS OTHERWISE STATED. CONSTRUCTUED FROM 1/16" SHEET STEEL; ALL THK 1/16". SYMMETRIC UNLESS OTHERWISE INDICATED

DO NOT SCALE DRAWING	REVISION
TITLE: Motor Mount Face	
DWG NO. Hoos Wiping	A4
SCALE:1:2	SHEET 1 OF 1



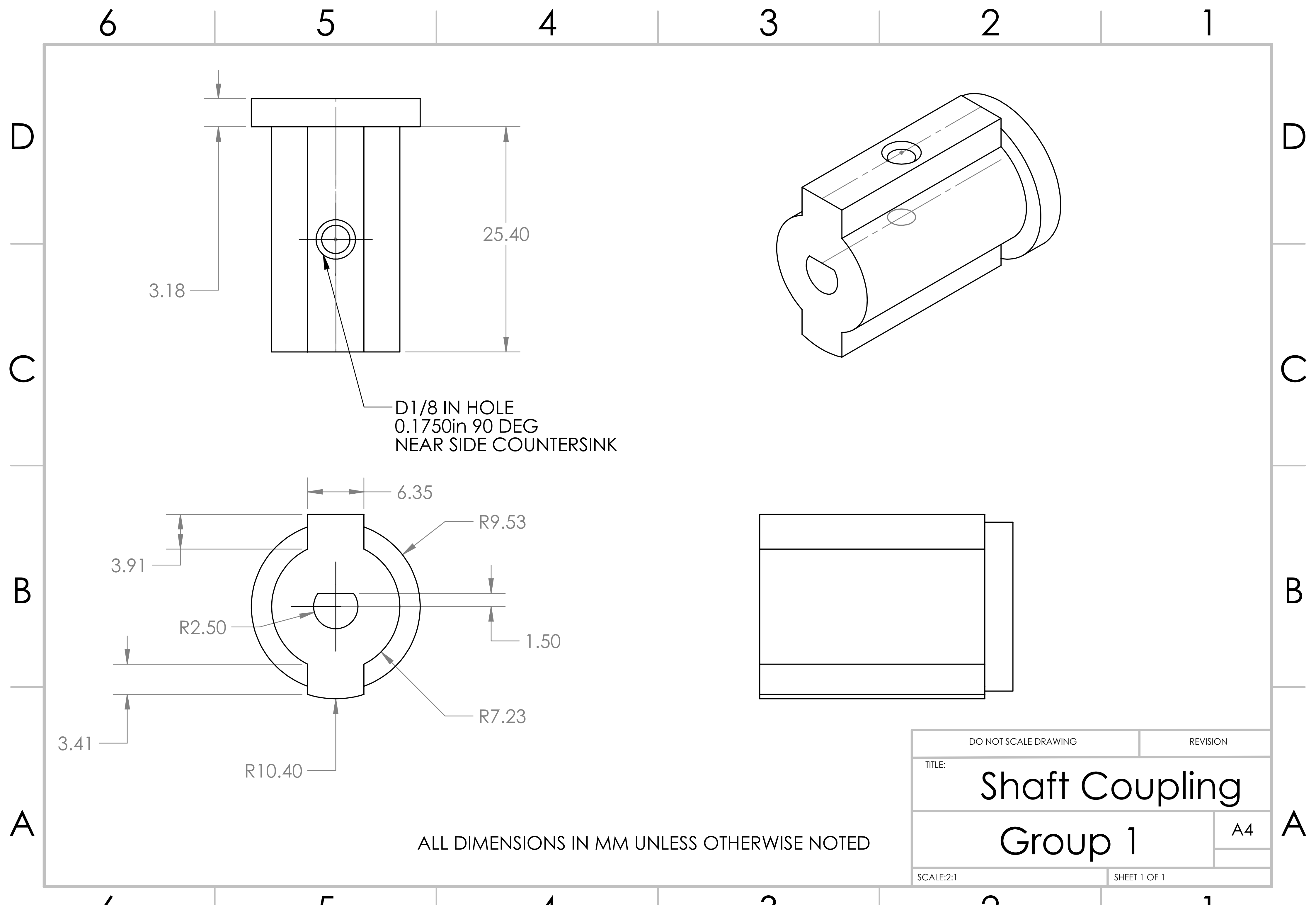
CONSTRUCTUED 0F 1/2" MDF BOARD GLUED TOGETHER; ALL THK 1/2". BASE FOR THE MOTOR MOUNT FACE PLATE. SYMMETRIC UNLESS OTHERWISE INDICATED. ALL DIMENSIONS IN INCHES UNLESS OTHERWISE INDICATED.

DO NOT SCALE DRAWING		REVISION
TITLE: Motor Mount Base		
GROUP Hoos Wiping		A4
SCALE:1:2	SHEET 1 OF 1	

