Solar Scrubber

ECE 445 Design Document - Spring 2026

Project No #57

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February 27 2026

1.1 Problem and Solution

Solar panel efficiency is highly sensitive to surface obstructions such as dust, snow, and bird droppings. These contaminants create a layer of soiling that can critically reduce power output by blocking sunlight from reaching the photovoltaic cells. Since many solar installations are located in remote areas or on hazardous rooftops, manual cleaning is often impractical, expensive, and dangerous. There is a clear need for an autonomous solution that can maintain these panels without human intervention. A major flaw in many existing automated cleaners is their lack of diagnostic intelligence. Most systems operate on fixed schedules, cleaning every panel regardless of its actual condition. This leads to a significant waste of water and electrical energy by running the cleaning module when it is not necessary. A more effective system must be able to identify which specific sections of an array require maintenance, ensuring that energy is spent only when a measurable efficiency drop is detected.

The Solar Scrubber utilizes a 2-axis linear guide rail system to navigate across solar arrays with precision. The system integrates real-time power analysis to detect specifically which panel in an array is underperforming. By comparing power output data against ambient light levels, the system can distinguish between temporary shading and actual debris accumulation, triggering an autonomous cleaning cycle only when needed. The robot is controlled by an ESP32-S3 microcontroller, which handles the complex logic required for navigation and sensor integration. The ESP32-S3 manages the locomotion through L298N motor drivers and coordinates the activation of the water pump and scrubbing brush. Additionally, the system features integrated Bluetooth communication, allowing for a manual override and real-time data monitoring. This combination of autonomous sensing and manual control ensures the robot remains efficient, safe, and easy to manage while maximizing the power generation of the panels.

1.2 Visual Aid

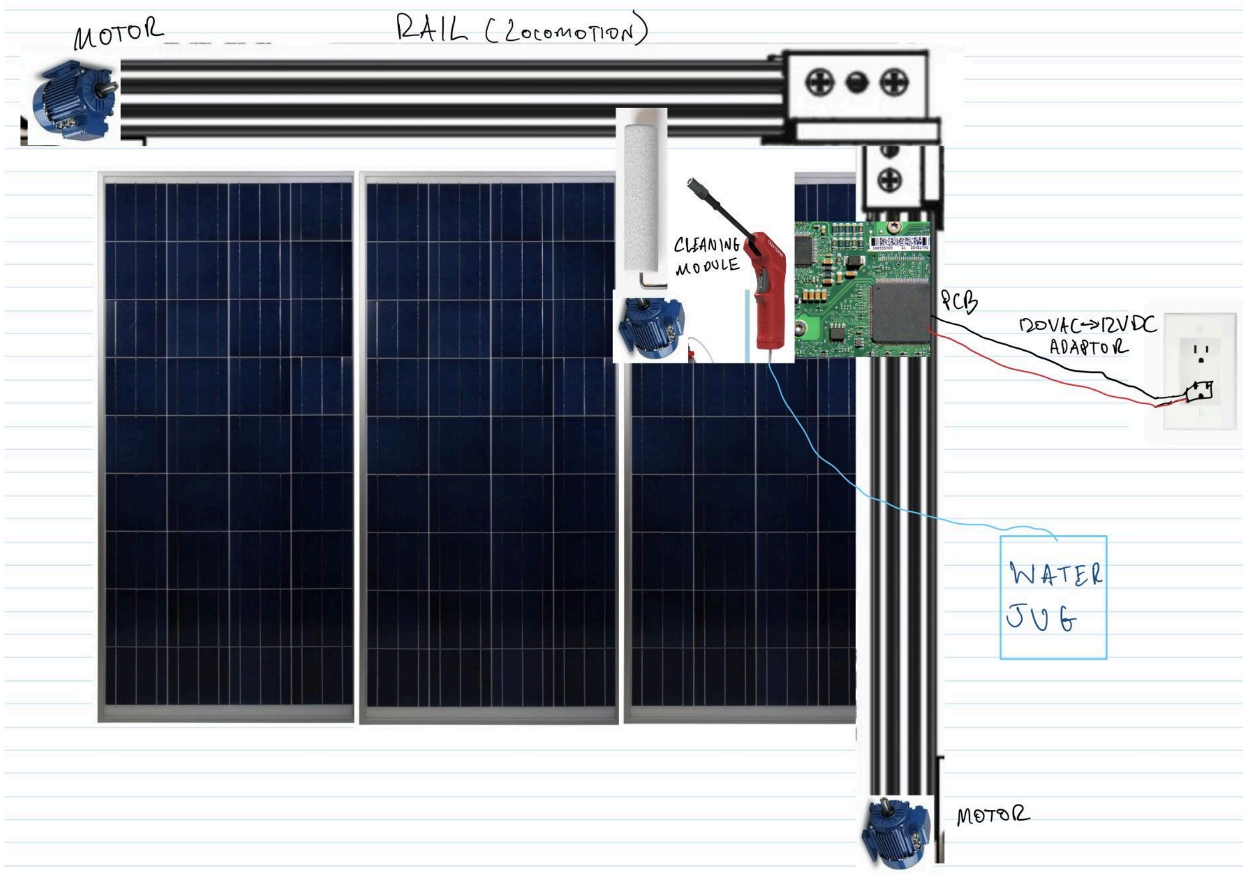


Figure 1: System Visual Aid (Top View)

1.3 High-Level Requirements

- MPPT and Diagnostic Accuracy: The system must track the maximum power point with at least 95% efficiency and distinguish between ambient shading and debris by cross-referencing sensor data to detect a 25% power drop; the controller must successfully transition from "Idle" to "Active-Clean" mode within 2 seconds of a confirmed debris detection.
- Cleaning and Restoration Efficiency: The integrated cleaning module, utilizing a pressurized sprayer and a motorized brush, must successfully remove surface soiling to restore the solar panel power output to at least 90% of its nominal capacity as measured in direct, ideal sunlight.
- Dynamic Control and Synchronization: The system must allow a user to toggle between autonomous and manual control modes in real-time within 500ms without a system restart, while the control unit simultaneously manages four PWM channels and maintains a stable 3.3V logic rail during peak motor and pump draw.

- Safety Response and Override: The control unit must prioritize a physical or remote "Stop" command over any autonomous routine, successfully cutting all power to the drive motors and cleaning module in less than 200ms to prevent mechanical failure or damage to the solar panel surface.

