Solar Panel Cleaner

ECE 445 Design Document - Spring 2025

Team # 26

Cameron Little (clittle5), Thomas Cai (wcai10), Geoffrey Swisher (swisher5)

Professor: Arne Fliflet

TA: Maanas Agrawal

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1 Introduction

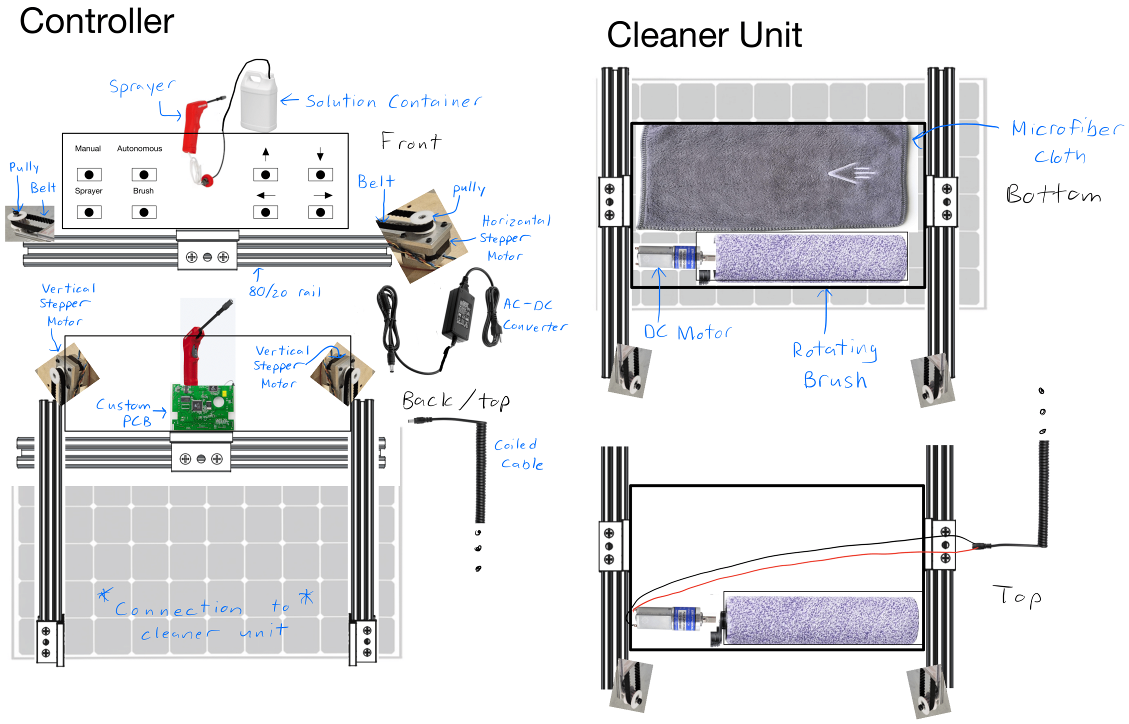
1.1 Problem

Solar panels are constantly exposed to environmental elements like dust, pollen, and even bird droppings, all of which can accumulate on the surface and block sunlight. Even partial shading or debris on the surface can reduce the panel's output power, especially if there is partial shading across individual cells due to a solar panel's properties. Manual cleaning of panels is labor-intensive and impractical for large arrays. In addition, improper cleaning can damage the delicate anti-reflective surface of solar panels, causing long-term performance degradation.

1.2 Solution

Our goal is to create an affordable, reliable, consistent, and adaptable solar panel cleaner to improve energy efficiency among solar panels on the roof of the ECEB. For demonstration purposes and proof of concept, we will demonstrate on a solar panel borrowed from the senior design lab from a previous year's project. This panel will be used due to space constraints in the lab as it is quite smaller, at 40.1 x 26.4 inches^2 in area. The panels on the roof are much larger, at 64.5 x 39.5 inches^2. With the help of the machine shop, we are designing a rail-based solar panel cleaner that have two degrees of motion: vertically and horizontally. The controller will sit at the top of the solar panel along a horizontal spanning rail to move the cleaner unit along the panel. The cleaner unit will be attached two rails spanning vertically to scale the cleaning unit up and down the panel. Both the controller unit and cleaner unit will be connected to a stepper motor, pulley system, and belt to guide them along the rails. The cleaning action is planned to have an interchangeable microfiber cloth, rotating brush, and cleaning solution dispenser.

1.3 Visual Aid



((a)) Visual Aid of Controller Unit

((b)) Visual Aid of Cleaner Unit

Figure 1: Pictorial representation of our solar panel cleaner with the controller and cleaner unit

The solar panel cleaner design, as seen in Figure 1, has the cleaning solution dispenser attached to the controller unit sitting at the top of the panel. This is to allow the spray to reach the panel section currently being cleaned by the cleaner unit. The user can manually press the button associated with the sprayer to dispense the cleaning solution. There are also buttons to turn on the rotating brush, as well as to move the panel in four directions. There are also three stepper motors and their associated pulleys and timing belts. A coiled cable is connected from the controller PCB to the DC motor in the cleaner unit to provide power for the brush to spin and clean the panel.

1.4 High Level Requirements

- The user can switch between manual and autonomous modes for the cleaning unit to run on without needing to restart the cycle.
- The cleaner must complete a full vertical sweep (top to bottom and back to top) in under 10 minutes.
- Have the cleaning system implementation work for its entirety without damaging the solar panel surface; the sprayer dispenses solution on the panel, the brush is able to spin on the cleaner unit, and the microfiber cloth picks up leftover debris.