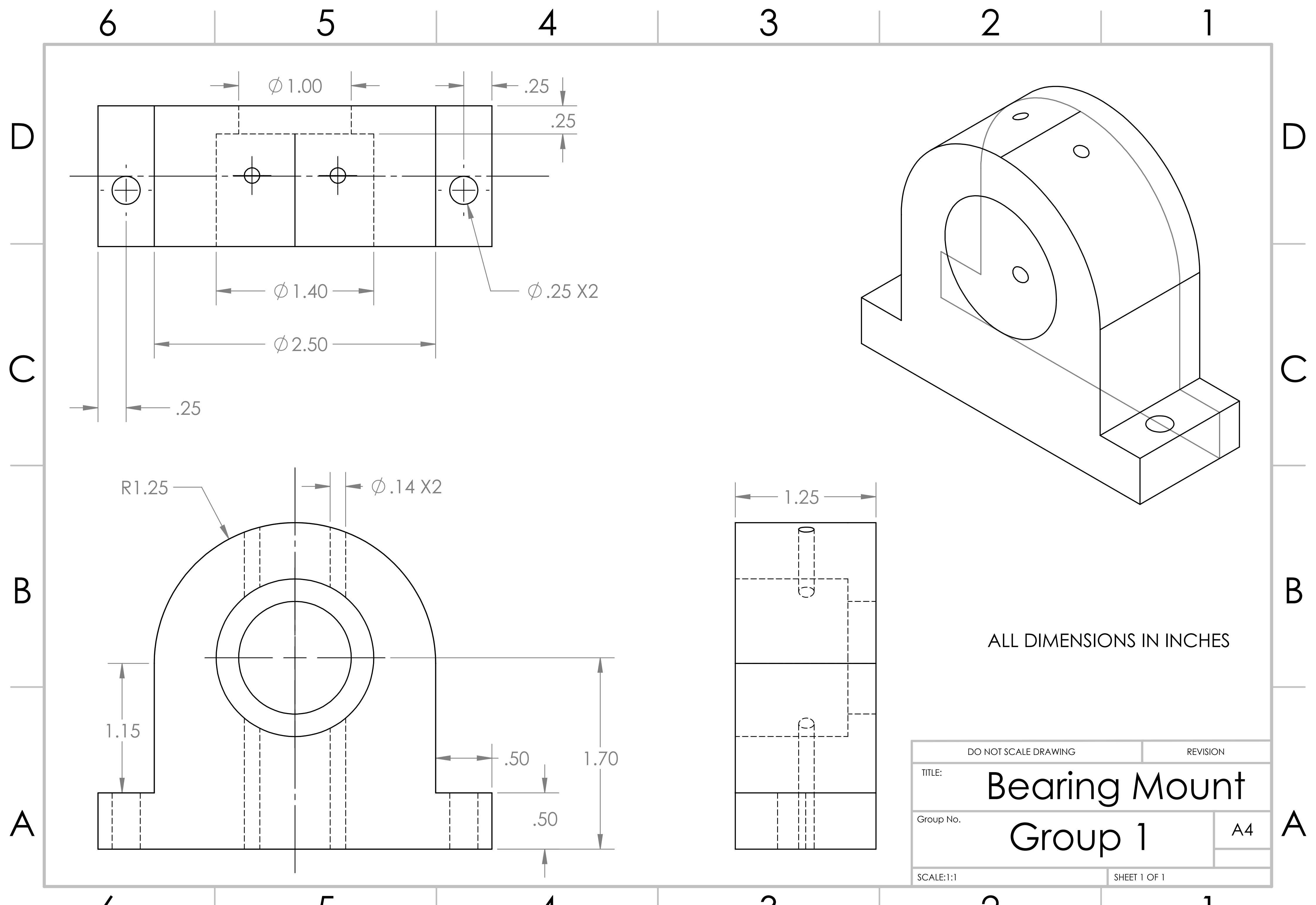


ACCEPTS M3 HEX NUT IN SLOT; M3 SCREW ACTS AS SET SCREW TO THE MOUNTING RAIL
ALL DIMENSIONS IN MM UNLESS OTHERWISE INDICATED

DO NOT SCALE DRAWING	REVISION
TITLE: Limit Switch Mounts	
GROUP Hoos Wiping	A4
SCALE:1:1	SHEET 1 OF 1



3.18
25.40
D1/8 IN HOLE
0.1750in 90 DEG
NEAR SIDE COUNTERSINK
6.35
R9.53
3.91
R2.50
1.50
R7.23
3.41
R10.40
ALL DIMENSIONS IN MM UNLESS OTHERWISE NOTED
DO NOT SCALE DRAWING
REVISION
TITLE:
Shaft Coupling
Group 1
A4
SCALE:2:1
SHEET 1 OF 1



Ø1.00
.25
.25
Ø1.40
Ø.25 X2
Ø2.50
.25
R1.25
Ø.14 X2
1.25
1.15
.50
1.70
.50
ALL DIMENSIONS IN INCHES
DO NOT SCALE DRAWING
REVISION
TITLE:
Bearing Mount
Group No.
Group 1
A4
SCALE:1:1
SHEET 1 OF 1

Appendix L: Initial Concepts and Concept Scoring Idea Selection

	Compressed on rollers
	Squeegee on rollers
	Squeegee on rotation
	Static
	Compressed air rotation

