# Tab 1

**<u>Project Proposal</u>**
Solar Scrubber
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The system is designed for the 280W solar panels located on the ECEB rooftop. The project focuses on retrofitting existing installations, so the design will accommodate standard panel dimensions without requiring the purchase of a new panel.

**1.1 Problem and Motivation**

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.

**1.2 Solution**

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-WROOM-32U microcontroller, which handles the complex logic required for navigation and sensor integration. The ESP32 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.
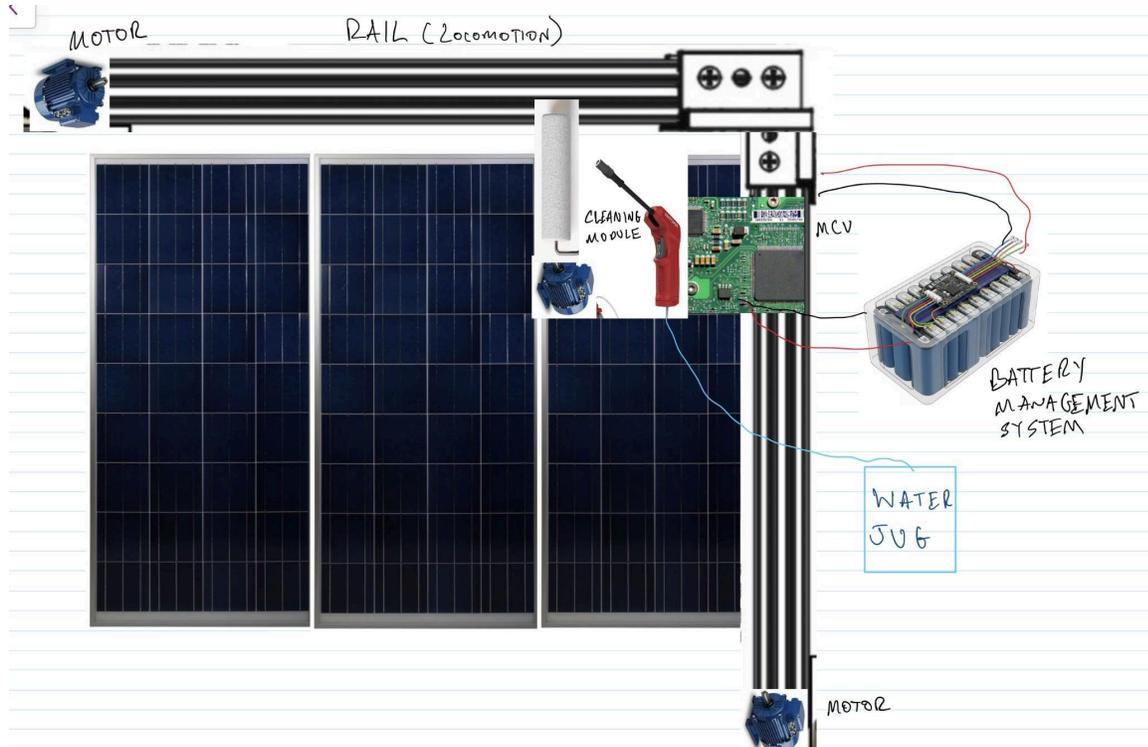
**Figure 1: System Visual Aid (Top View)**

## 1.3 High-Level Requirements

- The cleaning system must work entirely: The sprayer must dispense the solution and the brushless dc motor must be able to spin to clean the panel with a cloth.
- Using a custom algorithm that monitors each panel's power output, the system must be able to detect a noticeable dip in power of each individual panel (>25%) and be able to attribute it to dirtiness or basic shading.
- We will have a rough baseline for what the panel's power output should be in ideal conditions (e.g. in direct sun); the cleaning system must restore power output to at least 90% of the nominal power output after cleaning.
- The robot must successfully transition from autonomous to manual control once asked by the user.
- The power conversion system must maintain a stable 3.3V rail for the MCU during peak motor/pump draw.
- Automation Logic: The controller must successfully transition from "Idle" to "Active-Clean" mode within 2 seconds of the MPPT detecting a debris-related power loss exceeding 25%.
- I/O Synchronization: The subsystem must simultaneously manage four PWM output channels (two for locomotion, one for scrubbing, and one for the pump) while maintaining a Bluetooth data uplink.
- Safety Override: The controller must prioritize a physical or Bluetooth "Stop" command over any autonomous routine, cutting power to all drive motors in less than 200ms.