2 Design

2.1 Block Diagram

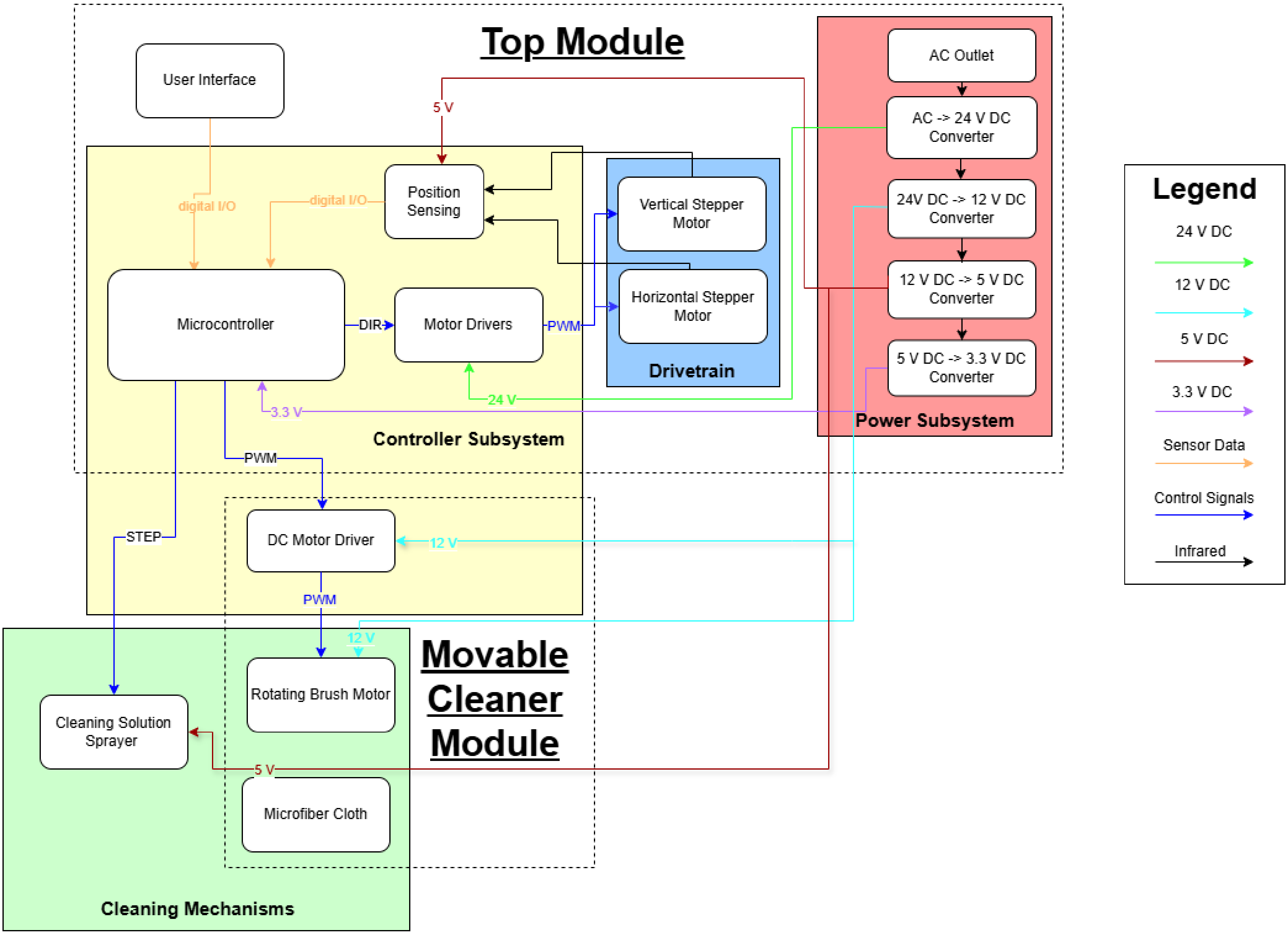


Figure 2: Block diagram of solar panel cleaner

2.2 Physical Design

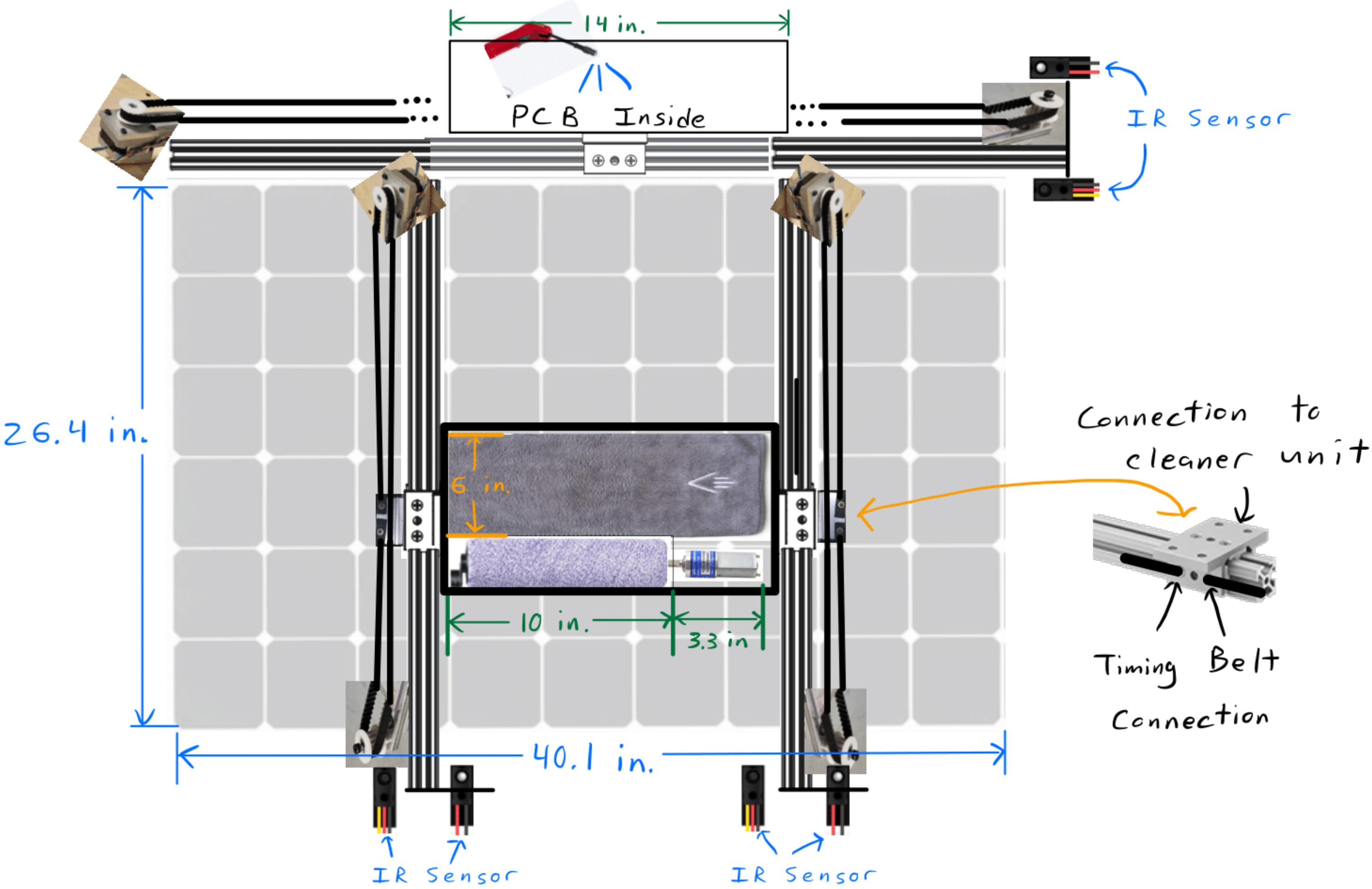


Figure 3: Physical Design of solar panel cleaner

The physical design of the solar panel cleaner consists of a horizontal rail spanning the top of the solar panel. This would likely extend at least 3.3 inches beyond the end of the panel to clean all the cells horizontally. There also are two vertical rails that span 26.4 inches of the solar panel. They will most likely extend beyond the panel by at least 8 inches for the cleaner unit to reach the bottom of the panel. This will allow for full coverage of the 40.1 x 26.4 inches^2 area of the panel. The cleaner unit will be at least 13.3 inches wide to house the entire brush and motor. Note that the machine shop is designing a jig to connect the motor to the brush, so it may be larger than 13.3 inches. The cleaner unit will also have a microfiber cloth, which will be around 6 inches wide. Thus, the entire cleaner unit module will be around 14 x 9 inches^2. Infrared sensors are mounted at each corner of the frame to assist with boundary detection. This will allow for the system to detect the edges of the panel surface and adjust motion accordingly. The drivetrain incorporates a timing belt mechanism, which connects to the cleaning unit and enables precise horizontal motion across the panel.