2. Design

2.2 Block Diagram

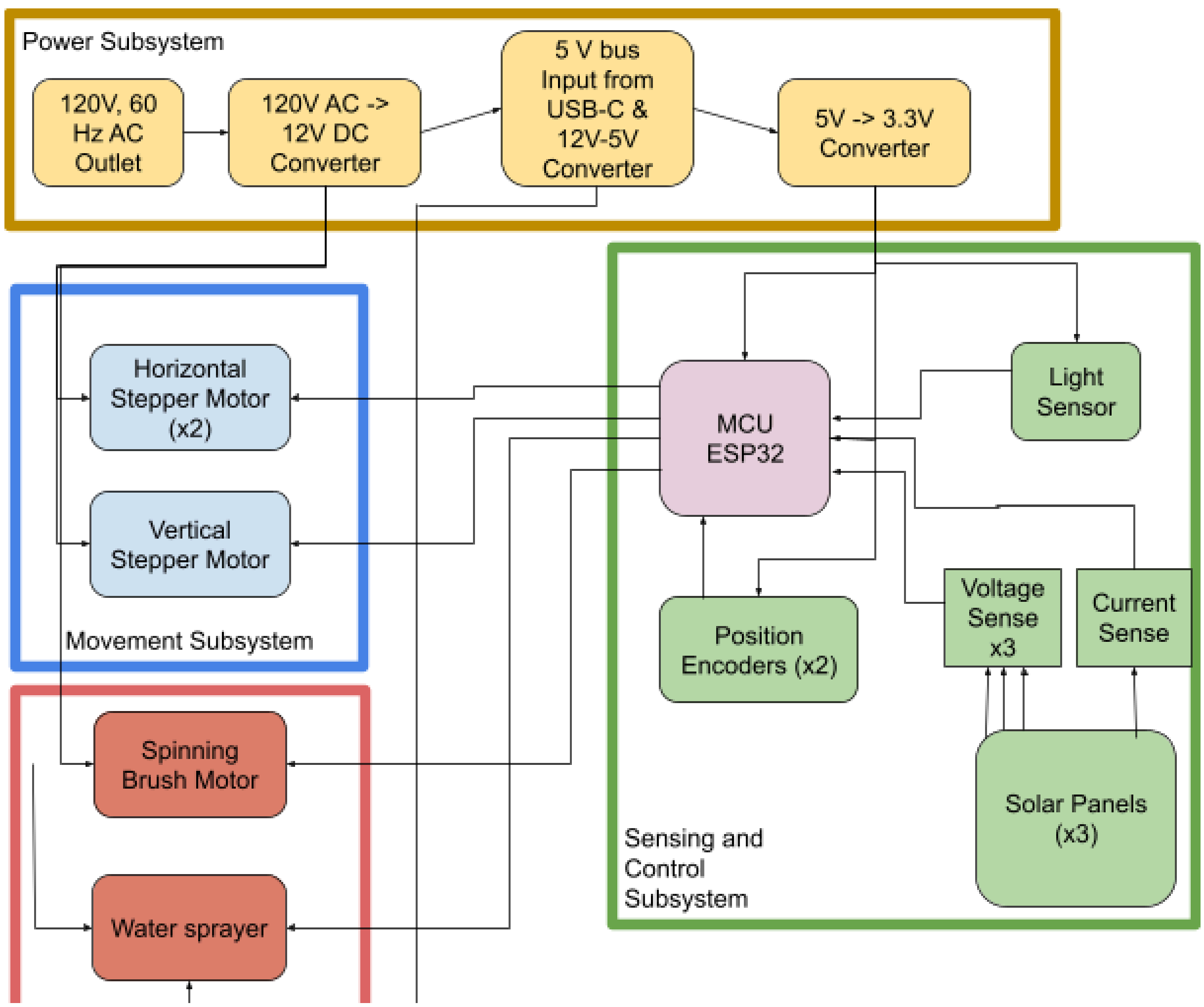


Figure 3: Block Diagram

2.1 Physical Design

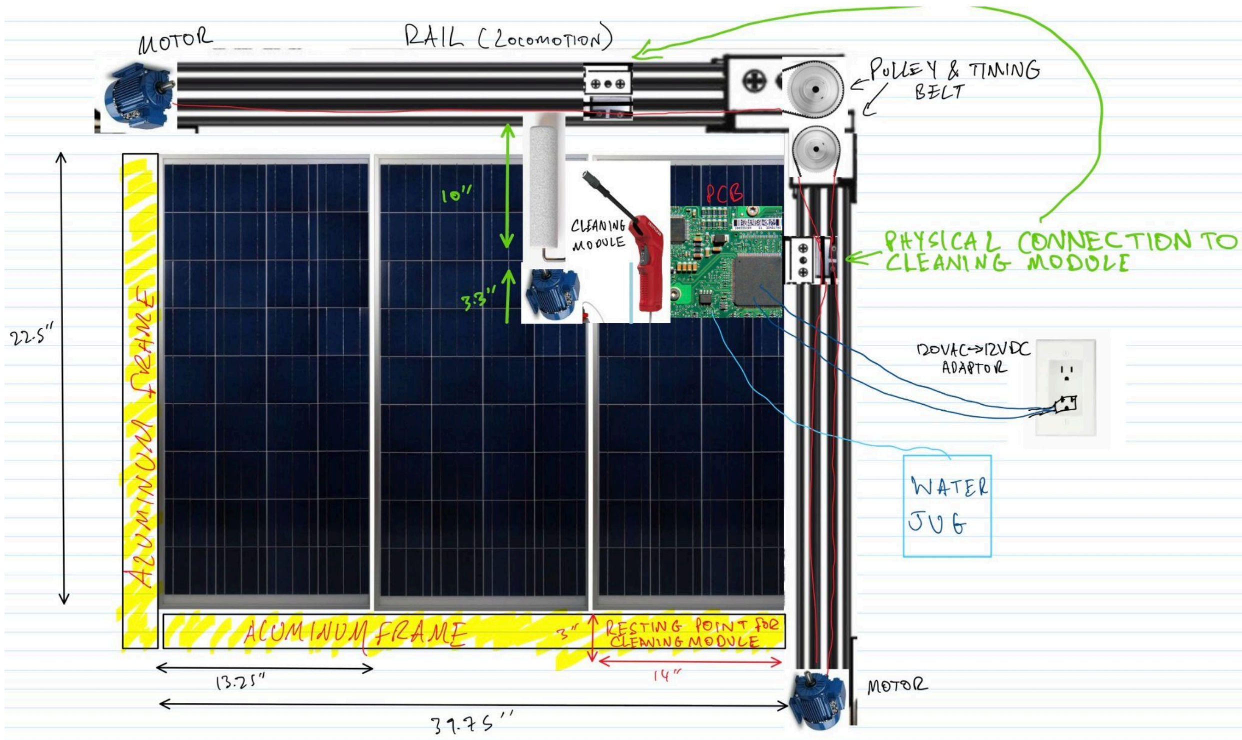


Figure 2: Physical Design

2.2 Subsystem Overview

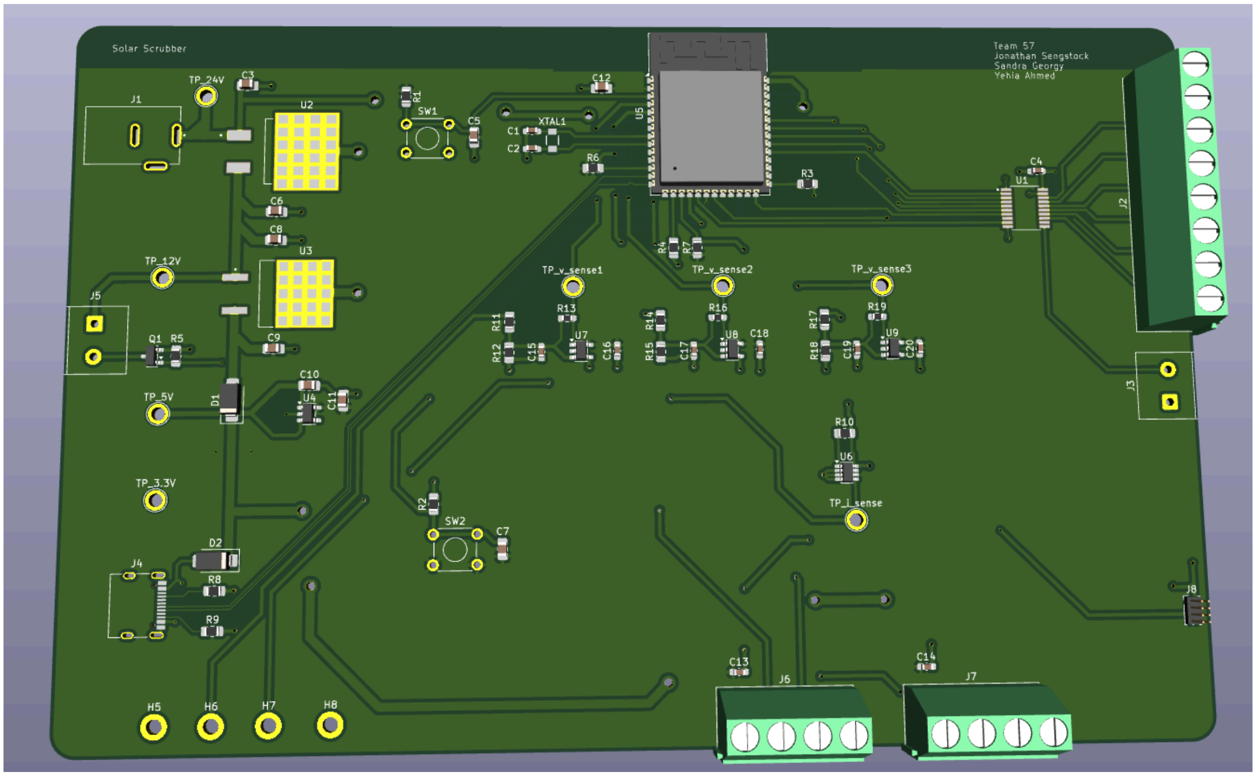


Figure 4: 3D view of PCB

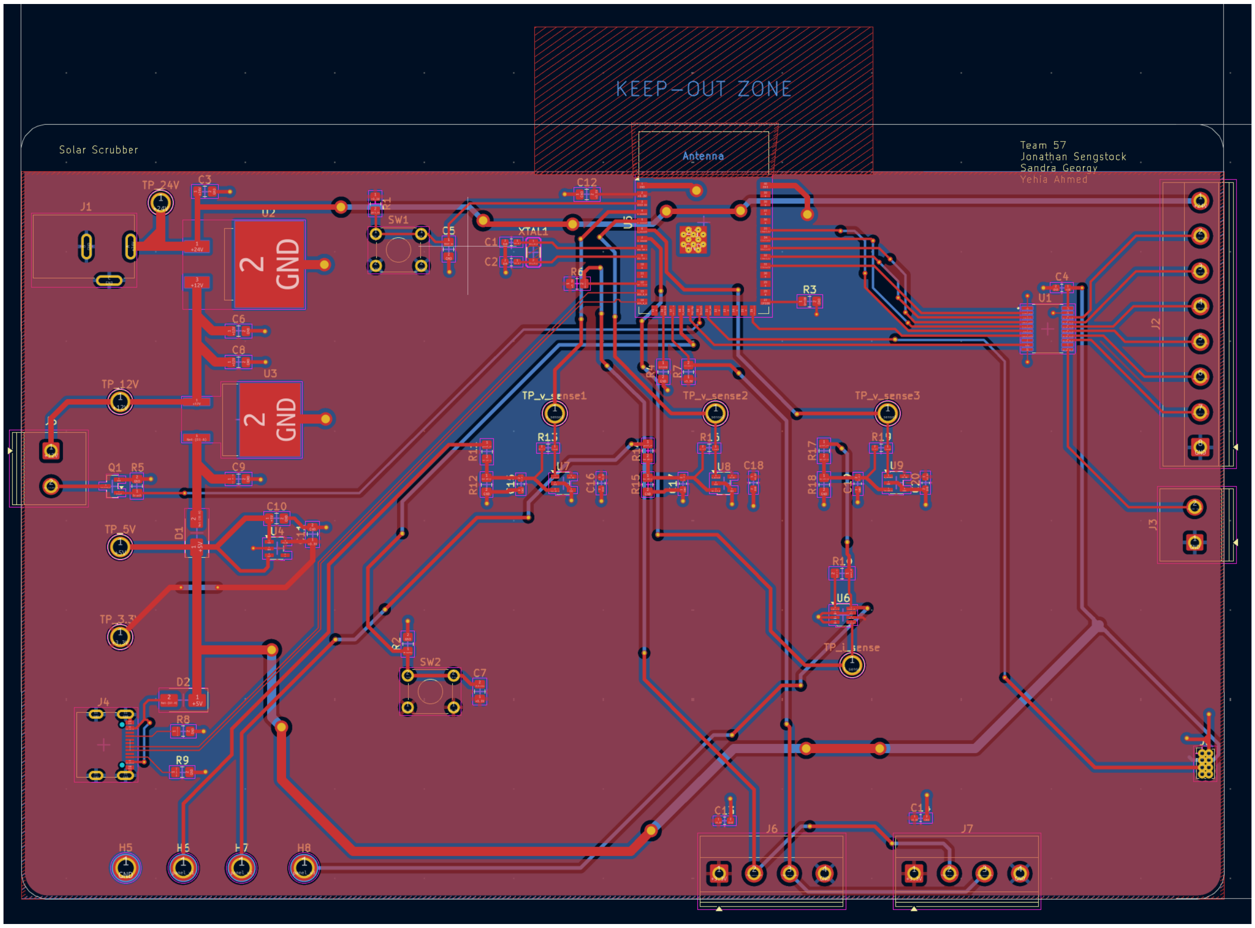


Figure 5: PCB Layout

The Solar Scrubber is an autonomous maintenance system designed to maximize the efficiency of a 3-panel solar array through targeted, data-driven cleaning. To achieve this, the system integrates six core subsystems: Locomotion/Movement, MPPT and Algorithm, the Cleaning Module, the Control Unit (MCU), Power Conversion, and the Solar Panel array itself. The system operates by continuously monitoring panel performance via the MPPT Subsystem and Sensing devices, using an ESP32-S3 to identify significant power drops caused by debris or stains. Once a cleaning cycle is triggered, the Locomotion Subsystem navigates a 2-axis gantry to the affected area, where the Cleaning Module utilizes a pressurized sprayer and motorized brush to restore the panel to 90% of its nominal power output. All electrical processes are managed by the Power Conversion Subsystem, which ensures a stable logic rail and efficient energy processing during high-current mechanical operations.

2.3 Locomotion/Movement

The Locomotion Subsystem facilitates the mechanical translation of the cleaning module across a three-panel solar array with a total width of approximately 40 inches (where each panel measures 22.5 x 13.25 inches) using a 2-axis gantry configuration structurally similar to a 3D printer. This design features a primary horizontal rail mounted at the top of the array that supports the main controller housing, while two parallel vertical rails attached to this central carriage extend downward to suspend the cleaning module. Precise movement is achieved through 12V DC motors integrated with gears, pulleys, and timing bands, utilizing Hall Effect encoders to send distance-calculating pulses to the ESP32-S3. One motor assembly drives the entire robot horizontally along the top rail to transition between panels, while a synchronized secondary motor set drives the cleaning module vertically. To ensure consistent accuracy and prevent path drift, the system executes a homing sequence upon startup, reversing until it triggers physical limit switches at the (0,0) position to reset the pulse counters to zero. This block is essential for meeting the high-level goal of 90% power restoration by ensuring 100% surface coverage and precise pinpoint cleaning, interfaced with the Control Unit via PWM speed signals and binary direction pins.

	Requirements	Verification
Structural Load Capacity	The gantry assembly and horizontal rail must maintain structural stability while supporting the total combined mass of the central carriage and cleaning module without mechanical deflection exceeding 2mm.	Secure the horizontal and vertical rails in their final mounting configuration and place a test weight equal to 1.5x the robot's total mass at the center of the longest span. Use a dial indicator or digital calipers to measure the vertical distance from a fixed reference point to the rail before and after the weight is applied to confirm the bend is less than 2mm.