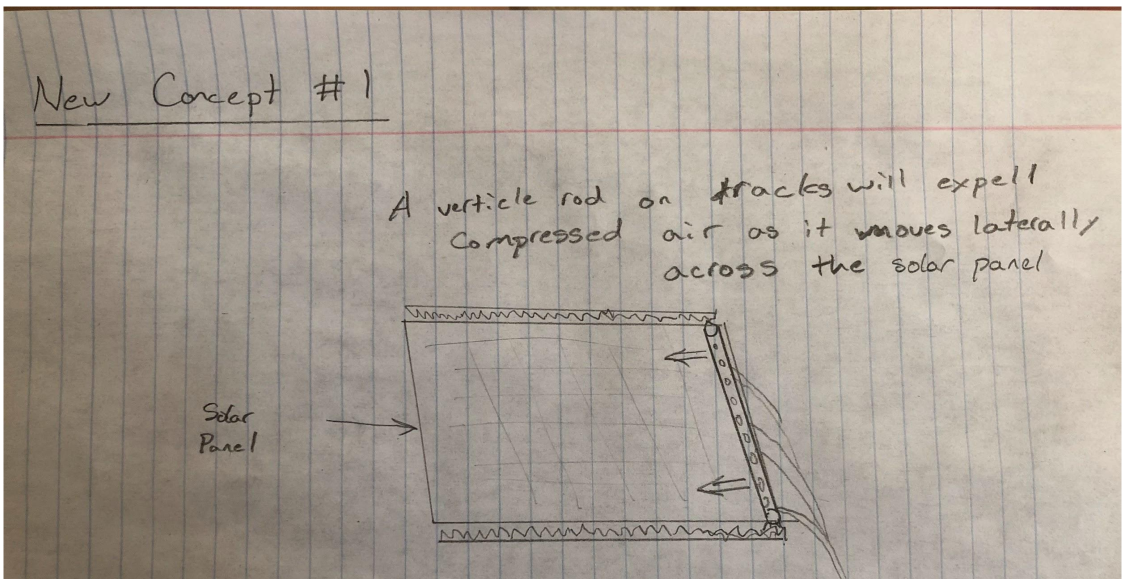


Figure L1: Compressed air on rollers

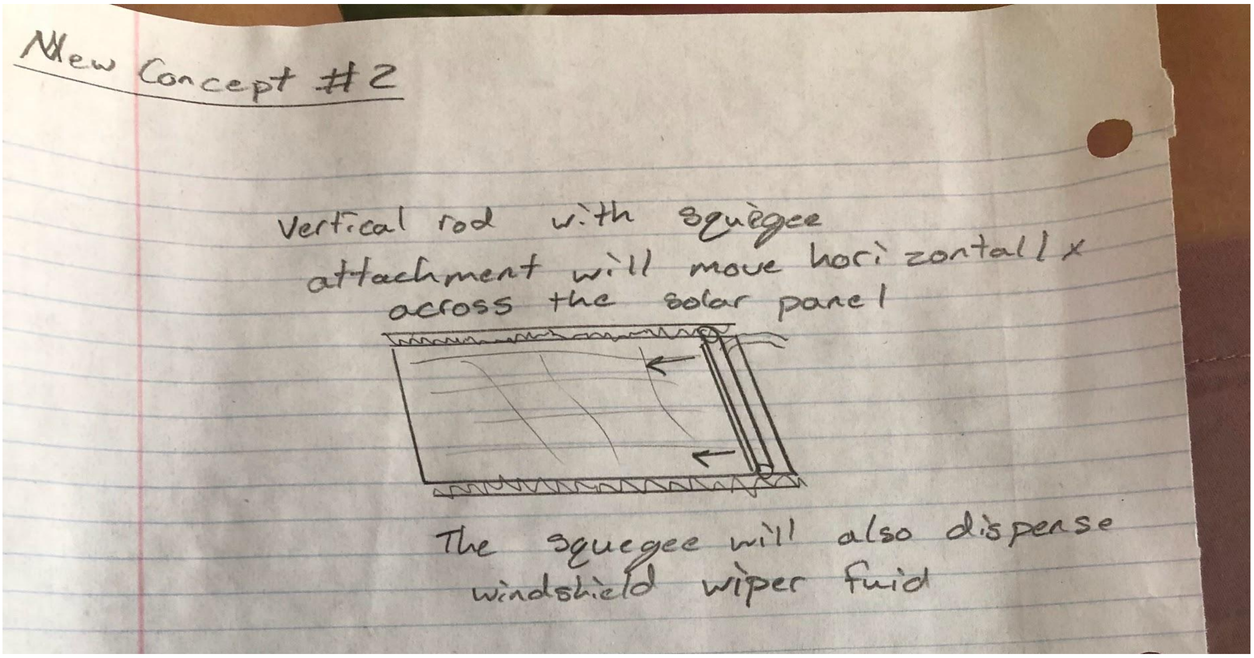


Figure L2: Squeegee on rollers

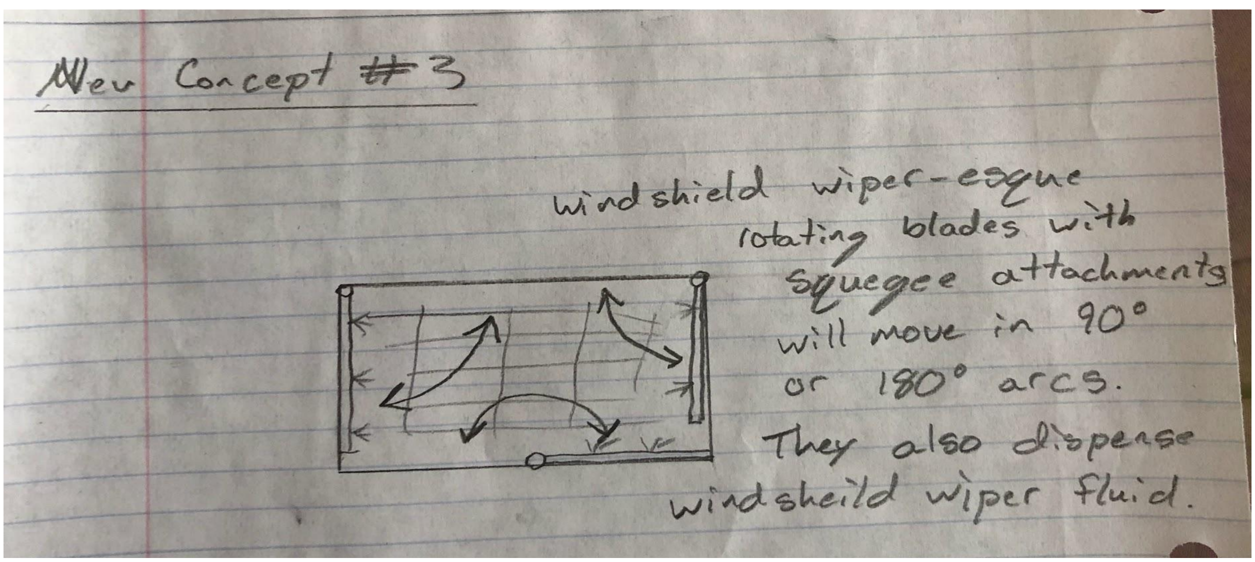


Figure L3: Squeegee on Rotation

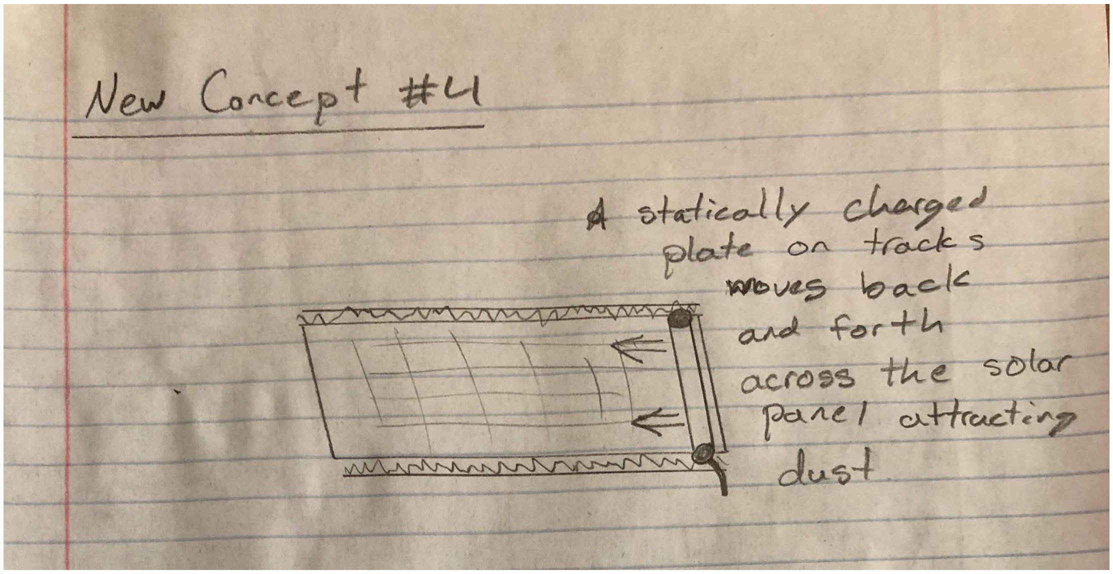


Figure L4: Static

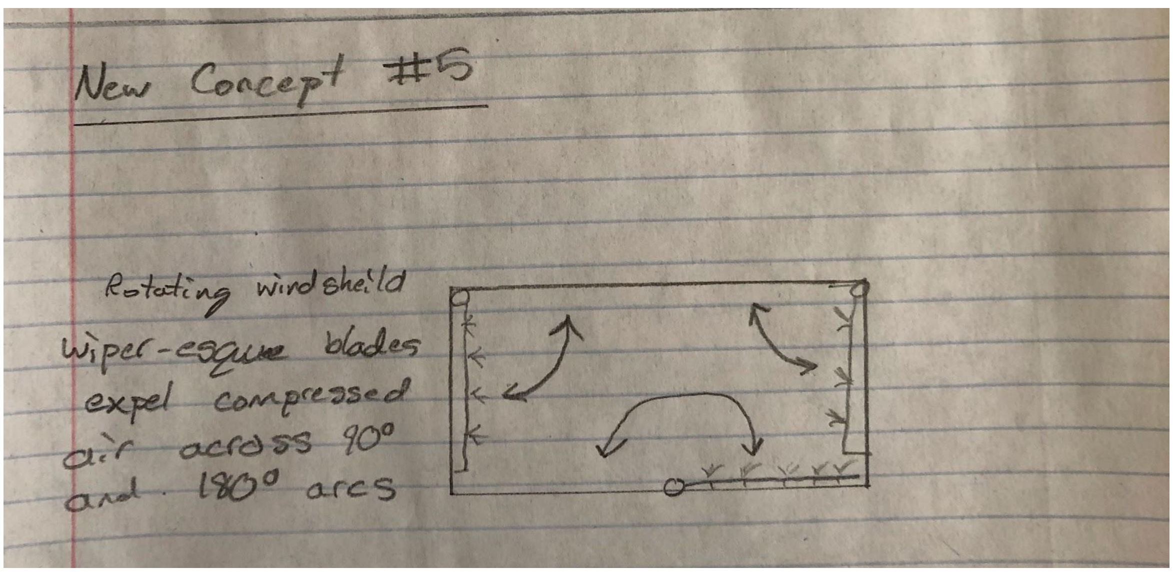


Figure L5: Compressed air rotation

Appendix M: Bill of Materials

Part number	Part name	Quantity	Manufacturing Method	Unit cost	Cost
W1000	Wiper Mount	1	3D print	$0.00	$0.00
SC1000	Shaft Coupling	1	3D print	$0.00	$0.00
BM1000	Bearing Mount	2	3D print	$0.00	$0.00
9001K984	Aluminum U-Channel	1	OEM	$60.30	$60.30
W1001	Wiper Blade	1	OEM	$5.99	$5.99
82862206	DC Geared motor	1	OEM	$122.34	$122.34
W1004	Motor Mount Body	1	Saw	$0.00	$0.00
W1014	Motor Mount Face	1	Saw	$0.00	$0.00
W1005	#10 2-1/2" Wood Screw	2	OEM	$0.12	$0.24
W1006	#8 1-1/4" Wood Screw	14	OEM	$0.08	$1.12
93882A148	6-32 1/2" Bolt	2	OEM	$0.24	$0.48
94355A222	6-32 1" Set Screw	1	OEM	$0.36	$0.36
MP001	MDF Mounting plate	1	Saw	$16.48	$16.48
A000066	Arduino Uno Rev3	1	OEM	$27.60	$27.60
MH04010	Motor shaft (1/2" Copper Pipe)	1	OEM	$12.73	$12.73
60355K505	R8 Bearings	4	OEM	$6.75	$27.00
9293K263	Negator Spring	2	OEM	$4.40	$8.80
60355K506	R10 Ball Bearing	2	OEM	$6.43	$12.86
91125A240	#6 Standoff 6-32	2	OEM	$4.34	$8.68
90107A033	1.25" OD Stainless Steel Washer	2	OEM	$0.18	$0.36
M000006	USB 2.0 Cable Type A/B	1	OEM	$7.60	$7.60
8923T115	50lb Test Cable	1	OEM	$8.30	$8.30
CECOMINOD012186	L298N Motor Drive Controller	1	OEM	$6.99	$6.99
MXR-PL-YBKG	Limit Switch	2	OEM	$5.99	$11.98
	Total				$340.21

Appendix N: Constitutive Equations and Load Calculations

Motor Torque:

$$T_{\text{motor}} = \frac{D_{\text{shaft}} \left(F_{\text{spring}} + \frac{W \ \sin(\theta)}{2} \right)}{2} \tag{1}$$

Bolt Stress due to Weight:

$$\sigma_{\text{bolt,tensile}} = \frac{W \ \sin(\theta)}{2 \, A_{\text{cross,bolt}} \, n_{\text{bolt}}} \tag{2}$$

Wind Load at 142 mph (as per Virginia 13VAC5-63-27):

$$F_{\text{wind}} = \frac{A_{\text{panel}} \, c \, \rho_{\text{air}} \, {v_{\text{wind}}}^2}{2} \tag{3}$$

Bolt Shear due to Wind Load:

$$\sigma_{\text{bolt,shear}} = \frac{F_{\text{wind}} \ \sin(\theta)}{A_{\text{cross,bolt}} \, n_{\text{bolt}}} \tag{4}$$

```
% Matlab Code to implement calculations

clear
clc

g = 9.8 ; % [m/s2]
m_WWACWA = 1.241709 ; %[kg] mass of the WWACWA
m_rollers =  19.28 / 1000 ; %[kg] mass of R8 rollers as per solidworks assuming plain carbon
steel
W = (m_rollers + m_WWACWA)*g ; %[N] weight of moving assembly, assume spring
weights negligible

roof_pitch_deg = 30 ; % [deg]
n_screw = 12 ; % [num screws]

screw_diam_root = 0.25 / 39.37 ; %[m]
A_screw = pi * (screw_diam_root/2)^2 ; % [m^2]
```

```
% assuming a 30* roof pitch:
stress_screw_shear = 0.5*W*sind(roof_pitch_deg) / (n_screw*A_screw); % [Pa]

% Calculate the stresses on screws due to Wind
%(accounts for panel and mounting plate, overestimate)
wind_speed_max = 142 /  2.237 ; % [m/s] use VA building code of 142 mph
A_wind = 660.4 * 546.1 / (1e6) ; %[m2] assume the dimensions given

C_d = 1.28 ; % drag coeff; assume head on, worst case scenario
D_air = 1.225 ; % [kg/m3] density of air STP
wind_load = 0.5*A_wind*C_d*D_air*(wind_speed_max^2) ; % [N]

stress_screw_wind_tensile = wind_load / (n_screw*A_screw) ; % [Pa]

pull_out_force_per_screw = wind_load / 12 ; % [N]

%% Tentative torque calculations
% assume that each spring exerts 10 lbf = 44.4822 ;
lbfToN_factor = 4.448 ;
negatorSpringForce = 2*lbfToN_factor % [N] force of each negator spring
springForce = 2*negatorSpringForce  ; % [N] each spring force assumed (overkill)
D_spindle = 0.015875 ; % [m] for 1/2 in copper pipe
T_Motor_Required = ((2*springForce) + ((W)*sind(roof_pitch_deg))*0.5)*(D_spindle/2) ; %
[N-m]
ForceOnString = T_Motor_Required / (D_spindle/2) % [N]

safetyFactor = (100*lbfToN_factor)/ForceOnString
```

% Results:

Stress on screws due to tensile load: **3.00+06 [Pa]**
Stress on screws due to shear load : **8.129e+03 [Pa]**
Pull-out force on each screw due to wind-load: **94.9 [N]**
Total force exerted on *both* springs : **38.7 [N]**
Required motor torque to resist gravity and spring force: **0.307 [N-m]**
Safety factor assuming failure due to cable snapping: **11.5**

Appendix O: Misc.

