Automated Cleaning System for Solar Panels

By

Prudhvie Gudapati (prg3)

Alexander Perez (apere46)

Austin Delveaux (austind3)

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Professor: Arne Fliflet

TA: Uma Lath

Team 10

Abstract

This report goes over the information involved in developing an automated solar panel cleaning system. We first begin with the problem that we wished to address and then proceed into discussion of the solution that would help solve the issue. After this we discuss the high-level requirements that would need to be achieved to deem the solution successful. We then discuss each subsystem and their requirements that were needed to make the system work. After this we talk about the costs associated with making this. Finally we conclude the report along with discussions of what we would change, the ethical considerations of the project in the context of the IEEE Code of Ethics, and what further could be done to better the system.

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1 Introduction

1.1 Problem and Solution

As solar panels are constantly exposed to the outdoor elements to achieve maximum efficiency and performance, the natural dust in air or pollutants from nearby settlements can cover the surface of the photovoltaic arrays with particulate matter that negatively affects their power output [1]. Although panels on average only need to be cleaned two times per year this is just to be certain that panels can reach near max power output again and not really making sure that it produces as much power as it can [2]. Current methods to remove this contamination are also laborious and require human intervention to physically remove the dirt and dust which increases operation costs of solar farms [3]. In applications where solar panels are installed on rooftops, cleaning can also be difficult as it will be left to the homeowner who may not be able to easily access the panels without specialized equipment.

To solve this issue, our team developed an automated system which can detect decreased power output due to dirt coverage by using a hall sensor that tracks current output and checking a weather API that will let the system know the cloud coverage. It then deploys a cleaning spray followed by a wiper to remove contaminants from the solar panels. This system can also be utilized to clear snow in cold climates by activating the cleaning system to remove the snow.

The high level requirements that we would want this system to accomplish are:

1. The system will be able to clean the solar panel from all debris and coverings.
2. The cleaning of the solar panel with wiper and sprayer will happen when the power output reaches to 65%-75% [1] of the max output for a period of at least 7 days. The cleaning will return the solar panel back to 90+% power output.
3. The system will be self-sustaining as it will use less power to clean than it will gain from cleaning.

1.2 Block Diagram

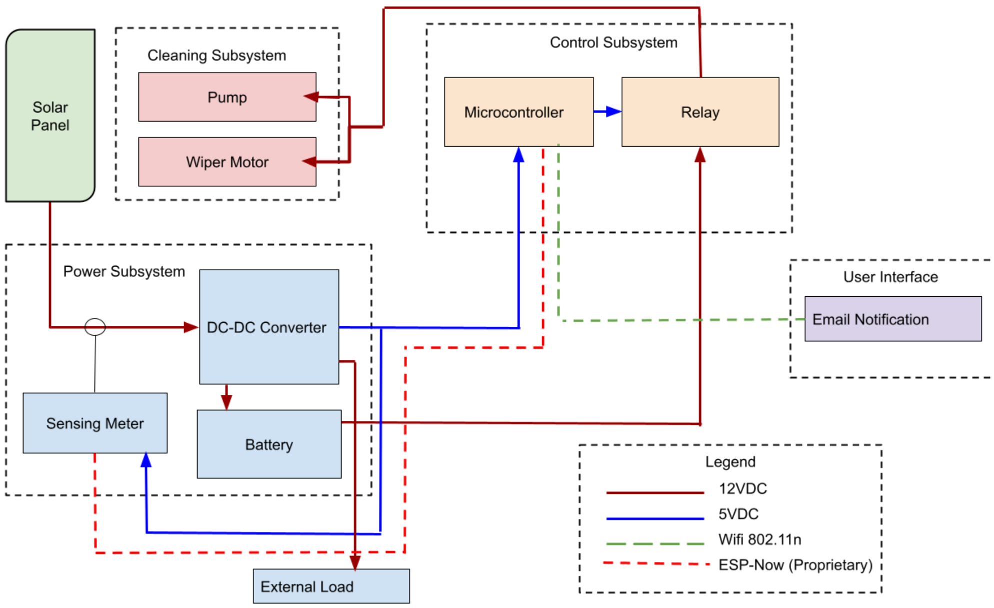

Figure 1.1: System Block Diagram

As we show in Figure 1.1 our system is split into three different subsystems, which are used in combination with each other that allows us to clean the solar panel autonomously and as efficiently as possible.