Full-Surface Coverage	The 2-axis drive system must provide a minimum physical travel range to ensure the cleaning module can reach and overlap 100% of the surface area across the three-panel solar array.	Manually command the robot to all four extreme corners of the 3-panel array via the ESP32-S3 control interface. Visually verify that the cleaning brush and microfiber cloth physically reach and overlap the edges of the photovoltaic cells at each extremity.
Coordinate-Based Precision	Utilizing Hall Effect encoders and a startup homing sequence, the locomotion system must achieve a positional repeatability of +/- 5mm when commanded to specific (x, y) coordinates for targeted spot-cleaning.	Mark three specific coordinate targets on the solar panels and command the robot to visit each target five times from different starting positions. Use a ruler to measure the distance between the center of the brush and the target mark to confirm the error is consistently within +/- 5mm.

Temporal Performance	The subsystem must be capable of moving the cleaning module from the home position (0,0) to the furthest diagonal coordinate of the array in under 60 seconds.	Use a stopwatch to time a full diagonal transit from the home position (0,0) to the maximum (x, y) coordinates to ensure the duration is under 60 seconds.
Environmental Resilience	All locomotion components, including DC motors, gears, and timing bands, must operate reliably within an outdoor temperature range of 0C to 50C without material degradation or loss of torque. Specifically, the DC motors must not exceed an internal operating temperature of 70C during a continuous 10-minute cleaning cycle to prevent torque degradation.	Review component data sheets to confirm DC motors and drivers are rated for 50C ambient operation. Perform a continuous 10-minute cleaning cycle in direct sunlight and use an infrared thermometer to verify the motor casing temperature does not exceed 70C while maintaining consistent torque and speed.

2.3.1 MPPT and Algorithm

The MPPT and Algorithm Subsystem serves as the central power processing and diagnostic component of the robot, designed to optimize energy collection from a three-panel solar array with a total width of approximately 40 inches where each individual panel measures 22.5 by 13.25 inches. To monitor performance, the system utilizes three independent voltage sensors (one for each panel) buffered by OPA376 precision operational amplifiers and a single INA241B ultra-precise current sense amplifier that measures total system current across a shunt resistor. These analog measurements are routed directly to the GPIO pins of the ESP32-S3 microcontroller, which uses its internal 12-bit ADC units to sample the data. The MCU itself handles running the perturb and observe algorithm, computing the power in real time and iteratively adjusting the PWM duty cycle of a DC-DC buck converter that acts as the dynamic load for the tracking process. By tracking the maximum power point with an expected 95 percent efficiency, the MCU can identify underperforming panels to trigger targeted cleaning cycles instead of full array sweeps, verifying the high-level requirement of 90 percent power restoration. Interfaces are defined by the four analog 0 to 3.3V sensor signals entering the MCU and the high-frequency PWM control signal output to the MOSFET gate driver in the power conversion block.