Figure O1. Current state of the art, manual labor.
(https://greensolver.net/top-tips-for-cleaning-solar-pv-modules/)

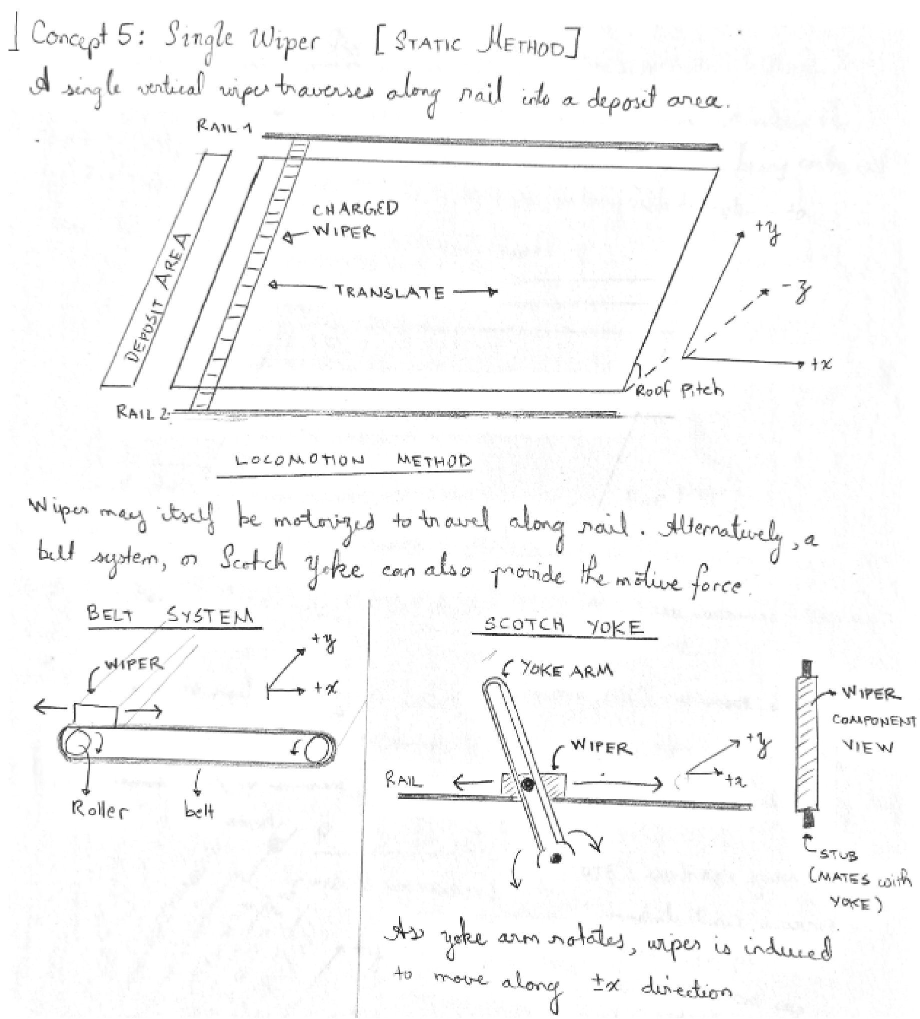


Figure O2. Example of roller on tracks. (Chris Le)