The cleaning subsystem is made up of just a motor and pump which are controlled by inputs from the control subsystem. The parts of the cleaning subsystem will receive voltages from the power subsystem that are controlled by the control subsystem. The voltages will be held for determined times to be sure that the panel gets cleaned as well as being sure that energy is not wasted by running the system for too long of a time.

The power subsystem consists of the DC-DC converter, battery charging circuit, and sensing meter. All of these components aside from the sensing meter are on a custom PCB. A linear regulator is used to supply a steady 5VDC supply for the microcontroller. An operational amplifier (op-amp) based circuit checks if the solar panel output is high enough to charge the connected battery and allows for current to flow. If the panel output is too low (either through soiling or nightfall), the system will switch to allowing the battery to act as the main supply. Finally, the sensing meter uses a hall effect sensor to measure the output current of the solar panel and communicates this information wirelessly to the microcontroller on the PCB.

The control subsystem consists of the main microcontroller which acts as the brain of the overall system and the relay modules which control the wiper and sprayers motors. Based on the readings of the sensing meter and the results of the weather API, the main microcontroller can send control signals to the relays in order to close the circuit and provide current to the wiper and sprayer motors. This subsystem also sends notifications to the user through WiFi signals.

2 Design

2.1 Cleaning Subsystem

2.1.1 Motor

When working with the cleaning subsystem one of the first considerations that needed to be taken when trying to determine the parts of the cleaning subsystem was the overall design of the setup. When we initially began we needed to determine how we wanted the panel to be wiped as there were possible different ways that it could be done. The first idea was to have the wiper attached to a chain system that would pull the wiper along by a motor and gear setup as shown in Figure 2.1.

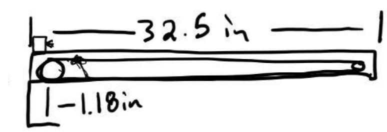

Figure 2.1: Initial design of wiper setup

After our initial discussion with the machine shop they told us that the chain system had two major issues with it. One being that since we wanted the wiper to be able to properly clean and push debris off and wipe soiling the chain system would not be able to apply pressure to do so. The other issue that was brought up with this system was that the chain would cause wear and tear and break down the surrounding area or itself after some time. This was something that we wanted to avoid at all costs as our system's goal was to have little to no human interaction and if a part needed to be replaced often it would be extremely counterproductive.

The next idea that we took into consideration was using a linear attenuator to push a wiper down the panel. With the wiper length being able to cover the majority of the 26 inch width of the panel, as shown in Figure 2.2, it seemed like a good idea, but we could not find an attenuator that reached more than 12 inches and within our budget. We were able to find attenuators that were able to reach across the width of the panel, but the issue then came that we could not find a wiper greater than 28 inches and the panel length is 32.5 inches, shown in Figure 2.2. Two wipers and attenuator were considered, but this is two motors that we would have to run and twice the power consumption which is not wanted. With one attenuator another issue arises is that the wiper has a single point of force while being pushed so gripping and wobbling of the wiper blade can occur. The issue is then for the wiper to overcome gripping and wobbling the motor would need to consume more current and therefore more power to clean.

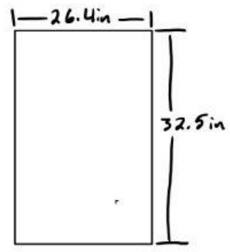

Figure 2.2: Panel dimensions

Finally as shown in Figure 2.3 we decided to use a worm gear that ran the entire length of the panel at and moved a wiper arm up and down. With this setup we desired a motor with a high torque leading us to go with a gear motor. We went to the machine shop with this idea and they agreed that it was the best course of action as there would be little wear compared to the chain idea and we use less power compared to the linear attenuator as we would only need one gear motor.