2.3 Subsystem Overview

The solar panel cleaner is divided into four subsystems: power, controller, drivetrain, and cleaning mechanisms. Each subsystem is necessary for the project to work and interacts with other subsystems to solve the initial problem.

Seen in Figures 4 and 5 is the initial PCB design for the solar panel cleaner. It contains the power subsystem as well as the controller subsystem. Note that one of the DC-DC converters did not have a footprint available, so a custom one was made. The 3D CAD model was not made, however. The mechanical components are still being developed with the help of the machine shop.

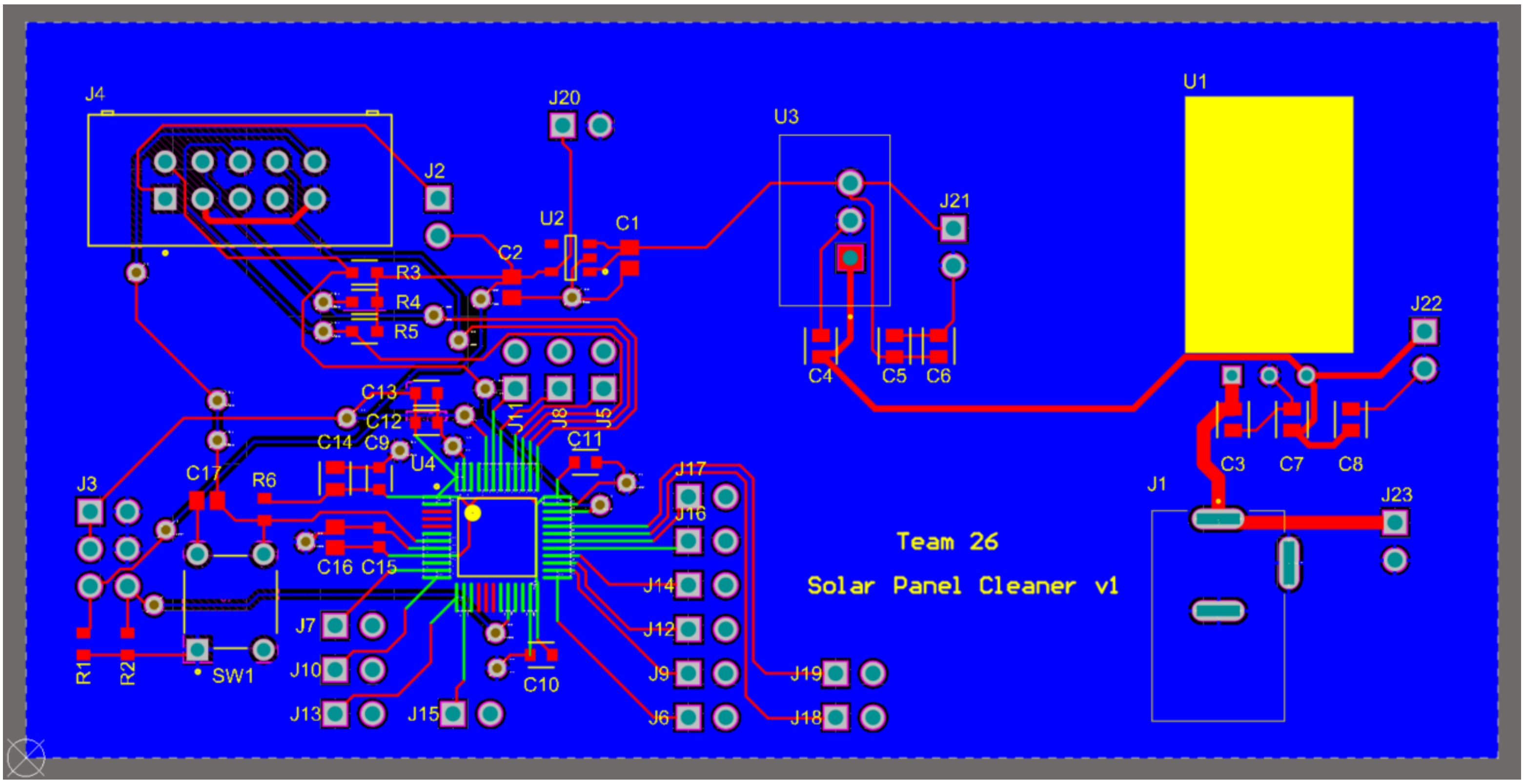


Figure 4: Layout of initial PCB design

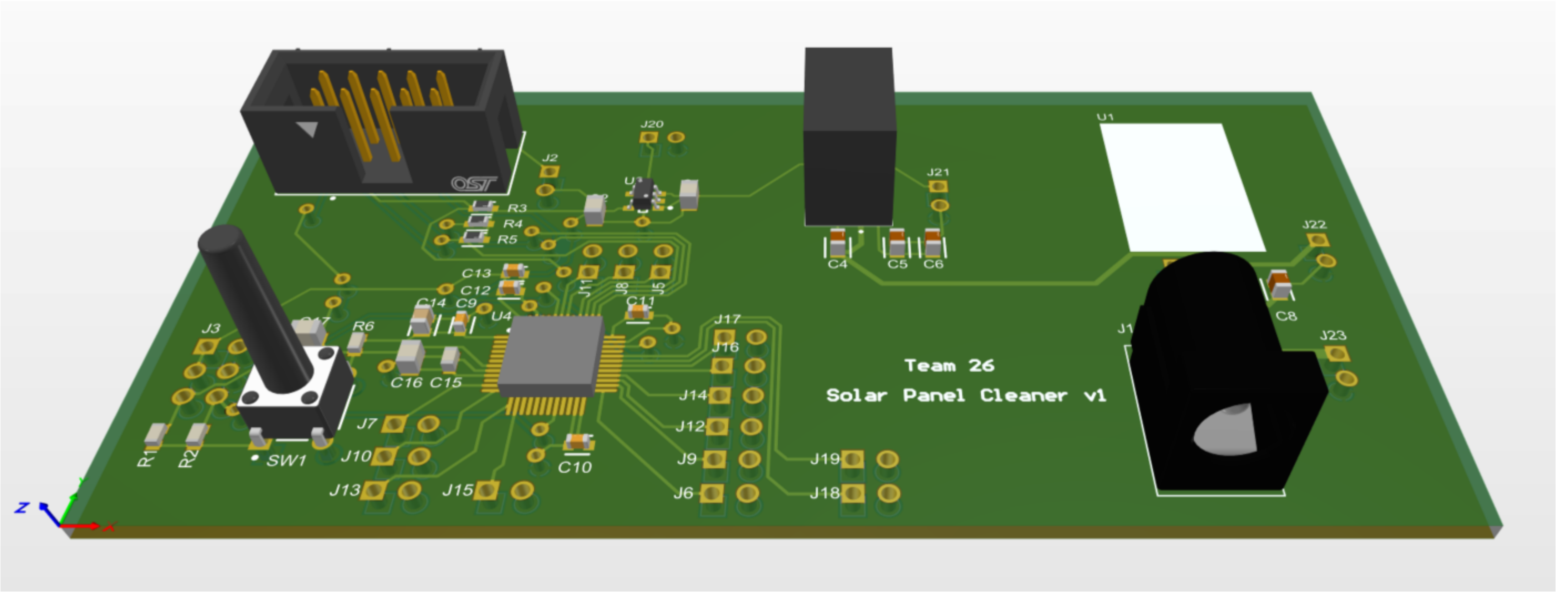


Figure 5: Three-dimensional model of initial PCB design

2.3.1 Power Subsystem

The power subsystem is responsible for supplying power to our cleaner. It draws power from a standard 120V AC outlet and rectifies and converts its voltage into regulated DC power at multiple voltage levels: 24V, 12V, 5V, and 3.3V, respectively. These DC buses are then connected to other subsystems to power stepper motor drivers, DC motor, sensors, cleaning solution dispenser, and microcontroller. The main components of this subsystem are a 120V-24V AC-DC converter, followed by cascaded DC-DC converters to step down to 12V, 5V, and 3.3V. In addition, fuses will be used for overcurrent protection to protect the user, the motors, the solar panel, and the digital components. Seen in Figure 6 is the schematic of the power subsystem of the PCB. It has the AC-DC converter and three DC-DC converters.

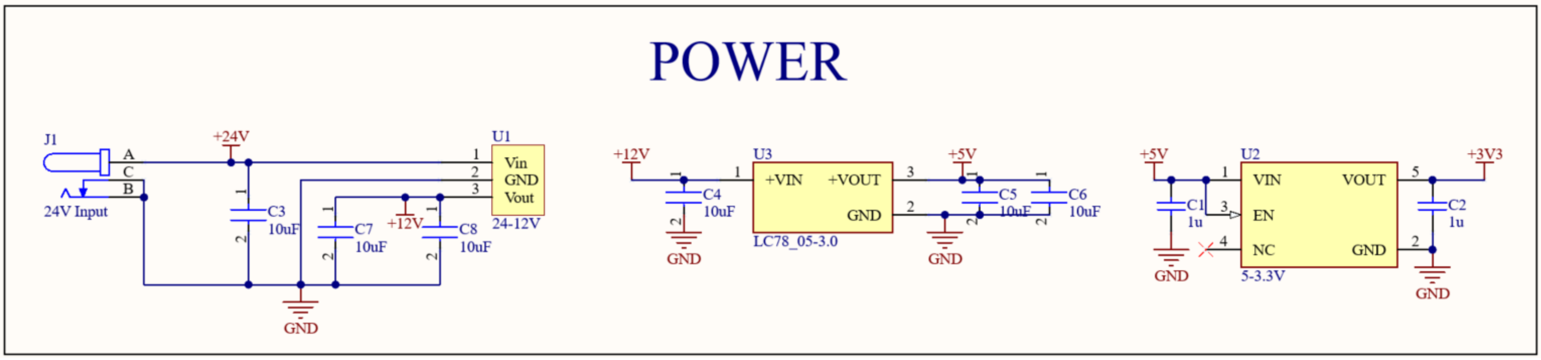


Figure 6: Schematic of power subsystem on PCB

Requirements	**Verifications**
AC wall voltage is converted to appropriate levels of DC voltage.	120VAC is converted to DC levels of 24V, 12V, 5V, and 3.3V. Each level has a tolerance of ±10% and can be measured using a digital multimeter.