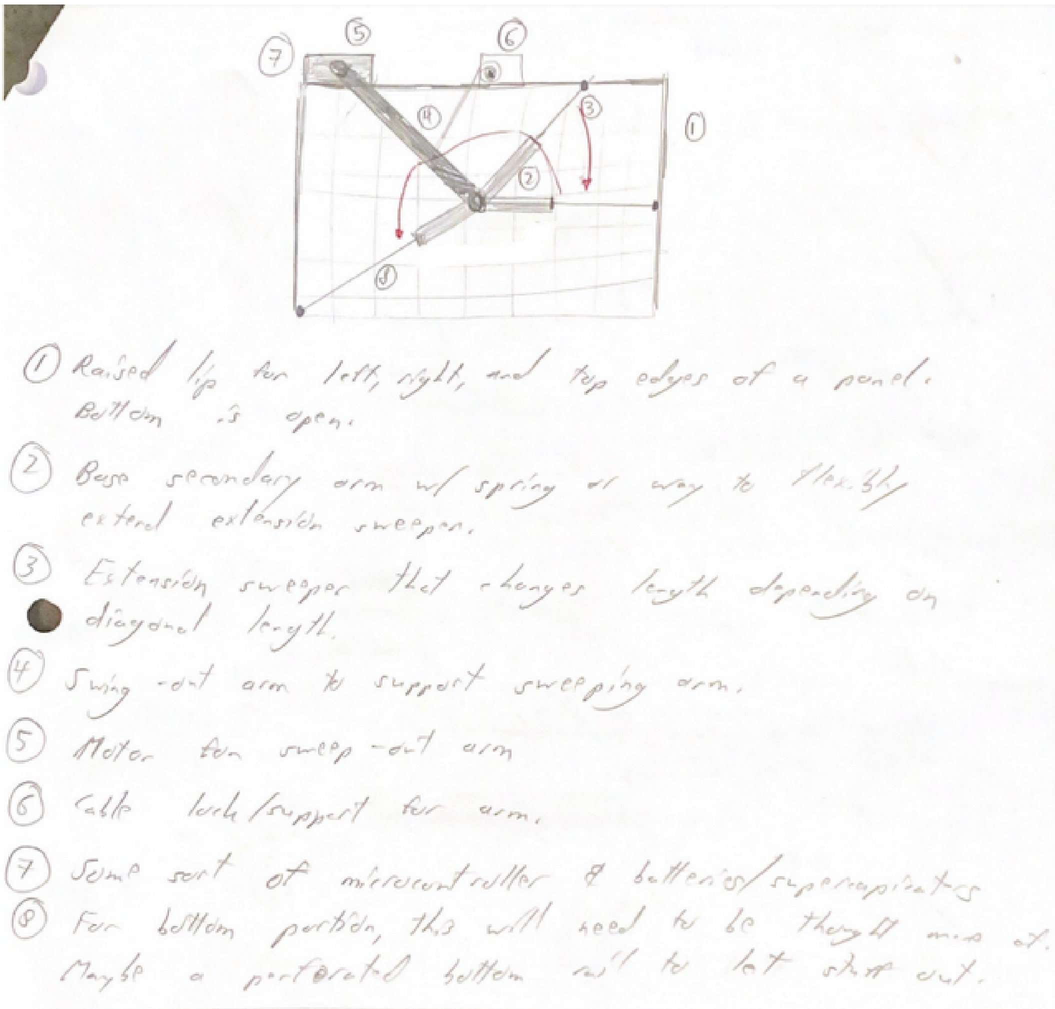
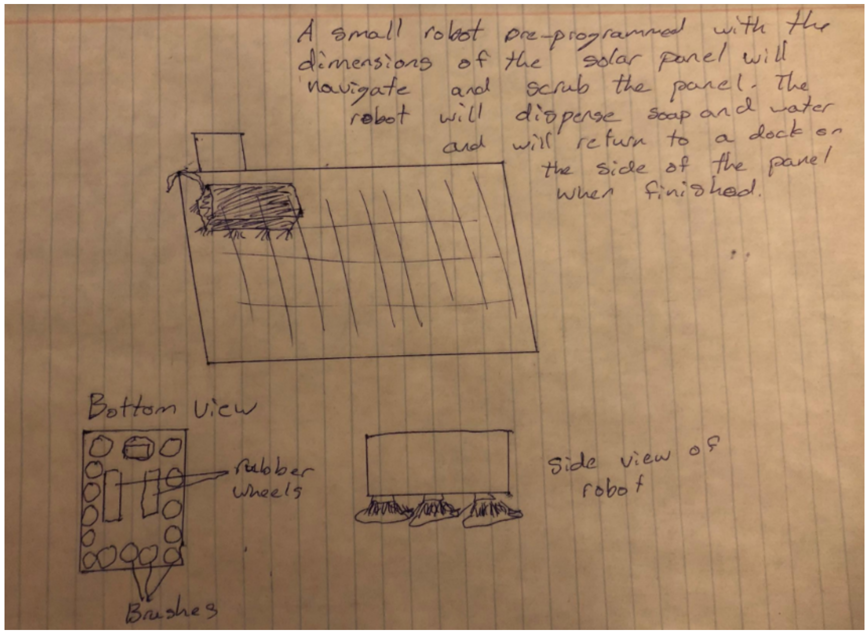
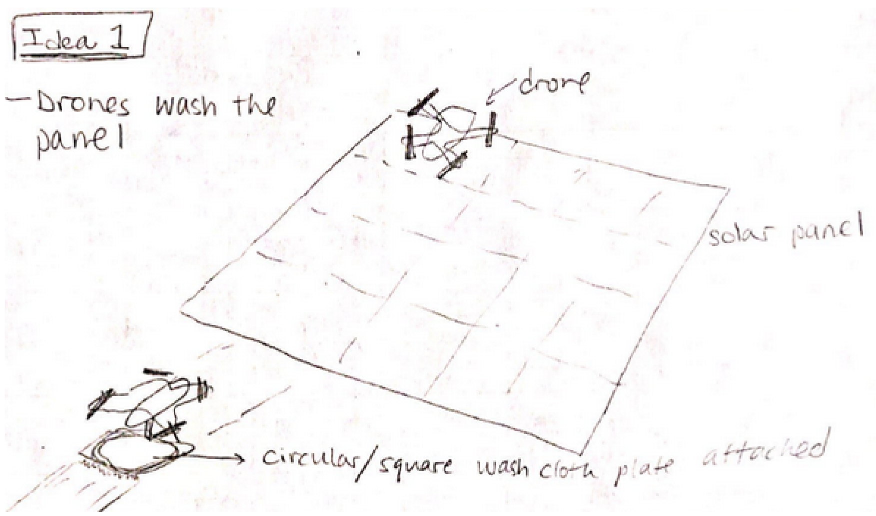


Figure O3. Example of Rotation (Matthew Kim)



a.



b.

Figure O4. Example of robot cleaner a. (Chris Davis) and b. (Nicole Piatko)

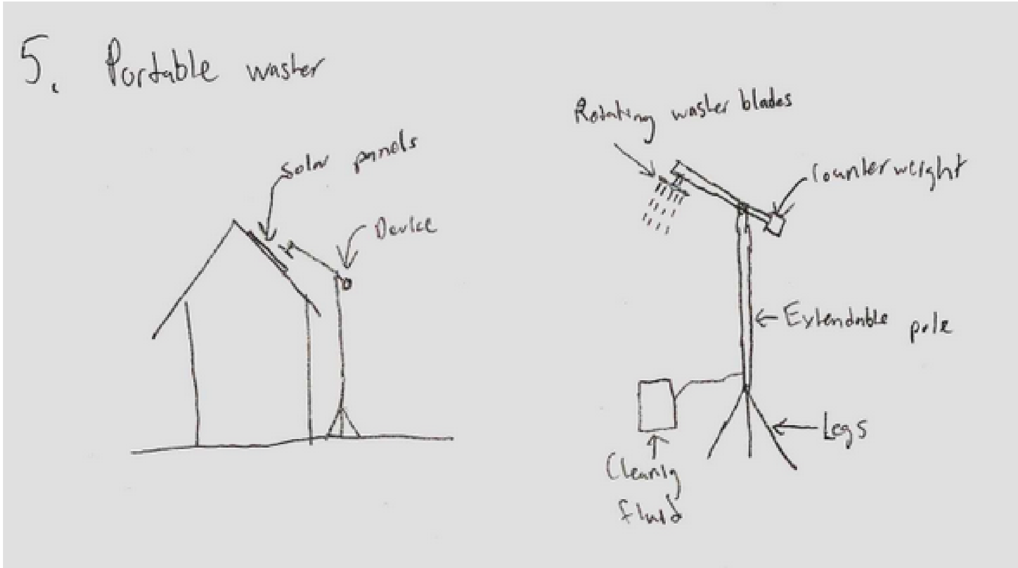


Figure O5. Example of portable assembly. (Dereck Habron)