## 2. Design

### 2.1 Past ECE 445 Group

Our group would like to acknowledge a past ECE 445 group (Team 26, Spring 2025) that designed a solar panel cleaner with some similar ideas to ours. We are adding some key components that differ from theirs, including the multiple panel-array and power output tracking. After speaking with the machine shop staff, they recommended reusing the other group's movement section to save time, labor, and materials costs. This includes their horizontal and vertical axis motors, and the pulley and rail system. All other components in the project will be our own.
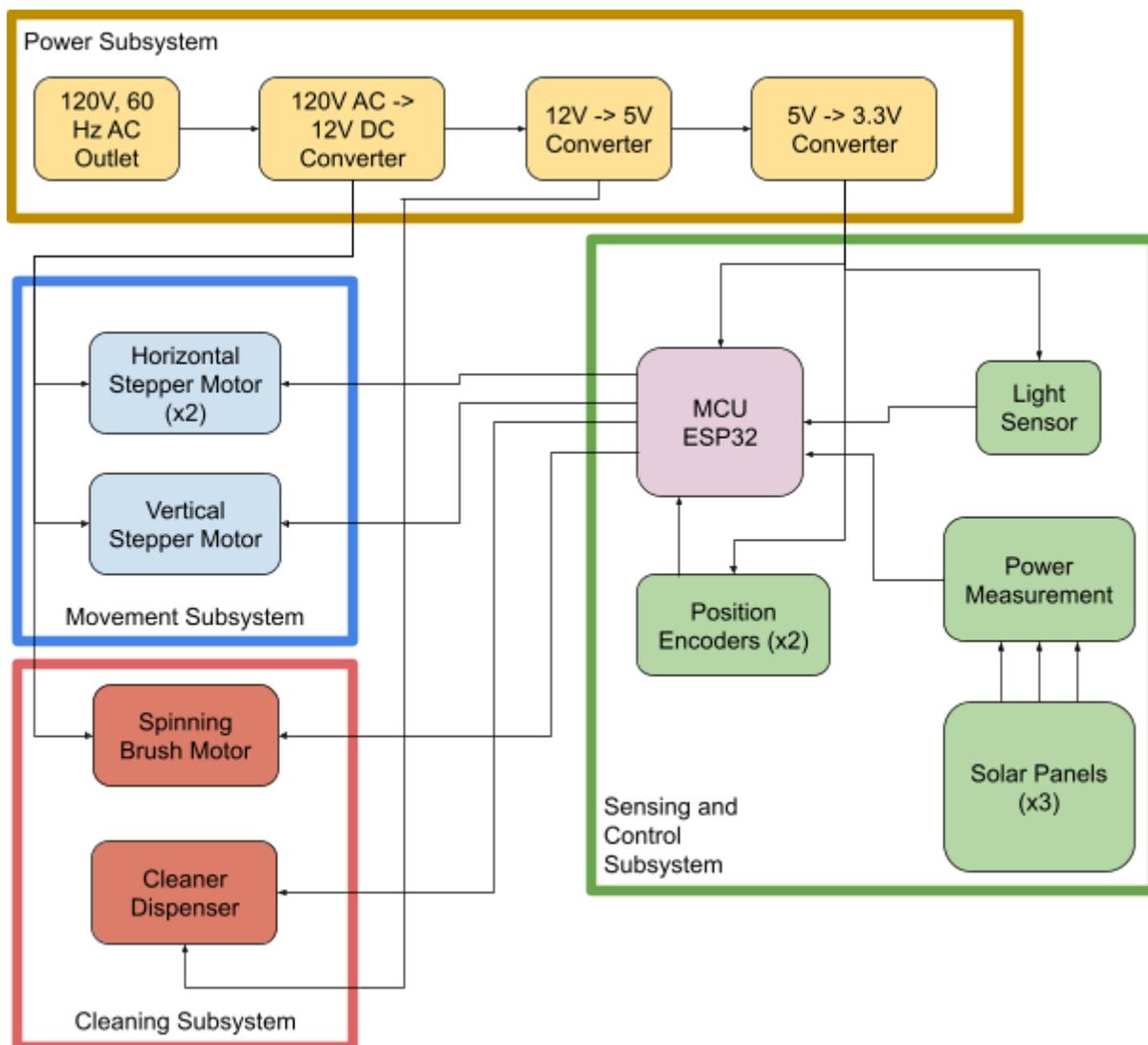
### 2.2 Block Diagram