The converters can handle full motor load without significant change in voltage.	The DC and stepper motors, as well as the internal motor and gear pump in the sprayer, are engaged at their designed speed and voltage. Each DC voltage level is monitored using an oscilloscope to ensure they remain within ±10% of their rated values.
The output of the converters falls to 0 when the input to the system fails.	The AC wall voltage is removed from the system at time $t = 0$. Each DC voltage level should drop to $< 10\%$ of its rated value within $t < 500ms$, measured using a DMM.
Motor power lines include overcurrent protection to prevent overloading of subsystems.	An intentional overcurrent event is triggered by a sudden load increase of 30%. A fuse blow or other shutdown is observed and recorded, and time to disconnect is measured with a stopwatch.
The power subsystem must operate reliably in ambient temperatures from 0°C to 45°C.	The entire system is placed outside on a warm, sunny day while running motors and sensors. Voltage rails are measured to confirm they remain within ±10% of nominal with the environmental stress

Table 1: Requirements and Verifications for the Power Subsystem

2.3.2 Controller Subsystem

The controller subsystem consists most primarily of the microcontroller and its connecting inputs and outputs. It also includes the user interface, which is comprised of eight buttons that control movement and operation of the drivetrain and cleaning mechanisms. The buttons create digital inputs to the microcontroller, which uses internal logic to send output signals to the stepper and DC motor drivers and the sprayer. The microcontroller also receives input from the IR positioning sensors. The subsystem is almost exclusively at a voltage level of 3.3V, but the subsystem also includes the mechanism to convert 3.3V output signals to 5V for the motor drivers and the sprayer. Seen in Figure 7 is the controller schematic implemented in the PCB. It has the STM32 microcontroller, as well as necessary decoupling capacitors, reset, and programming components.