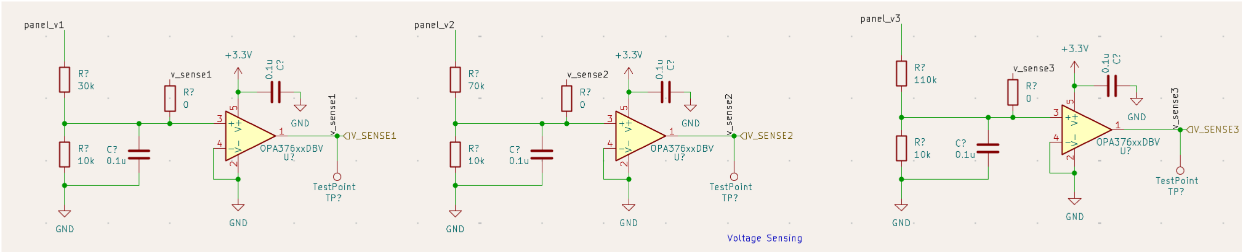


Figure 4: Voltage Sensor Schematics

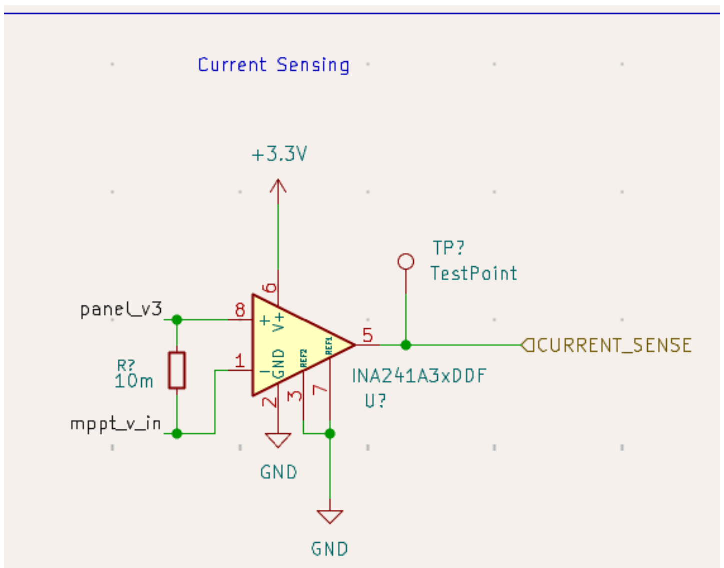


Figure 5: Current Sense Schematic

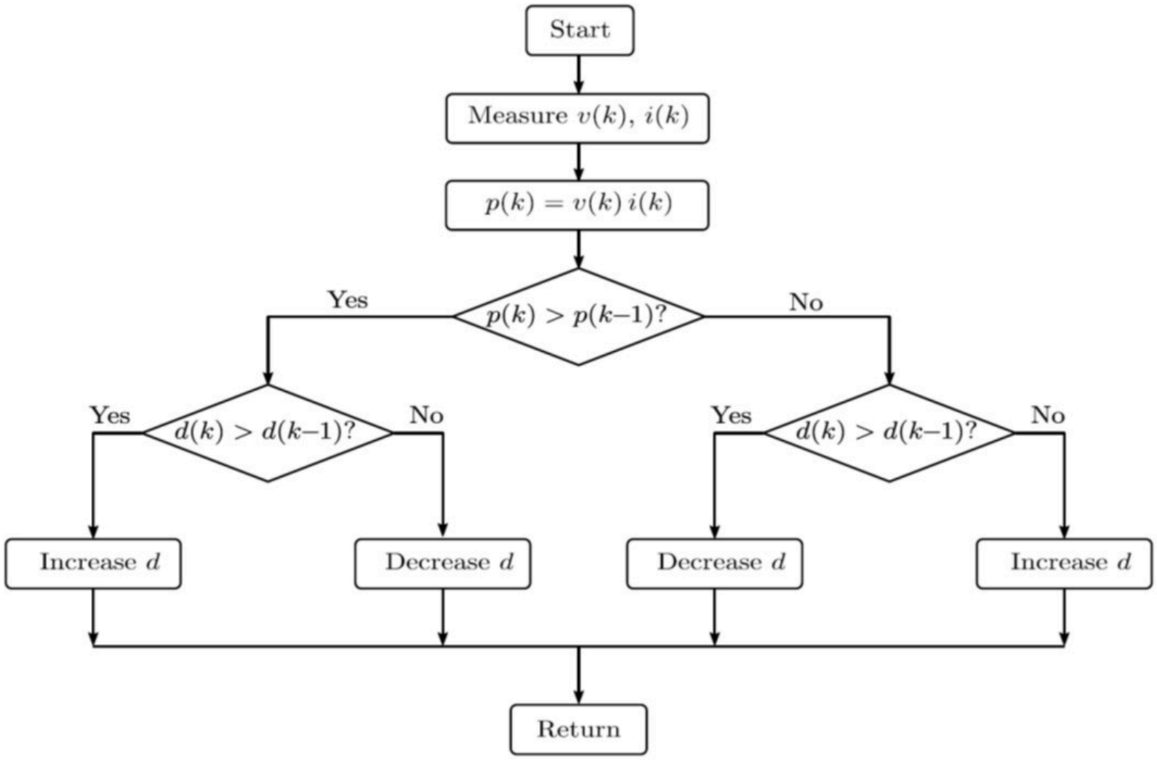


Figure 6: Perturb and Observe MPPT Algorithm (Provided from ECE 469)

	Requirements	Verification
Sensing Precision	The sensing circuits must measure individual panel voltages (0 to 12V) and total system current (0 to 2A) with a maximum error of 1% to provide the high-resolution data necessary for the ESP32-S3 to reliably detect efficiency drops.	Apply a known DC voltage from 0V to 12V (Voc) to each of the three voltage sensor inputs and a known current from 0A to 2.5A to the shunt resistor using a calibrated power supply or electronic load. Compare the readings sampled by the ESP32-S3 ADC with a handheld digital multimeter to verify that the measured error for both voltage and current remains below 1%.
MPPT Tracking Efficiency	The Perturb and Observe algorithm implemented on the MCU must maintain a tracking efficiency of at	Connect a 20W solar panel to the system under stable sunlight and measure the actual power

	least 95% under steady-state solar irradiance.	delivered to the load using an external power meter. Compare this value to the theoretical maximum power point calculated from the panel's I-V curve at that moment and verify the tracking efficiency is at least 95%.
PWM Control Resolution	The ESP32-S3 must generate a PWM signal for the buck converter gate driver with a resolution of at least 10 bits and a frequency of 50kHz to allow for fine adjustments to the operating point.	Connect an oscilloscope to the ESP32-S3 PWM output pin that drives the buck converter. Use the MCU's console to sweep the duty cycle from 0% to 100% in 1-bit increments and verify the signal maintains a consistent frequency of 50kHz with distinct, monotonic changes in pulse width.
Fault Isolation and Detection	The algorithm must use the three independent voltage sensor inputs to isolate and identify the specific panel (1, 2, or 3) exhibiting a power drop of 25% or more compared to the others, correctly flagging it as "dirty" for the locomotion subsystem.	Set up all three panels under uniform lighting. Apply a physical obstruction (stain) to Panel 2 only, reducing its individual voltage and power output by approximately 30%. Verify through the serial monitor that the ESP32-S3 correctly identifies Panel 2 as the outlier and triggers the targeted cleaning flag while maintaining normal status for Panels 1 and 3.

2.3.2 Cleaning Module

The Cleaning and Fluid Delivery Subsystem integrates mechanical scrubbing with an automated irrigation process to remove debris from the solar array. This module is housed within a central container attached to the vertical rails and features a 12V DC motor that drives a rotating brush to loosen resilient stains. The scrubbing motor is controlled via an L298N motor driver, which receives its 5V logic power directly from the USB-C input. For fluid delivery, the system utilizes a 12V Craftsman 1 handheld sprayer pump connected to an external reservoir via flexible tubing. This pump is triggered by a dedicated spray enable pin from the ESP32-S3, which switches 12V power from the main subsystem rail to the sprayer. The control logic is hard coded to trigger the sprayer first, ensuring the panel surface and microfiber cloth are sufficiently saturated before the scrubbing motor begins rotation. This fully automated multi-stage process ensures consistent high pressure cleaning without manual intervention, directly supporting the high level goal of 90% power restoration.

	Requirements	Verification
Command Responsiveness:	The scrubbing motor and water pump must respond exclusively to MCU logic levels, transitioning from an idle state to active mechanical rotation or fluid flow within 200 ms of the ESP32-S3 signal going high.	Connect an oscilloscope to the 12V output of the L298N motor driver and the sprayer pump supply line. Program the ESP32-S3 to toggle the control pins from low to high. Measure the time delta between the logic signal going high and the motor/pump reaching 90% of their operating voltage to confirm the transition occurs within 200 ms.
Effective Cleaning Coverage and Contact:	The gantry-mounted module must maintain uniform pressure against the panel glass across the entire 40-inch horizontal travel path to ensure the rotating brush and microfiber assembly make contact with at least 95% of the total solar panel surface area.	Saturate the entire length of the rotary microfiber towel with water and place the module on the panel array. Manually command the gantry to move across the 40-inch horizontal path while the cleaning mechanism is active. Visually inspect the panel surface to ensure a consistent "wet trail" is left across at least 95% of the surface area, confirming the brush maintains mechanical contact without lifting or skipping.
Environmental and Thermal Tolerance:	The subsystem must operate reliably in ambient temperatures ranging from 0°C to 50°C. Specifically, the DC motors must not exceed an internal operating temperature of 70°C during a continuous 10-minute cleaning cycle to prevent torque degradation.	Operate the brush motor and sprayer pump continuously for 10 minutes in an environment reaching up to 50°C. Use an infrared thermometer or thermocouple to monitor the DC motor casing to ensure it stays below 70°C. Confirm that the motor maintains consistent rotational speed and the pump maintains steady fluid flow throughout the duration of the test.