**Figure 2: Block Diagram**

## 2.2 Subsystem Descriptions

### 2.2.1 Locomotion/Movement

The locomotion subsystem is responsible for the mechanical translation of the cleaning module across a three panel solar array using a 2-axis gantry configuration. The design features a primary horizontal rail mounted to the top of the solar panel array which supports the main controller housing. Two parallel vertical rails are attached to this central carriage, extending downward across the face of the panels with the cleaning module suspended between them.

Movement is achieved through 12V DC motors integrated with a system of gears, pulleys, and timing bands. This setup is structurally similar to the Cartesian motion of a 3D printer. To track position, the locomotion motors feature Hall Effect encoders that send pulses to the ESP32 to calculate distance. One motor assembly drives the entire robot horizontally along the top rail to transition between panels. A synchronized secondary motor set drives the cleaning module vertically along the parallel rails.

This 2-axis control allows the ESP32 to automate a precise cleaning path. On startup, the bot executes a homing sequence, reversing until it hits physical limit switches at the (0,0) position to reset the pulse counter to zero. This ensures the robot can cover the entire surface area of each individual panel before navigating autonomously to the next without the path drifting over time.

The locomotion system should be able to accurately report position on both axes to the microcontroller, and move the cleaning module to all points over the solar array's surface.

### 2.2.2 MPPT and Algorithm

The Maximum Power Point Tracking (MPPT) component extracts power from the solar panel. The MPPT analyzes the I-V characteristics of the solar panel so that MCU can identify sections that are not meeting expected performance. These measurements enable targeted cleaning rather than a full array sweep and allow the system to compare output power before and after maintenance to verify efficiency gains.

The MPPT will use a voltage sensor to measure the solar panel's voltage and feed it into the MCU's ADC. We will also use a shunt resistor with an op-amp for current sense measurement. We multiply the voltage and current to get the power output of the panel.

The power measurement system should be able to accurately measure the output power of the panels with a small enough margin of error to predict if the panel is dirty.

The MPPT control algorithm implemented on the ESP32 uses a Perturb and Observe method. The MCU periodically perturbs the operating point of the panel by slightly adjusting the duty cycle of a DC-DC converter connected to the panel. After each perturbation, the MCU computes the new power and compares it with the previous power measurement. If the power increases, the algorithm continues adjusting in the same direction. If power decreases, direction is reversed.
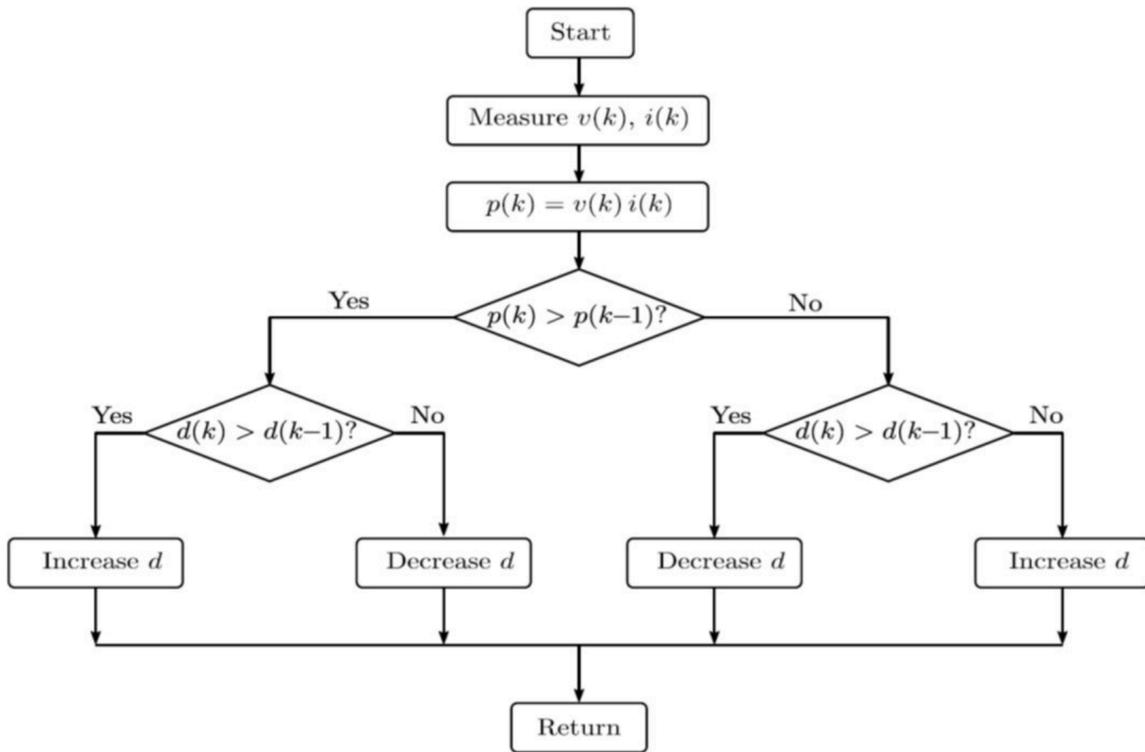
**Figure 3: Perturb and Observe MPPT Algorithm (Provided from ECE 469)**