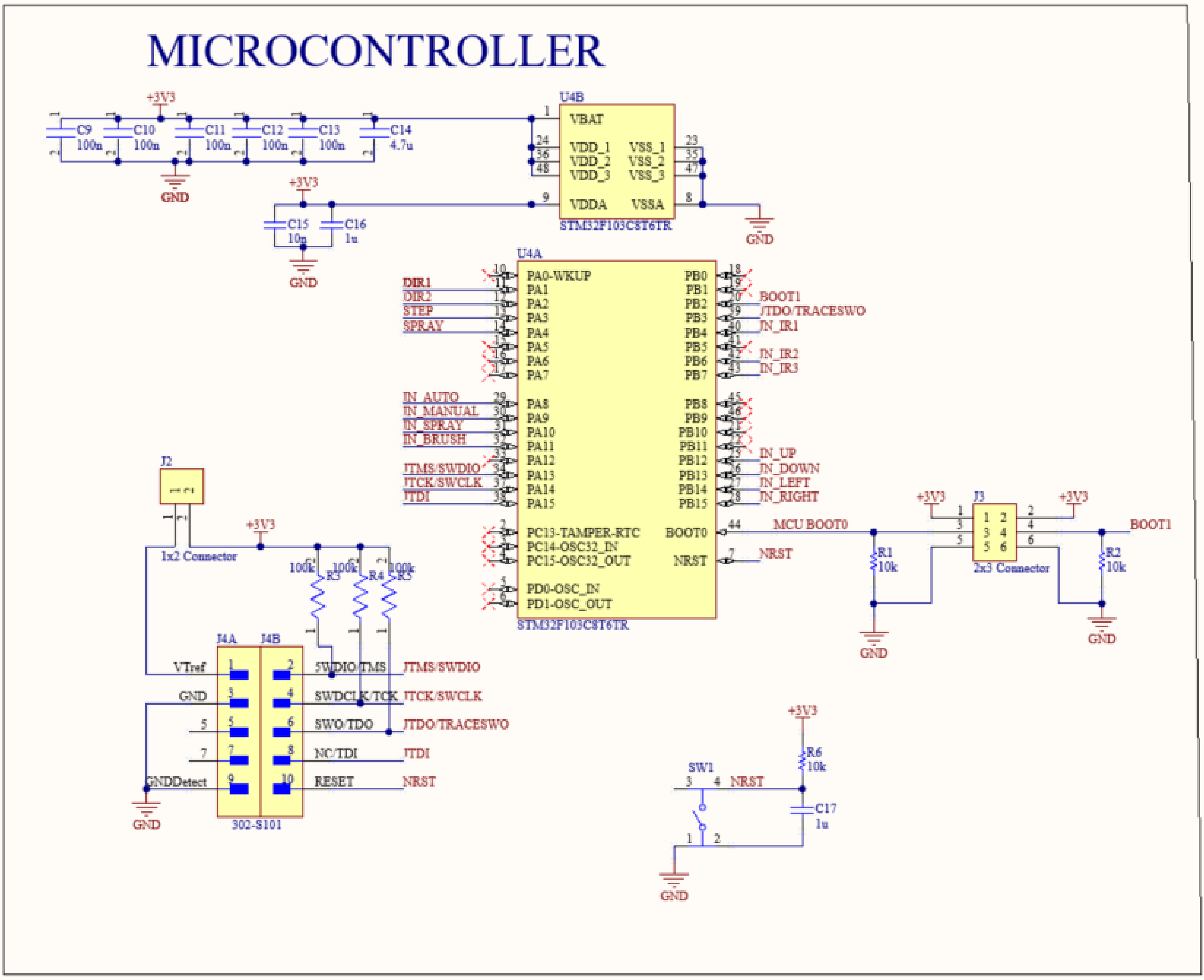


Figure 7: Schematic of controller subsystem on PCB

Requirements	**Verifications**
The microcontroller is able to read from the position sensors.	A voltage of 4.3-5V on the signal wires (IN_IRX on the MCU) is detected as HIGH, and a voltage of 0-0.7V is detected as LOW.
The microcontroller sends a signal to the position stepper drivers to engage/disengage stepper motors in a given direction.	A voltage of 4.5-5.5V is detected at the input (STEP) of the positioning stepper motor driver when the ouput logic is HIGH to engage the motor, and a voltage of <1.0V is detected when the output logic is LOW. When direction needs to be switched, the direction input (DIR) of the stepper motor driver switches from 4.5-5.5V to <1.0V or vice versa.
The microcontroller sends a signal to the brush motor driver to engage/disengage the DC brush motor.	A voltage of 4.5-5.5V is detected at the input (STEP) of the brush DC motor driver when the ouput logic is HIGH, and a voltage of <1.0V is detected when the output logic is LOW.
The microcontroller sends a signal to the sprayer to turn on/off the spray.	A voltage of 4.5-5.5V is detected at the input of the sprayer control when the output logic is HIGH, and a voltage of <1.0V is detected when the output logic is LOW.
The manual control buttons create corresponding signals for each movement or action.	Each movement/action button on the user interface inputs either HIGH (∼3.3V) or LOW (∼0V) to the microcontroller. The microcontroller outputs HIGH or LOW in repsonse to these inputs on signals STEPX, DIR and SPRAY.
The manual and autonomous mode buttons switch the internal logic mode.	The manual and autonomous mode buttons on the user interface inputs either HIGH (∼3.3V) or LOW (∼0V) to the microcontroller. When the system is switched to autonomous mode, output signals will change from HIGH to LOW without user input. When manual mode is pressed, output signals will cease to switch state without user input.
The controller responds to all input changes within 100ms to avoid perceived lag.	Apply step changes to position sensors and manual buttons while measuring output pins using oscilloscope. Verify time between input change and output response is <100ms.
Microcontroller software must perform self-check on startup and detect invalid states.	Reset the microcontroller and monitor serial debug output or onboard LED status indicators to confirm self-check routine executes correctly. Intentionally apply an invalid state to verify detection.
All unused GPIO pins should be configured as inputs with internal pull-down resistors to avoid floating pins.	Read all unused pin states after power-up and confirm they remain LOW. Use multimeter if necessary to measure pin voltages.

Table 2: Requirements and Verifications for the Controller Subsystem

2.3.3 Drivetrain Subsystem

The drivetrain subsystem is mainly mechanical and is responsible for moving the cleaning module on the solar panel. The drivetrain subsystem consists of a horizontal rail, two vertical rails, and complementary motors, gears, pulleys, and timing belts, providing precise positioning along the length and width of the panel. their movements. The horizontal rail will be attached to the top of the solar panel, housing the controller subsystem. The two vertical rails are attached to the controller subsystem in parallel, one on each side. The cleaning module is then connected between these vertical rails. The stepper motors receive power from the power subsystem and control signals from the controller subsystem. The drivetrain also relies on IR sensors to detect the panel edges, preventing the system from running off the panel. Mechanical components, including belts and rollers, translate motor rotation into linear motion.