2.3.3 Control Unit (MCU)

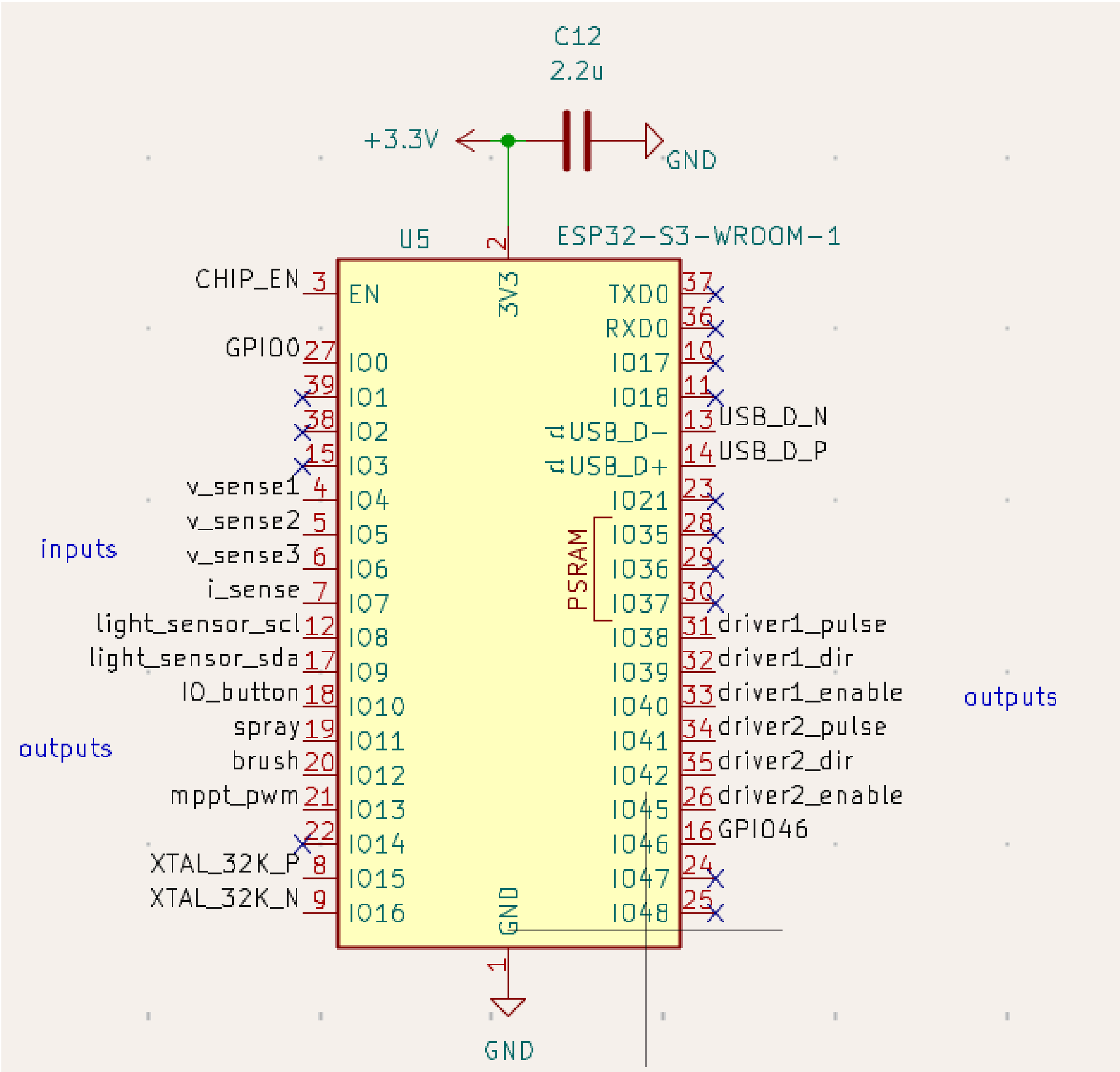


Figure 7: Microcontroller Schematic and Pinouts

The Control Subsystem serves as the centralized brain of the Solar Scrubber, leveraging the ESP32-S3 microcontroller to orchestrate 2-axis navigation and autonomous cleaning based on real-time performance data. The core logic is governed by a Finite State Machine (FSM) that simultaneously processes analog telemetry from three voltage sensing channels (IO4–IO6) and one current input (IO7) to maintain a complete environmental and operational data set. By executing a comparative analysis of these independent panel voltages against ambient light data from the dedicated sensor pins (IO8, IO9) and the manual IO button (IO10), the controller distinguishes between global environmental shading and localized debris to trigger targeted cleaning cycles. It outputs coordinated Pulse, Direction, and Enable signals to two dual-channel motor drivers (IO38–IO42, IO45) to regulate the 12V DC motors for horizontal and vertical movement, while concurrently managing the spray (IO11) and brush (IO12) outputs for the cleaning module. To ensure system stability, the MCU maintains a 50kHz PWM frequency for the MPPT (IO13) with a command-to-execution latency of less than 200 ms, ensuring the gantry accurately services underperforming panels without manual intervention.

	Requirement	Verification
I/O Interface and Driver Integration	The controller must successfully sample three analog voltage inputs (IO4–IO6) and one current input (IO7) while simultaneously monitoring the light sensor (IO8, IO9) and generating coordinated Pulse, Direction, and Enable signals for two dual-channel motor drivers (IO38–IO42, IO45).	Using a regulated power supply and a signal generator, apply known analog voltages to pins IO4–IO7 and toggle digital inputs IO8–IO10; verify via the serial monitor that the MCU accurately registers all values within a 2% margin. Simultaneously, use a four-channel oscilloscope to confirm that movement commands produce synchronized, non-interfering signals on the driver pins (IO38–IO45).
Sequential Cleaning Execution	The control logic must execute a mandatory "Spray-then-Scrub" sequence where the 12V water pump is activated for a brief 1-second burst to lubricate the panel before the brush motor begins rotation.	Use a two-channel oscilloscope to monitor the spray (IO11) and brush (IO12) output pins. Trigger a cleaning cycle and verify that the spray signal stays high for exactly 1 second and then turns off before the brush signal is asserted high.
Open-Loop Grid Navigation	The Finite State Machine must utilize a hard-coded coordinate grid and step-counting logic to navigate the gantry across the 40-inch array, ensuring the module can move to any specific panel coordinate from a fixed starting point.	Place the gantry at the designated "Start" position. Command the robot to navigate to three different pre-defined coordinates on the 40-inch array and use a tape measure to verify the gantry stops within 1 inch of the target location.
MPPT Algorithmic Accuracy	The control subsystem must execute the Perturb and Observe algorithm using sampled telemetry to adjust the duty cycle on IO13, ensuring it converges on the maximum power point within 2 seconds of a detected irradiance change.	Use a programmable DC load to simulate a solar panel curve. Introduce a sudden change in simulated irradiance and use an oscilloscope to confirm the PWM signal on IO13 adjusts and stabilizes at the new maximum power point within 2 seconds.

Signal Timing and Stability	The controller must maintain a 50kHz PWM frequency for the MPPT output on pin IO13 and cleaning components on pins IO11 and IO12, with a command-to-execution latency of less than 200 ms.	Use an oscilloscope to measure the time delay between a simulated "dirty" sensor input and the output of the spray enable or brush motor signals. Verify the transition from state detection to output high occurs in under 200 ms.