### 2.2.3 Cleaning Module

The cleaning module features a 12V DC motor with a rotating towel and a 12V water pump for fluid delivery. To bridge the gap between the 120V wall power and the 3.3V logic of the ESP32, the system uses an AC-DC power adapter and an L298N motor driver. The driver acts as a high speed electronic switch, directing 12V power to the scrubbing motor and pump based on low voltage commands from the MCU. The module features a 12V DC motor with a rotating towel and a 12V water pump.

To facilitate fluid delivery, the system utilizes a battery powered Craftsman sprayer as an external reservoir located off the panel array in a separate jug or bucket. This sprayer is connected to the cleaning module via extended flexible tubing. The L298N motor driver serves as the control interface between the ESP32 and the sprayer. Since the Craftsman unit is already battery powered, the motor driver does not step up the voltage but instead acts as an automated switch that allows the 3.3V logic of the MCU to trigger the high current pump.

The fluid delivery process is fully automated within the control logic. When the cleaning function is called, the ESP32 triggers the sprayer to pump water from the external reservoir directly onto the panel surface. This sequence is hard coded to ensure the microfiber cloth is saturated for a set duration before the scrubbing motor begins rotation. This setup allows for

consistent high pressure cleaning without requiring manual intervention or a persistent wireless connection.

### 2.2.4 Control Unit (MCU)

The controller subsystem serves as the centralized "brain" of the Solar Scrubber, responsible for automating the robot's movement and cleaning cycles based on real-time environmental data. Using an ESP32-WROOM-32U, the subsystem manages a complex array of inputs and outputs to ensure precise 2-axis navigation across the three-panel array.

The automation logic is governed by a Finite State Machine (FSM) that processes inputs from the MPPT circuit (voltage and current), the light sensor (ambient irradiance), and limit switches (physical position markers). When the MPPT detects a power dip that the light sensor confirms is due to debris rather than shade, the controller triggers the locomotion sequence.

The controller outputs pulse-width modulated (PWM) signals to the L298N motor drivers, which regulate the speed and direction of the 12V DC motors driving the horizontal and vertical pulley systems. Simultaneously, it manages the cleaning module by activating the scrubbing motor and water pump in a synchronized pattern based on the robot's current coordinates.

### 2.2.5 Power Conversion
The robot will have 2 modes of operation: a plugged in mode and an off-grid/solar-powered mode.

The power conversion subsystem supplies and regulates the voltages for all electronic components. For the on-grid mode, an AC–DC converter steps down the 120V AC from the building grid to a stable 12V DC rail. From there, DC-DC buck converters are used to provide the 5V and 3.3V rails required for the sensors and the ESP32 logic.