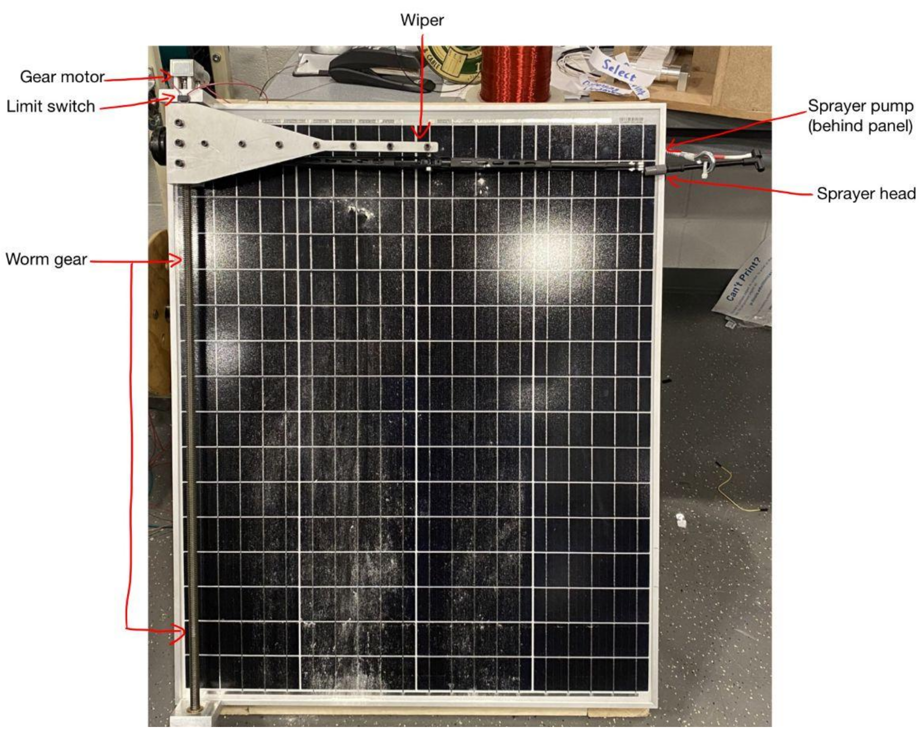

Figure 2.3: Final design of system

With the plan to use the gear motor as our driving we gave the supplies to the machine shop with some of our ideas and produced what we see in Figure 2.3. The gear motor is placed at the top driving the worm gear which will allow us to move the wiper up and down for cleaning. After the plan was all set, selection of the motor was easy as we knew we needed a 12VDC motor and high torque. We ended up initially getting Bringsmart JGY-370 10 rpm motor, which had a torque of 17 Kg*cm which was high enough for our use. However, after testing it on the panel we saw that it took two minutes to travel 2 inches down the panel meaning it would take an hour to go up and down. We decided that this was too long for a cleaning cycle and felt we wanted to have quarter the time of wiping so we got a Bringsmart JGY-370 40 rpm motor that allowed us to do so. The Bringsmart JGY-370 40 rpm motor had a torque of 4.5 KG*cm which had us concerned it would not be strong enough. We ran some tests and found that it was able to properly move the wiper up and down with no strain and would travel 2 inches in 30 seconds.

2.1.2 Sprayer
For the sprayer we didn't have much of an idea of what we would actually want, except some requirements that we wanted the sprayer to meet. Our initial discussion with the machine shop consisted of the wiper and motor discussion as explained above, but also explaining our idea behind the spraying. We explained that we wanted a sprayer that ran off less than 12VDC and that would also be able to spray the width of the panel, 26 inches, and reach about half way down the length of the panel, 15 inches. With these requirements the machine shop recommended that we look into a hand held sprayer from Lowe's, the CRAFTSMAN 1-gallon Handheld Sprayer. Looking into it we saw that it ran on less than 12VDC, at 5VDC, which was wanted as our max voltage output. The sprayer also met the requirement for spraying as it had a reach of 20 feet when on jet and on the shower setting it covered the panel perfectly.