2.3.4 Power Conversion

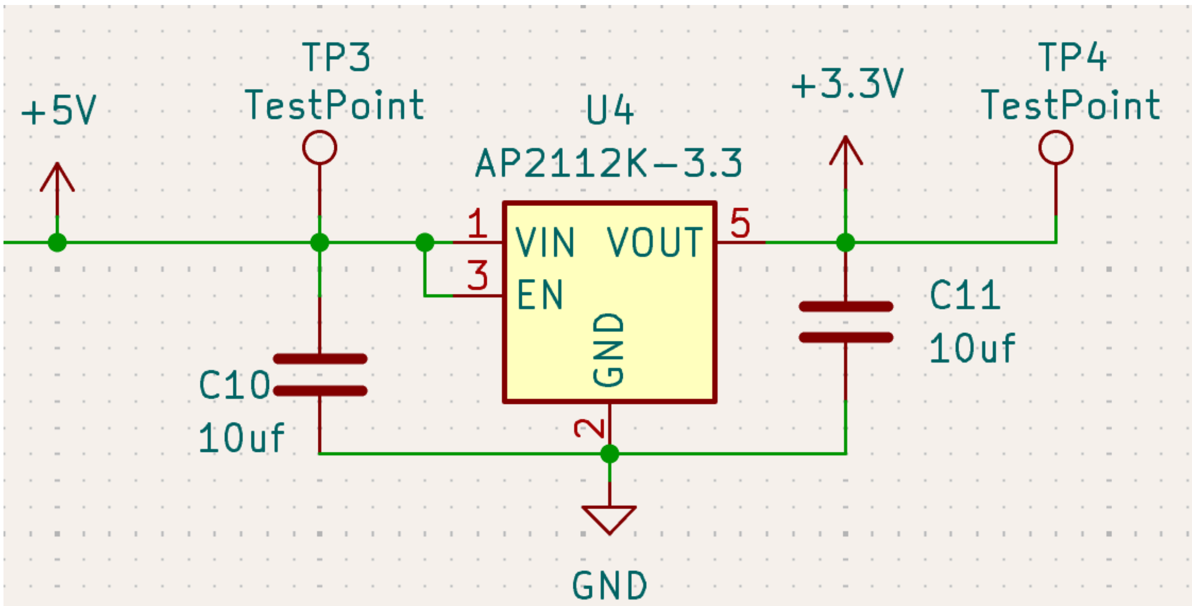


Figure 8: 5->3V LDO Schematic

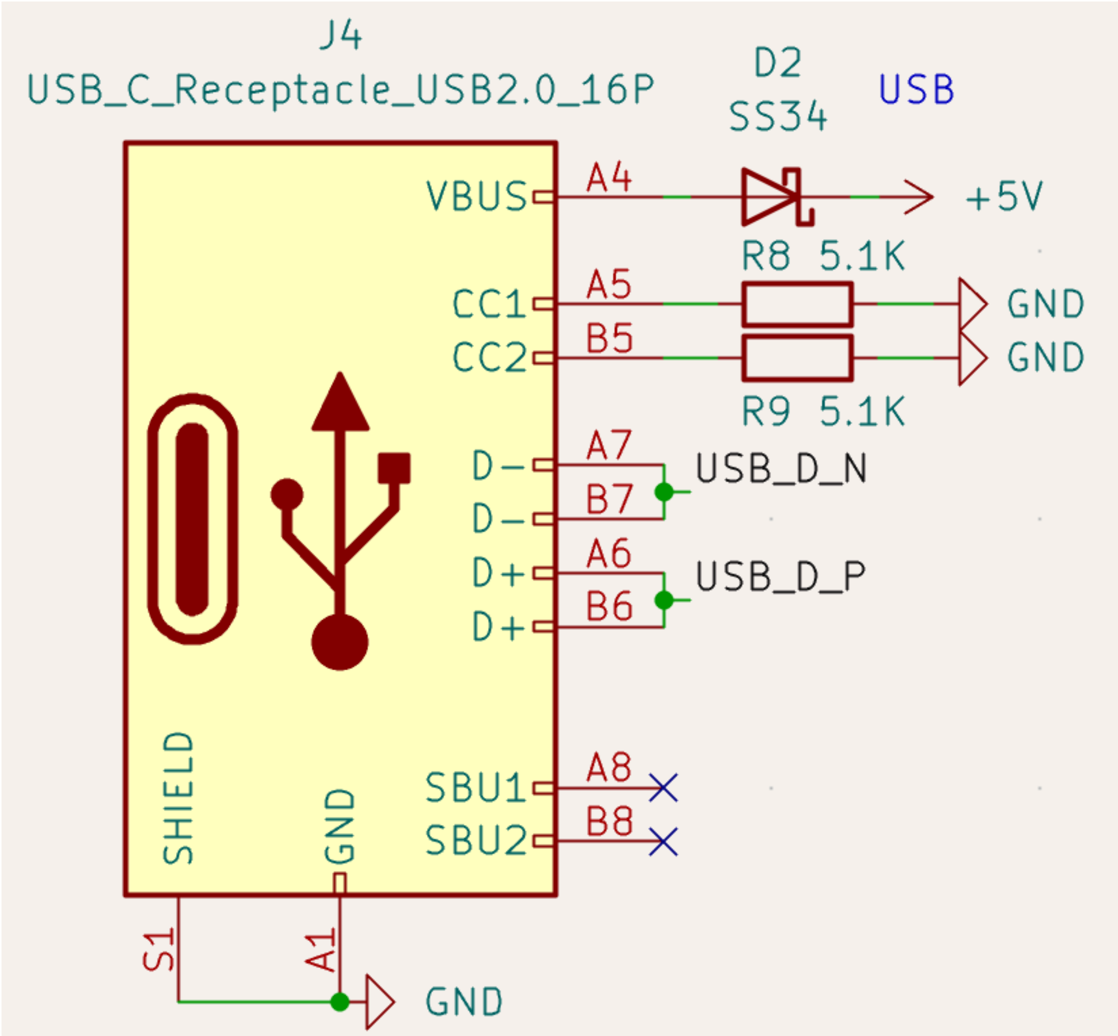


Figure 9: USB Type C Driver 5V input

The Power Subsystem provides regulated voltage rails by separating high current mechanical energy from sensitive digital logic. The system operates using a dual input architecture: a 12V DC wall adapter serves as the primary power source for the high torque components including the scrubbing motor, water pump, and 2-axis locomotion motors. A USB-C 5V input provides the primary logic supply. This 5V rail powers the SN74AHCT541 buffer, which acts as a level shifter to ensure 5V signal integrity for the motor drivers. Furthermore, an AP2112K-3.3 low dropout (LDO) regulator steps this 5V supply down to a precise 3.3V rail to power the ESP32-S3, light sensors, and analog telemetry circuits on pins IO4 through IO7. By drawing logic power from a dedicated USB-C source rather than stepping down the 12V motor rail, the system protects the microcontroller from electrical noise and voltage transients caused by DC motor switching.

	Requirements	Verification

Dual Input Isolation	The subsystem must successfully distribute a 24 V DC rail from a wall adapter for mechanical loads and a separate 5 V DC rail via USB-C for logic components to prevent motor induced noise from affecting the MCU.	Current should not flow back into either source (USB or wall supply) from the 5V bus when operating at rated load when measured with an oscilloscope current probe. Each DC bus (24 V, 12 V, 5 V, 3.3 V) should have less than a 2% ripple when measured with an oscilloscope.
3.3V Logic Regulation	The subsystem must maintain a 3.3V (±2%) output rail derived from the 5V USB-C input to power the ESP32-S3, sensors, and analog sensing pins.	The subsystem must maintain a 3.3V (±2%) output rail with less than a 2% ripple when probed with an oscilloscope.
Signal Level Shifting	The 5V logic rail must power the SN74AHCT541 buffer to reliably shift 3.3V MCU control signals to the 5V levels required by the motor drivers.	The level shifter must output 5 V with less than a 5% ripple when measured with an oscilloscope.
LDO Thermal Performance	The AP2112K-3.3 regulator must operate without thermal shutdown while the ESP32-S3 is at peak processing load of approximately 240mA.	Monitor the system using a thermal camera at standard operating conditions for 15 minutes. It must not rise above the rated temperature during this time.