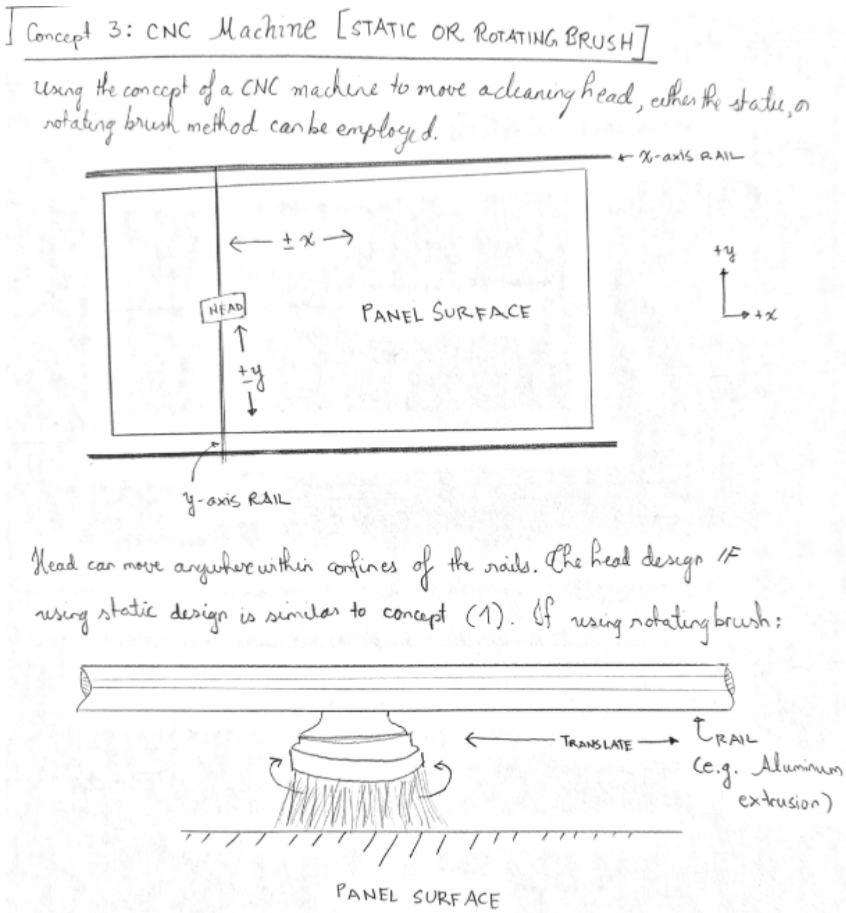


Figure O6. Example of CNC. (Chris Le)

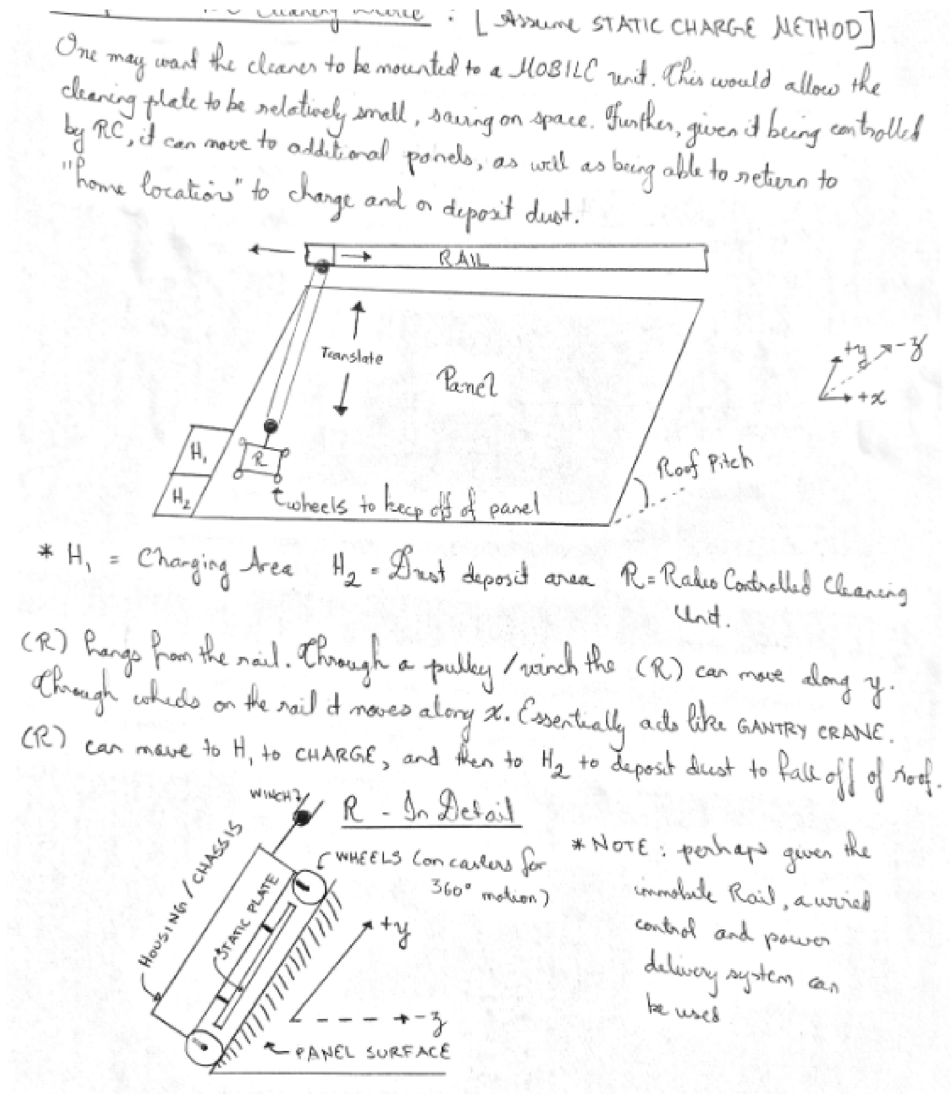


Figure O7. Example of static. (Chris Le)

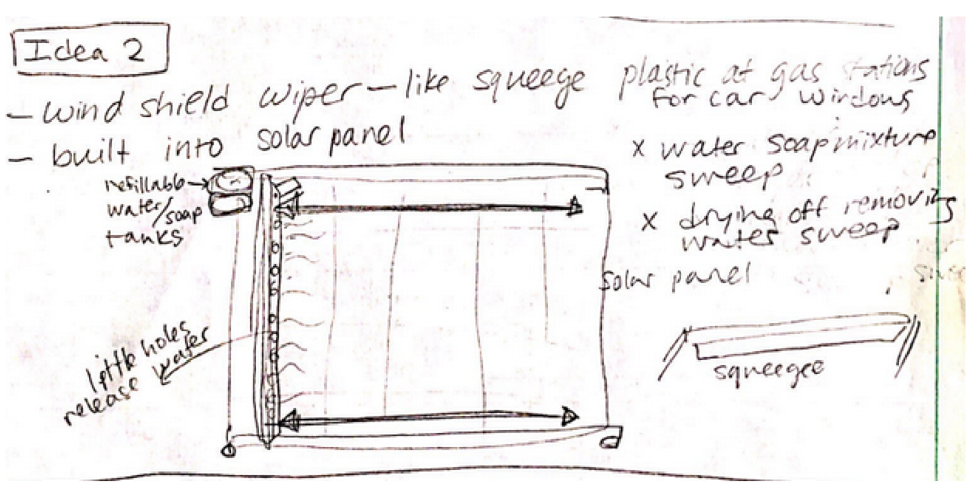


Figure O8. Example of Windshield Wiper, Squeegee. (Nicole Piatko)