Requirements	**Verifications**
The drivetrain must support the cleaning module and the control module.	Perform static and dynamic load tests to simulate the operation of our cleaner and ensure the drivetrain is stable and remains operational while maintaining structural integrity. The cleaning module mount should also cover at least 80% of the solar panel, which can be verified by measuring the distances covered.
The speed of the two stepper motors controlling the vertical movement of our cleaning module must be similar. The mismatch should be within 1% between the two.	Use a tachometer to measure the actual speed of each motor under operation conditions and verify that the actual speed of the two motors are within 1% of each other.
The infrared sensor at different locations can be activated and output desirable signals to the microcontroller.	The infrared sensors can be powered at desired distance by our power subsystem using the +5V bus and can transfer the detection signal +5V back to the control module. The signal can be measured and verified by using an oscilloscope at operating distance away. Confirm motors stop or reverse within 100 ms when triggered by the IR sensor.
The drivetrain subsystem must be able to move the cleaning module across the entire solar panel without exceeding the ratings of all components.	When we are testing the drivetrain subsystem, we would first use a power meter to ensure the total power being drawn does not exceed our rectifier ratings. Then, we would use individual power meters to measure the power drawn by each stepper motor as they operate as desired. During the entire operation, all current being drawn should not exceed 95% of the corresponding maximum ratings. In addition, the motors and the belts must be able to drive the cleaning module horizontally and vertically across the panel.
The system must complete a full vertical sweep (top to bottom and back to top) in under 10 minutes.	A stopwatch can be used to time our system. The time it takes to complete a vertical sweep should be strictly less than 10 minutes.
Stepper motors must not exceed their rated temperature (e.g., 80°C case temperature) during operation.	After 30 minutes of continuous operation, measure the surface temperature of each motor using an infrared thermometer or thermocouple. Confirm measured temperature is below 80°C.

Table 3: Requirements and Verifications for the Drivetrain Subsystem

2.3.4 Cleaning Mechanism Subsystem

The cleaning mechanism subsystem is responsible for physically removing dirt and debris from the solar panel surface. It consists of a rotating brush and driver by a DC motor, a cleaning solution gallon container and its associated sprayer, a microfiber cloth, and the container that houses all these components that is attached to the vertical rails. The brush motor receives power from the power subsystem and control signals from the controller subsystem. The sprayer is driven by an internal pump, which also receives power and control signals from their respective subsystems. The cleaning solution sprayer would spray the solution periodically to moisten the resilient stains, while the rotating brush rotates and brushes them off. The microfiber cloth will do the final round of cleaning, wiping off the remaining residue.

Requirements	**Verifications**
The sprayer and roller must operate when the control signals are HIGH and they must not operate when the signals are LOW.	Use an oscilloscope to ensure that when the control signals are LOW, the roller and sprayer will not draw power. In addition, use a power meter to assist in measuring the roller power while they are operating.
The cleaning brush and sprayer must engage/disengage within 200 ms of receiving control signals.	Monitor the motor and sprayer power lines using an oscilloscope while commanding on/off transitions. Confirm that actual activation/deactivation occurs within 200 ms of command signal changes.
The cleaning mechanism should clean up most of the debris and cover at least 80% of the solar panel's total surface area.	Prepare the solar panel by adding a thin layer of dust on its surface, then operate our cleaner to ensure most of the dust are cleaned off, and measure the remaining dust to ensure it covers less than 20% of the entire solar panel's surface area.
The cleaning brush must maintain consistent contact with the panel surface throughout operation.	Place the system on a mock panel surface with intentional unevenness (simulated dirt buildup). Observe brush contact visually to determine if there are any gaps between the brush and panel at multiple points.
The cleaning mechanism must not damage the solar panel.	An alternative glass or plastic surface should be used during initial trials. A thin, fragile layer could be added before operating the cleaning module to ensure it does not damage the solar panel surface.
The cleaning mechanism must operate reliably in ambient temperatures from 0°C to 45°C.	Place the system outside on a warm, sunny day. Operate the brush and sprayer continuously for 5 minutes. Monitor RPM, flow rate, and current draw to ensure stability.

Table 4: Requirements and Verifications for the Cleaning Mechanism Subsystem

2.4 Tolerance Analysis

One of the most crucial parts of our design is the cleaner unit moving vertically along the solar panel surface to perform the cleaning process. To properly select the motor responsible for this motion, we need to estimate the required torque for the vertical motors that drive the cleaner up and down the panel. In this analysis, we account for two primary forces: the gravitational force acting on the sloped solar panel, and the centrifugal forces generated by the rotating cleaning brush. Additionally, we aim to determine the optimal operating speed for the brush itself. To guide our motor selection process, we plotted the expected torque versus brush rotational speed, which helps us choose motors for both the brush (focusing on RPM) and the pulley system (focusing on torque).

The torque contribution due to gravity can be calculated using:

$$\tau_{gravity} = mg\sin(\theta)r$$

The centrifugal torque requires a different approach. The centrifugal force acting on a mass element is given by:

$$F_c = mr\omega^2$$

The corresponding centrifugal torque is:

$$\tau_{centrifugal} = F_c r = mr^2\omega^2$$

Since the brush's moment of inertia is $I = mr^2$ and rotational acceleration is $\alpha = \frac{d\omega}{dt}$, under steady-state operation (constant speed), the centrifugal torque simplifies to:

$$\tau_{centrifugal} = I\omega^2$$

By summing the gravitational and centrifugal torques, we computed the total torque demand as a function of brush speed. This analysis allowed us to select an appropriate target speed for the brush, which in turn enabled us to choose a compatible NEMA stepper motor that could provide the required torque. This analysis can be seen in Figure 8.