2.3.5 Solar Panel

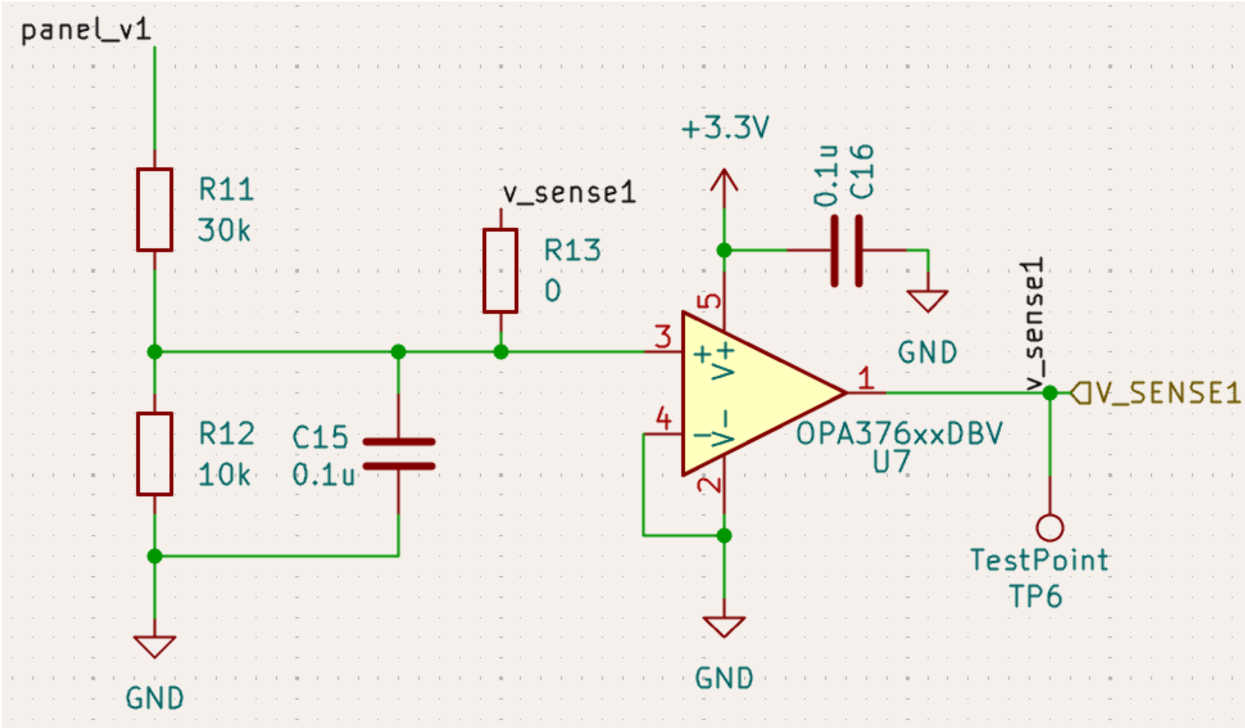
The Solar Panel Subsystem consists of three 20W photovoltaic modules arranged in a parallel configuration to maximize current output for the MPPT circuit. According to the manufacturer specifications, each panel has an open circuit voltage Voc of 12V and a voltage at maximum power Vmp of 9.5V. With individual panels measuring approximately 22.5 by 13.25 inches, the combined three panel array forms a 40 inch wide horizontal target for the cleaning gantry. This subsystem provides the primary performance data for the robot; the ESP32-S3 monitors the current and voltage from each panel to detect localized power drops caused by debris.

	Requirements	Verification
Parallel Array Configuration	The three 20W solar panels must be wired in parallel to provide a combined maximum power output while maintaining a common 9.5V rail for the MPPT subsystem.	Use a multimeter to verify continuity between the positive terminals of all three panels and confirm the total open circuit voltage at the array output matches the 12V specification of a single

		panel.
Individual Panel Telemetry	The subsystem must allow for independent voltage sensing of each panel (IO4 through IO6) to enable the Control Subsystem to distinguish between global shading and panel specific debris.	Temporarily shade one panel at a time while monitoring the analog inputs on pins IO4 through IO6 on the ESP32-S3 to verify the MCU accurately identifies which specific panel voltage has dropped.
Current Capacity:	The wiring and connectors must safely handle the panels' short-circuit current (2.5 A) without excessive voltage drop or overheating.	Under full solar irradiance, short the array through a calibrated shunt resistor and measure the current to verify that the wiring maintains a temperature below 50C and the measured current reaches at least 90% of the rated 7.5A.

2.3.6 Tolerance Analysis:

Through discussion with our group, we have determined that the voltage and current sensing and MPPT converter is the part of our project that poses the most challenging requirement. The input voltage read by the MCU, sourced from a voltage divider, is how our algorithm will determine whether a panel is dirty. The resistor-based voltage divider will be sensitive to value ranges. Shown below is one of our voltage sensing circuits, where the input panel_v1 is the voltage across the first solar panel, and it is put through a resistor voltage divider and read by an op-amp that acts as a voltage buffer. In a nominal case, the voltage v_sense1 will equal 25% of the total input voltage.



There are two scenarios that will most significantly impact our voltage readings: the top resistor being x% above tolerance while the bottom resistor is x% below tolerance; and the top resistor being x% below tolerance while the bottom resistor is x% above tolerance. These two scenarios result in the minimum and maximum values of the voltage read by the MCU pin, respectively.

For example, with a tolerance value of 10% for our resistors, the input voltage to the MCU pin will be between [21.42%, 28.95%] of the input voltage rather than the ideal 25%. This will raise problems with our algorithm if we assume all of our solar panels and voltage sensing circuits have the exact same specifications (i.e., open-circuit voltage, series resistance, op-amp gain). However, we plan to calibrate each panel and sensor pair individually such that the code will be able to predict its status based on laboratory experiments.

The worst case scenario for the resistor tolerance values is one that results in an input voltage to the MCU pin that is higher than its rated voltage. The ESP32-S3 runs on a standard 3.3 V throughout the device, including its GPIO pins. However, its datasheet states an absolute maximum of 3.6 V on its pins. In the maximum possible output voltage scenario described above, the MCU GPIO pin voltage will be:

$$Voc \frac{R11(1+x)}{R11(1+x)+R12(1-x)} < 3.6\,V$$

Where *x* is the resistor's tolerance (e.g. a 10% tolerance equates to $x = 0.1$), *R11* and *R12* are the nominal top and bottom resistor values, respectively, and *Voc* is the actual voltage across the solar panel. Setting *Voc* to 12V (the value given by our panel's data), and *R11* and *R12* to 30k and 40k respectively, the equation can be solved for *x*. This yields $x = 0.125$, which means that any resistors we purchase need to have a 12.5% tolerance or less. We plan to use resistors with a 5% tolerance to balance safety and cost.

The same is true of the other two voltage sensing circuits but with different values; our selection of 5% tolerance resistors is safe on these as well.

The op-amp in this circuit, used as a voltage buffer, is also non-ideal. However, when configured as an open-loop buffer like we have, any manufacturing non-idealities cause the gain to be slightly *less* than 1. Due to the device construction, the gain cannot be greater than 1 in a buffer configuration and it does not need to be considered for tolerance analysis of this system.

3 Cost and Schedule

3.1 Cost of Labor

The labor costs are estimated based on a typical starting salary for an Electrical Engineering graduate from the University of Illinois at Urbana-Champaign. The professional labor rate is derived from the average starting salary for Electrical Engineering graduates at the University of Illinois [1], with an average annual salary of $90,000, the hourly rate is approximately $43.27 per hour. The following calculation assumes each of the three partners contributes 20 hours per week over the final 9 weeks of the semester leading up to the final presentation.

Partner	**Hourly Rate**	**Overhead Multiplier**	**Hours per Week**	**Total Weeks**	**Total Labor Cost**
Yehia Ahmed	$43.27	2.5	20	9	$19,471.50
Sandra Georgy	$43.27	2.5	20	9	$19,471.50

Jonathan Sengstock	$43.27	2.5	20	9	$19,471.50
Total Labor			**60**	**9**	**$58,414.50**

3.2 Cost of parts

The parts list reflects the market value of all components required to build the Solar Scrubber. Because the team is reusing several structural and mechanical elements, the actual out of pocket expenditure is lower than the listed total. Furthermore, utilizing pre-assembled sections significantly reduces the required machine shop labor hours, as the primary work shifts from fabrication to minor modifications and assembly.

Description	**Manufacturer**	**Part #**	**Quantity**	**Cost**
Solar Panel (20W)	Solar Power Industries	SPI-020M-9.5	3	$150.00
Microcontroller	Espressif	ESP32-S3-WROOM-1	1	$15.00
DC Motor Driver	STMicroelectronics	L298N	2	$12.00
Buffer/Level Shifter	Texas Instruments	SN74AHCT541	1	$1.50

12V DC Motor (High Torque)	Generic	N/A	4	$60.00
12V Water Pump	Generic	N/A	1	$15.00
LDO Regulator (3.3V)	Diodes Inc	AP2112K-3.3	2	$2.00
Timing Belt and Pulleys	Generic	GT2	1	$30.00
Aluminum Extrusion Frame	80/20 Inc	10 Series	1	$80.00
Machine Shop Labor	UIUC ECE Shop	Services	10 Hours	$500.00
Total Parts/Shop				**$865.50**

The grand total represents the full investment in professional engineering time and the hardware necessary to deliver a functional prototype.

Total Labor: $58,414.50

Total Parts and Shop Services: $865.50

Grand Total: **$59,280.00**

This section lists only the costs incurred for new components. By repurposing the solar panels, frame, water pump, motors, and pulley system, these items are excluded from the cash budget. Machine shop labor is kept at 2 hours for minor adjustments to the existing assembly.