Next was the decision on how to place the sprayer on our design so that it was secure and would not mess with the other parts of the system. As shown in Figure 2.3 we decided to have it on the other side of the panel so that it was away from all electronic circuits and away from the motor. We also were sure to have the hose head spray downward to be sure that it would not reach near the motor.

2.2 Power Subsystem
As the power subsystem takes in the unregulated solar panel output and creates stable values for charging a battery, supplying a microcontroller with power, and running the cleaning subsystem, its design was of the utmost importance. The components which handle the DC-DC conversion and charge the battery were sized to handle the significant output current from the solar panel at maximum operating point which is determined to be 5.56 A at 18VDC as specified by the solar panel label. In addition, as many components as possible were chosen to be of the through-hole type as they are able to withstand higher power with an added benefit of being easier to solder. To conserve space, the finalized PCB design for all following subsections are in Appendix B.

2.2.1 DC-DC Converter and Battery Charging
For the DC-DC converter and battery charging circuit, an op-amp based regulator was chosen as it allowed for fluctuation in battery voltage while charging and discharging which is common with lead acid batteries [4]. To accomplish this, several op-amps were used in the comparator configuration which checks if a reference voltage (in this case the solar panel output voltage) is

above or below the test voltage (the battery voltage). The basic comparator configuration of an op-amp is shown in Figure 2.4 with analog inputs.

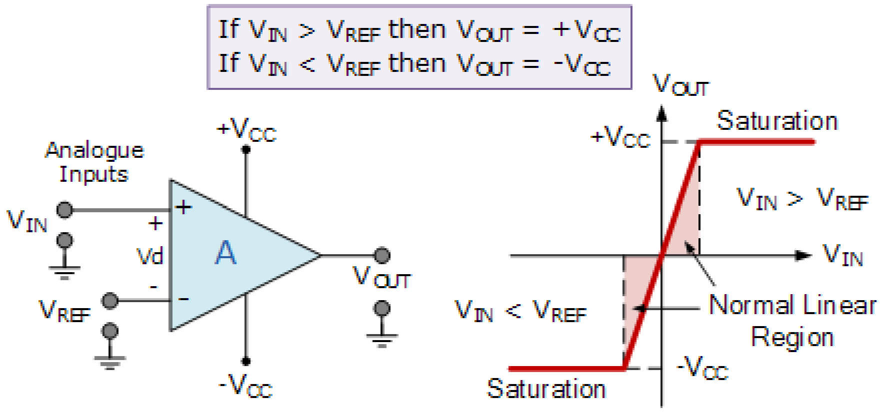

Figure 2.4: Basic op-amp comparator and output voltage graph.

As we intended to have several reference voltages for the regulator, multiple comparators were used with several types of methods to generate V_{REF}. The variations shown in Figure 2.5 which use Zener diodes, battery voltage, and resistor divider networks were used in creating the circuit. The variable position reference source which utilizes a potentiometer to create a variable V_{REF} was not implemented in this design.