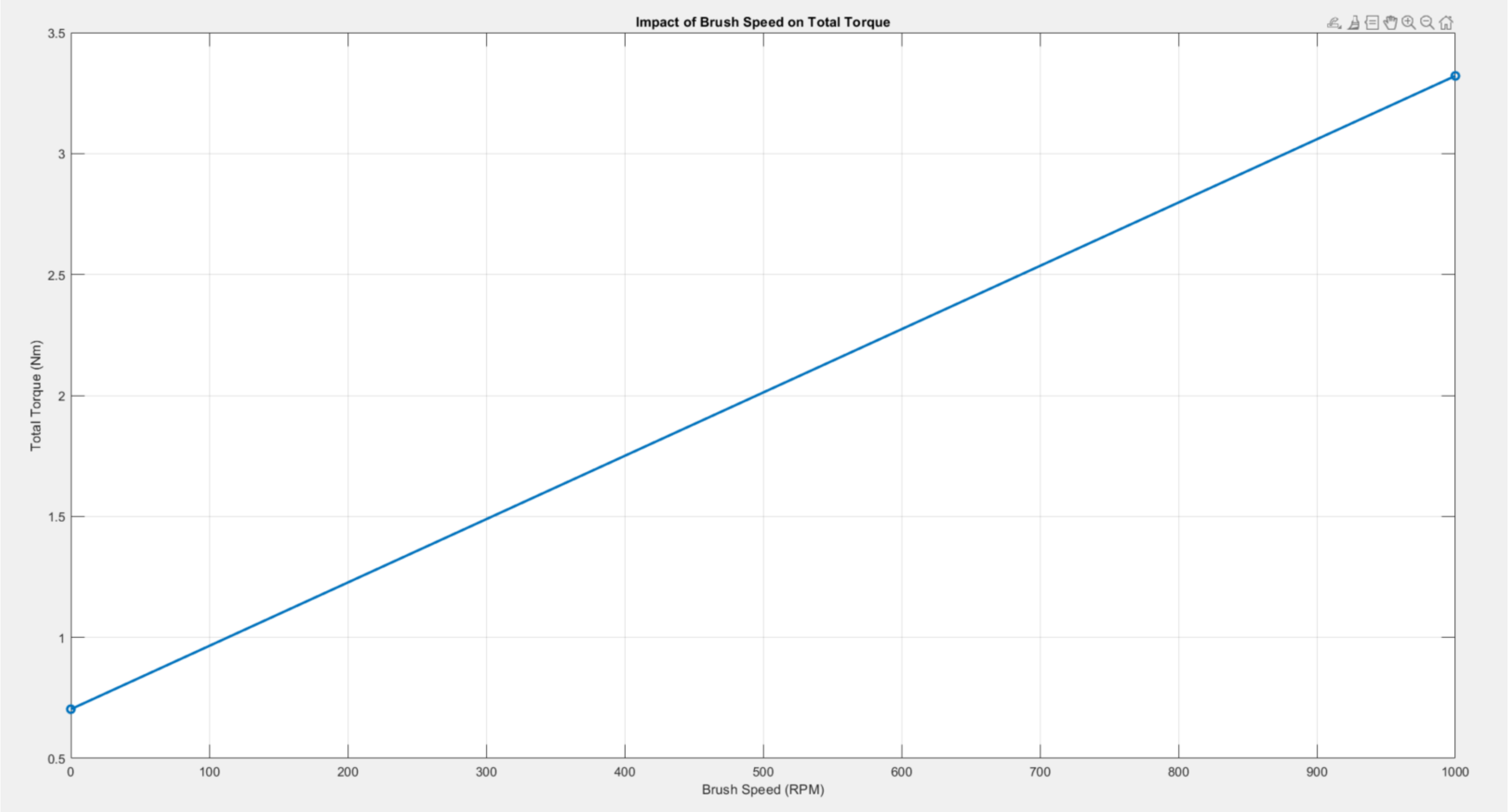


Figure 8: Estimated torque vs brush speed plot for cleaner unit module

3 Cost and Schedule

3.1 Cost Analysis

An critical factor in any project is the overall cost to the manufacturer to develop and produce the product. Below is a cost estimate of the prototype of the design of the solar panel cleaner, and the price of a company developing commercial-grade solar panel cleaners would cost.

3.1.1 Cost of Labor and Parts

According to the ECE department's statistics, the average starting salary for new graduates is $87,769 annually. To convert this into an hourly wage, it is approximately $42/hour. Therefore, the total cost of labor, including student labor and machine shop labor, can be calculated as follows:

Description	**Amount**
Hourly wage (students)	$42/hour
Students	3
Labor hours per student per week	$2.5 \times 15 = 37.5$ hours/week
Weeks	11
Additional hours	20 hours
Student labor cost	$42/hour × 37.5 hours/week × 11 weeks × 3 students + $42/hour × 20 hours = $52,815
Machine shop estimate	60 hours × $50/hour = $3,000
Total labor cost	$52,815 + $3,000 = $55,815

Table 5: Bill of Materials

Component	**Part Number/Link**	**Quantity**	**Unit Cost**	**Total Cost**
Control System and User Interface				
Momentary Push Buttons	E-Switch TL1105 Series	8	0	0
1x2 Connector	1x2 header	20	0.2	4
2x3 Connector	2x3 header	1	0.24	0.24
Tactile Switch	tactile switch	1	0.09	0.09
AC-DC Jack	barrel jack	1	0.66	0.66
10 Pin Header	10 pin header	1	0.26	0.26
10nF Cap	10nF cap	1	0	0
100k Resistor	100k resistor	3	0	0
1uF Cap	1uF cap	4	0	0
4.7uF Cap	4.7uF cap	1	0	0
0.1uF Cap	0.1uF cap	1	0	0
10uF Cap	10uF cap	1	0	0
10k Resistor	10k resistor	3	0	0
ESP 32 Microcontroller	ESP32-S3-WROOM-1-N8	1	0	0
80/20 Rails	Railing	3	0	0
T-Slotted Track Rollers	2 Flange Slot	3	0	0
Timing Belt	Belt	3	0	0
Drivetrain				
NEMA 23 Motors	NEMA 23 motors	0	18.91	0
Infrared Laser	IR laser	1	5.95	5.95
Motor Drivers	DM542T	0	9.99	0
Cleaning Mechanisms				
Microfiber Cloth	Microfiber Cloth	1	4.99	4.99
Rotating Brush (Soft)	Amazon Brush	1	16.99	16.99
DC Motor	DC motor	0	0	0
Solution Container	Container	1	5.09	5.09
Sprayer	Sprayer	1	9.88	9.88
Energy Conversion				
AC to DC Converter	24V 6A Converter	1	22.59	22.59
24V to 12V Converter	N7812-2CH	1	5.99	5.99
12V to 5V Converter	LC78 05-3.0	1	13.4	13.4
5V to 3.3V Regulator	MIC5317-3.3YM5-TR	1	0.22	0.22
Coiled Cable	Coiled Power Cable	1	4.99	4.99
Total				**95.34**

3.2 Schedule

Having and following a schedule is crucial for ensuring efficiency and meeting deadlines. Below is a table of our proposed schedule, with the general task of each week and individual member's assignments.

Week (Dates)	**Task**	**Person**
March 9 - March 15	Prepare for breadboard demo Work with machine shop Prepare second PCBway order	Geoffrey Cameron Thomas
March 16 - March 22 (Spring Break)	Program microcontroller Revise PCB design	Geoffrey Cameron, Thomas
March 23 - March 29	Solder PCB components Begin prototyping Initial testing Continue refining PCB design for third PCBway order	Cameron Geoffrey Thomas All
March 30 - April 5	Integrate subsystems Perform component verifications Modify PCB design for fourth PCBway order	Cameron Geoffrey, Thomas All
April 6 - April 12	Finalize integration Full system verification	All All
April 13 - April 19	Mount system on solar panel Begin full system testing	All All

Table 6: Schedule Table - Task Breakdown by Person

4 Ethics and Safety

4.1 Ethics

We recognize the importance of addressing potential ethical and safety issues related to our Solar Panel Cleaner. To ensure that the work performed is ethical and safe, we will closely follow the IEEE Code of Ethics.

4.1.1 Safety and Sustainability

Our top priority is the safety of our users, the solar panels, and the environment. Our goal is to design and assemble a cleaner that is safe to operate and gentle enough to avoid damaging the solar panels. We also plan to use environmentally friendly cleaning solutions to minimize harm to the environment.

4.1.2 Equality

We aim to design an inclusive and accessible product that can accommodate a wide range of users. We intend to create an easy-to-use cleaner at a low cost, enabling users from various backgrounds to benefit from it. The rail system of the cleaner is also scalable, making it adaptable to different setups.