Description	**Manufacturer**	**Part #**	**Quantity**	**Cost**
Microcontroller	Espressif	ESP32-S3-WROOM-1	1	$15.00
DC Motor Driver	STMicroelectronics	L298N	2	$12.00
Buffer/Level Shifter	Texas Instruments	SN74AHCT541	1	$1.50
LDO Regulator (3.3V)	Diodes Inc	AP2112K-3.3	2	$2.00
Machine Shop Labor	UIUC ECE Shop	Services	2 Hours	$100.00
Actual Parts Total				**$130.50**

The grand total represents the combined professional value of the engineering labor and the specific cash investment required to finalize the prototype.

- Total Labor: $58,414.50
- Actual Parts and Shop Services: $130.50
- **Grand Total: $58,545.00**

3.3 Schedule

The following table outlines the timeline from current development through the final presentation, based on the course milestones provided in the academic calendar.

Week (Date)	General Tasks	Yehia Ahmed	Sandra Georgy	Jonathan Sengstock
(March 2)	Design Review with Instructor/TAs; finalize system architecture; submit 2nd round PCB order.	Lead Design Review presentation and technical justification.	Complete PCB layout modifications for logic power rails.	Verify dimensions of repurposed frame for mounting adjustments.
2 (March 9)	Breadboard Demo; submit final machine shop revisions; order MCU and motor drivers.	Conduct sensor calibration tests on breadboard for telemetry.	Manage 3rd round PCB ordering and auditing process.	Coordinate with ECE Shop for frame and motor mount machining.
3 (March 16)	Spring Break	Independent study and preparation for assembly.	Hardware inventory check and documentation prep	Mechanical stress analysis of gantry pulleys.
4 (March 23)	PCB assembly/soldering; begin ESP32-S3 locomotion firmware; 4th round PCB order.	Develop control logic for the 2 axis locomotion sequence.	Assemble and test the 3.3V and 5V logic power rails.	Perform initial dry fit of motors and pulleys on machined frame.
5 (March 30)	Individual Progress Reports; integrate 12V mechanical rail; start solar telemetry.	Complete Progress Report and telemetry sensing code.	Complete Progress Report and level shifter signal testing.	Complete Progress Report and secure timing belts to gantry.
6 (April 6)	Progress Demo; test "Spray then Scrub" sequence; Team Contract Assessment.	Demonstrate sensor triggered cleaning cycles during demo.	Verify signal integrity of shifted pulses during motor load.	Calibrate horizontal and vertical travel limits on the array.

7 (April 13)	Full system endurance testing; debris detection calibration; refine step counting.	Optimize power saving dormant state logic for the MCU.	Monitor LDO thermal performance during peak cleaning loads.	Finalize mechanical cable management for moving gantry.
8 (April 20)	Mock Demo and Mock Presentation; submit Video Assignment; finalize slides.	Record and edit the Video Assignment of the scrubber.	Finalize data visualizations for energy yield improvements.	Perform final safety check on all electrical/mechanical links.
9 (April 27)	Final Demo and Presentation; submit final papers and Lab Notebook.	Lead the technical Q&A session for the final presentation.	Finalize all technical diagrams and citations in final paper.	Complete lab checkout and return all equipment.

4. Discussion of Societal Impact, Engineering Standards, Ethics, and Safety Considerations:

4.1 Public Health, Safety, and Welfare

A primary argument against widespread solar adoption is the high requirement for consistent physical maintenance and cleaning, which poses safety risks to workers. The Solar Scrubber provides a proactive solution to this welfare concern by automating a hazardous task, thereby reducing the incidence of workplace injuries related to solar array maintenance. Furthermore, by ensuring that renewable energy systems remain operational at peak efficiency, the project promotes the general welfare of the community through more consistent access to green energy.

4.2 Economic Factors

The Solar Scrubber directly combats the economic "maintenance trap" of solar energy. By providing a low-cost, automated alternative to manual cleaning services, the system lowers the total cost of ownership for solar installations. This allows for cheaper energy capture, which in theory reduces electricity costs for all consumers. The device's ability to remain in a low-power dormant state when cleaning is not required ensures that the operational cost remains negligible compared to the financial gain of increased panel output.

4.3 Environmental Factors

While the system does utilize water for cleaning, it is designed as an environmentally responsible solution. The "Spray-then-Scrub" sequence minimizes water waste by using short, targeted bursts rather than continuous flow. Additionally, the device is optimized for low power consumption, drawing only minimal current from the logic rails while dormant and using its 12V mechanical rail only during active cleaning cycles. By removing the debris that can cause significant power drops, the system ensures that the environmental benefit of the solar panels is fully realized without a heavy ecological footprint from the maintenance tool itself.

4.4 Social Factors

The Solar Scrubber promotes the democratization of renewable energy by making solar technology more accessible and less intimidating for the average consumer. Maintenance is one of the primary social deterrents for residential solar adoption; by providing a "set and forget" automated solution, the project reduces the social barrier to choosing green energy. Furthermore, by automating a labor intensive and dangerous task, the project contributes to a social shift where technology is used to protect human workers from avoidable physical risks, such as falls from heights or prolonged heat exposure.

4.5 Cultural Factors

Culturally, this project aligns with the global movement toward automation and the optimization of resource management. In many cultures, the transition to sustainable energy is seen as a collective responsibility, and tools like the Solar Scrubber embody that value by ensuring every watt of potential energy is captured efficiently. By utilizing an open source platform like the ESP32-S3 and standard motor drivers, the project also participates in the growing "Maker" culture, which emphasizes accessible, community driven engineering and the repairability of technology.

4.6 Global Factors

On a global scale, energy security and climate change are universal challenges. The Solar Scrubber provides a scalable maintenance solution that is applicable in any geographic region where solar energy is viable. In developing nations or arid climates where dust and debris significantly impact panel performance, an automated, water efficient tool is vital for the economic success of renewable infrastructure. Because the design minimizes power consumption and remains dormant when not in use, it is globally relevant as a low impact tool for maximizing the world's transition to a carbon neutral power grid.

4.7 Ethical and Safety Considerations

The Solar Scrubber project is built around several core engineering standards to ensure it meets industry expectations for safety and reliability. We are adhering to IEEE 1621-2004, which governs user interface elements for power control, specifically to manage the transitions between the device’s "dormant" and "active" states without wasting energy [4]. For the internal hardware, UL 61010-1 provides the necessary safety requirements for electrical equipment used in control and laboratory settings, ensuring our 12V and 5V power rails are properly isolated [5]. Furthermore, the custom PCB design follows IPC-2221B standards, which dictate the specific trace widths and clearances required to handle the high current surges from the four high-torque motors without overheating or failure [6].

Our ethical approach is grounded in the IEEE Code of Ethics, specifically the mandate to prioritize the safety and welfare of the public [3]. While automating the cleaning process might raise questions about displacing manual labor, we justify this transition by prioritizing human safety; replacing a person working on a high, slippery roof with a robot is a clear ethical win for worker welfare [3]. We’ve also addressed the social and environmental implications of water usage. By implementing a "Spray-then-Scrub" sequence using the CRAFTSMAN 1-Gallon Tank Sprayer [2], we ensure the device remains an environmentally responsible solution even in arid regions where water is a scarce resource. This design choice directly reflects our commitment to sustainable engineering and global resource management.

Safety concerns for this project are divided into electrical and mechanical risks, following the standard guidelines for the University of Illinois ECE department [7]. On the electrical side, the primary risk involves the proximity of the 12V water pump to the logic circuitry; any leak could cause a catastrophic short circuit [7]. We also have to manage the back-EMF from the motors, which could fry the ESP32-S3 if not properly isolated [7]. Mechanically, the gantry system creates pinch points along the 39.75-inch horizontal travel path, and the overall stability of the 22.5" x 13.25" panel array is a concern if the scrubber's weight shifts too abruptly during operation.

To mitigate these risks, we have implemented several hardware and software safeguards. The SN74AHCT541 buffer acts as a physical barrier and level shifter, isolating the sensitive 3.3V microcontroller logic from the higher-voltage components. To prevent water damage, all electronics are sealed in an IP65-rated enclosure positioned away from the spray nozzles. Mechanically, we’ve programmed "soft limits" into the firmware to ensure the gantry never attempts to move past its physical boundaries, and the timing belts are tensioned to minimize exposed pinch points. During development, all integration is performed using a current-limited power supply to prevent hardware damage, ensuring that both the developers and the end-users are protected from unsafe operating conditions [7].

References

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[3] "IEEE Code of Ethics," *IEEE*, [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: Feb. 27, 2026].

[4] "Standard for User Interface Elements in Power Control of Electronic Devices," *IEEE Standard 1621-2004*, 2004.

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