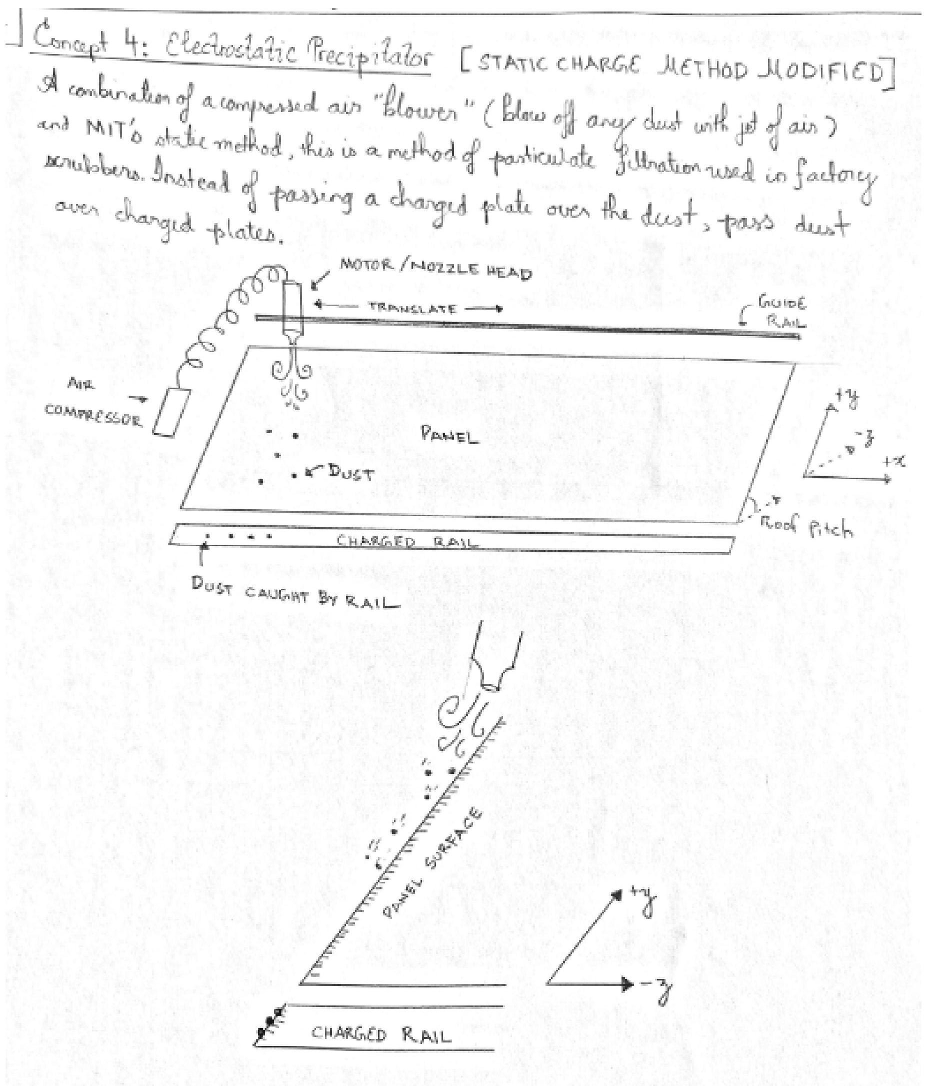


Figure O9. Example of Compressed Air. (Chris Le)

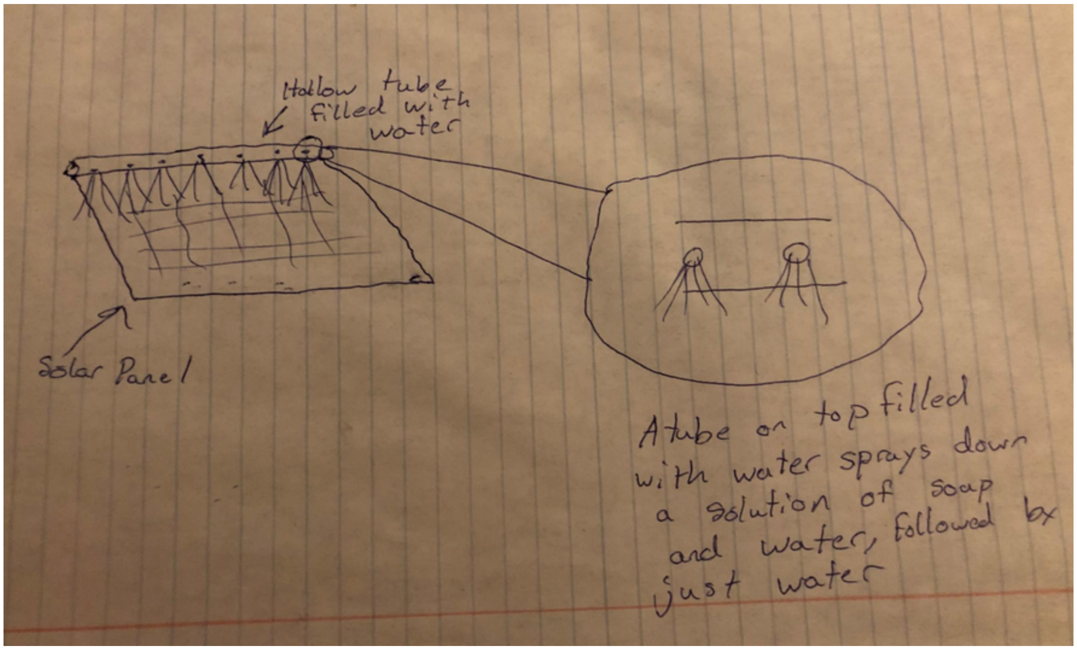


Figure O10. Example of Water Jet. (Chris Davis)

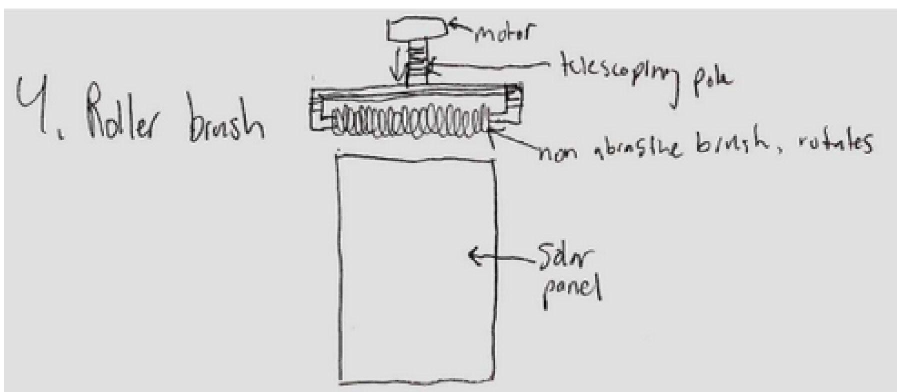


Figure O11. Example of brush. (Derek Habron)