The off-grid mode uses the TI BQ25798 chip configured as a buck-boost battery charger and power-path controller. The TI chip will allow us to draw power at different operating conditions and charge a battery pack using an external Battery Management System (BMS). The robot will be powered off the battery pack as it's charging.

### 2.2.6 Solar Panel

The solar panels we are designing our project around are 20 W panels, with an open-circuit voltage of 12 V and a short-circuit current of 12 A. They are about 22.5 by 13.25 inches for each panel, and we plan to place 3 of them in parallel.

### 3. Design Verification

### 3.1 Controller Subsystem

- The movement buttons must trigger the ESP32 to send pulse width modulation signals to the L298N drivers to engage the positioning motors.
- The sprayer button must successfully activate and deactivate the water pump nozzle.
- The brush button must trigger the microcontroller to engage and disengage the brush motor for the scrubbing cycle.
- The manual and autonomous buttons must cause the internal Finite State Machine logic to switch between user-controlled and sensor-driven modes.
- The microcontroller must be able to read and process digital signals from the limit switches and analog data from the MPPT and light sensors.
- In autonomous mode, the controller must react to power drops by calculating coordinates and sending signals to the motor drivers and cleaning module.

## 3.2 Drivetrain and Locomotion Subsystem

- The microcontroller must provide high and low logic signals to the L298N motor drivers to control the direction and speed of the 12V DC pulley motors.
- The system must be capable of completing a full sweep of the three-panel solar array (from the start position to the end and back) in under 5 minutes.
- The DC motors must operate at a nominal voltage of 12V plus or minus 10 percent and draw no more than 2.0A of current each under full load.
- The pulley and belt system must be able to support the weight of the cleaning unit and fluid tank without slipping or causing excessive mechanical tension.
- Failure of this subsystem could result in the motors drawing excessive current and overheating, or the robot becoming stuck in a stalled position on the array.

## 4. Conclusion

### 4.1 Accomplishments

By the conclusion of this project, we expect to have developed a functional robotic prototype capable of autonomous navigation and targeted cleaning of solar panels. We will have successfully integrated an ESP32 control unit with an MPPT-driven algorithm that leverages both power measurements and light sensor data to optimize cleaning efficiency. Furthermore, the system will demonstrate power management, by taking input from AC wall power, and regulating it to a variety of DC voltages for our equipment.

### 4.2 Uncertainties

The primary technical uncertainty involves the threshold calibration for the **MPPT algorithm**; specifically, determining if a percentage drop in power is from dirtiness or shading/weather. Additionally, there is uncertainty regarding the mechanical friction and traction of the rail system

when exposed to moisture from the cleaning solution or environmental rain, which may affect the consistency of the locomotion subsystem.

## 4.3 Ethical Considerations

## Ethics

The Solar Scrubber project is built upon the core principle of sustainable engineering, aiming to maximize the efficiency of renewable energy infrastructure. In accordance with the IEEE Code of Ethics, we prioritize environmental stewardship by utilizing a water-based cleaning module that eliminates the need for caustic chemical agents, thereby protecting the local soil and water from hazardous runoff. We also commit to honesty in our technical reporting, ensuring that the power-efficiency gains calculated by our MPPT logic are reported accurately. Furthermore, the project aims to reduce human risk by automating a maintenance task that would otherwise require manual labor in potentially hazardous rooftop or large-scale solar array environments.

## Safety

Safety is addressed through a multi-tiered approach involving physical, electrical, and logical failsafes. The 2-axis pulley system is bounded by physical limit switches that act as hard interrupts to the ESP32, ensuring the robot cannot travel beyond its mechanical frame even in the event of a software glitch. Electrically, the high-current 12V DC motors and cleaning pump are driven through L298N H-bridges that isolate the sensitive ESP32-WROOM-32U logic from back-EMF and power spikes. Finally, the autonomous Finite State Machine (FSM) includes a safety check that cross-references MPPT voltage drops with light sensor data to prevent the robot from initiating a cleaning cycle during low-light or nighttime conditions, which could lead to accidental operation while maintenance personnel are present.

## References

[1]  https://www.lowes.com/pd/CRAFTSMAN-1-Gallon-Tank-Sprayer/1001433038