4.1.3 Honesty and Transparency

Throughout the process, we will uphold the highest standards of integrity. We will present our product honestly and in accordance with the IEEE Code of Ethics.

4.2 Safety

In our project, we plan to power our cleaner through an electrical outlet. However, this could pose a safety risk if the outlet or cable is exposed to moisture or rain. Additionally, most of the electrical components in our cleaner are sensitive to the surrounding environment. Therefore, it is crucial to design weather-proof enclosures for the device and to ensure that users store hazardous components safely before inclement weather occurs.

We also intend to transfer power from the control module to the cleaning module. If not installed properly, the transmission wire could become entangled in the pulley system or the cleaning module, potentially causing short circuits or creating a shock hazard. To minimize this risk, we should use high-visibility cables and install appropriate accessories to reduce the likelihood of the cables getting caught. The pulley system poses another risk, as it could entangle objects such as hair or clothing. To account for these issues, we will incorporate fuses into our circuit to prevent huge in-rush currents, which responding to jammed motors, to prevent damage and preserve our circuit. For safety, it is recommended to maintain a safe distance from the cleaner during its operation.

Furthermore, the operating environment may experience high temperatures due to solar radiation, which could lead to material or device failures in extreme cases. To address this, we plan to incorporate reflective materials into the cleaner's surfaces to minimize heat absorption from solar exposure.

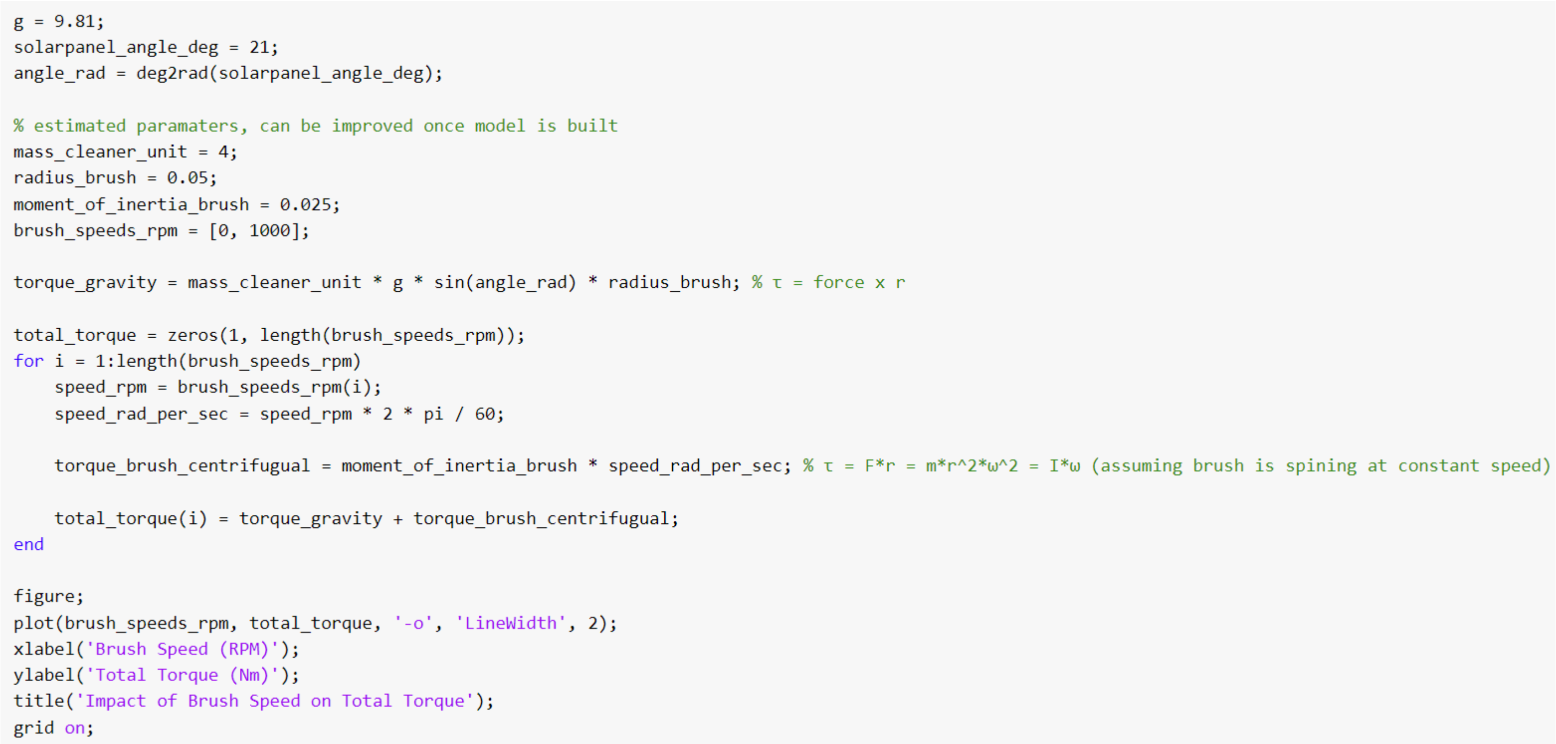
5 References

References

[1] IEEE, "IEEE Code of Ethics," Jun. 2020. [Online]. Available: `https://www.ieee.org/about/corporate/governance/p7-8.html`. [Accessed: Mar. 6, 2025].

[2] Wikipedia Contributors, "Centrifugal Force," Wikipedia, Wikimedia Foundation, 17 Nov. 2019. [Online]. Available: `https://en.wikipedia.org/wiki/Centrifugal_force`. [Accessed: Mar. 6, 2025].

A Appendix - MATLAB Code



```
g = 9.81;
solarpanel_angle_deg = 21;
angle_rad = deg2rad(solarpanel_angle_deg);

% estimated paramaters, can be improved once model is built
mass_cleaner_unit = 4;
radius_brush = 0.05;
moment_of_inertia_brush = 0.025;
brush_speeds_rpm = [0, 1000];

torque_gravity = mass_cleaner_unit * g * sin(angle_rad) * radius_brush; % τ = force x r

total_torque = zeros(1, length(brush_speeds_rpm));
for i = 1:length(brush_speeds_rpm)
    speed_rpm = brush_speeds_rpm(i);
    speed_rad_per_sec = speed_rpm * 2 * pi / 60;

    torque_brush_centrifugal = moment_of_inertia_brush * speed_rad_per_sec; % τ = F*r = m*r^2*ω^2 = I*ω (assuming brush is spining at constant speed)

    total_torque(i) = torque_gravity + torque_brush_centrifugal;
end

figure;
plot(brush_speeds_rpm, total_torque, '-o', 'LineWidth', 2);
xlabel('Brush Speed (RPM)');
ylabel('Total Torque (Nm)');
title('Impact of Brush Speed on Total Torque');
grid on;
```

Figure 9: Associated code for finding estimated torque vs speed