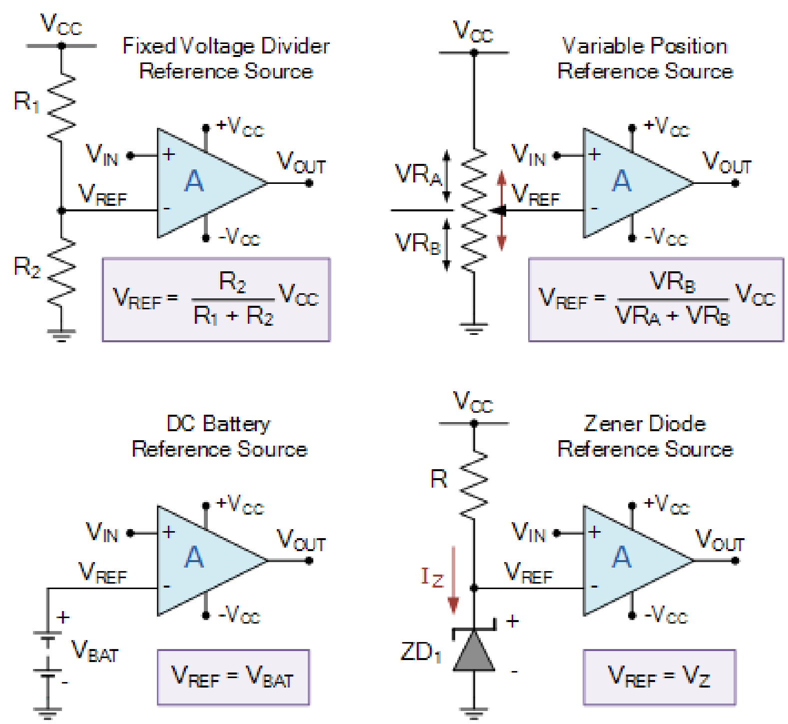

Figure 2.5: Examples of different comparator circuits using op-amps

A feature that was implemented in this circuit was LED indication of charging status with a green one used to indicate the battery was being charged and a red one to show the solar panel output was insufficient providing enough power for charging. An astable multivibrator was added to the red LED to blink it at a rate of 3Hz to make it more visible to the user that the solar panel is not charging the battery. Figure 2.6 shows the implementation of a multivibrator which uses another op-amp.

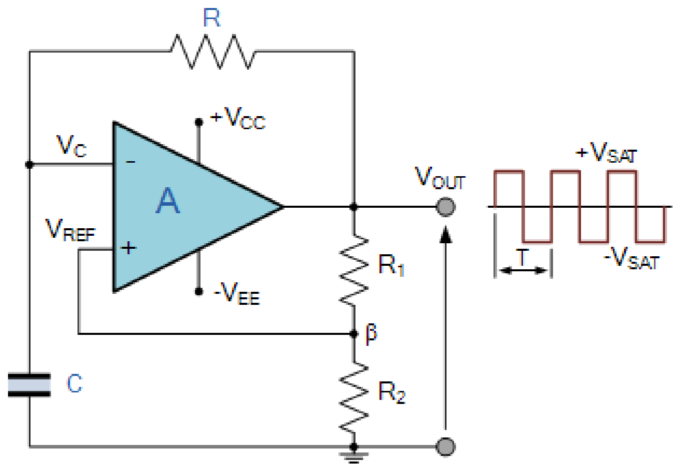

Figure 2.6: Comparator multivibrator implemented using an op-amp

The value β is the feedback fraction in Equation 2.1 which is then combined with Equation 2.2 to find the period of oscillation as the circuit is an RC oscillator. The inverse of period then gives the frequency of the blinking LED.

$$\beta = \frac{R_2}{R_1 + R_2} \tag{2.1}$$

$$f = \frac{1}{T} = \frac{1}{2RCln(\frac{1+\beta}{1-\beta})} \tag{2.2}$$

As we want the V^{+}_{SAT} to be 6VDC as obtained from a zener reference op-amp and V^{-}_{SAT} to be 0VDC and the LED to cycle between these values at a rate of 3Hz resistors R, R_1, and R_2 were chose to be 33kΩ, 10kΩ, and 820kΩ respectively. The capacitor was chosen to be a standard 1μF non polarized ceramic capacitor. Equations 2.1 and 2.2 were used to obtain:

$$\beta = \frac{820k\Omega}{10k\Omega + 820k\Omega} = 0.9880, f = \frac{1}{T} = \frac{1}{2RCln(\frac{1+\beta}{1-\beta})} = \frac{1}{2*33k\Omega*1\mu F*ln(165)} = \frac{1}{0.337} \approx 3Hz$$

The above op-amp theory, figures, and equations were obtained from [5] which was then applied to design a regulator which monitored solar output voltage and compared it with the battery floating voltage. The finalized schematic is shown in Appendix B. The LM324 quad op-amp chip [6] was used as the power draw is low (approximately 800mW) and the V_{CC} supply voltage could vary between 3VDC and 32VDC with no effect on performance. The output of the two comparators were then used to switch on and off power transistors which could handle the solar panel current, one op-amp provided a zener reference voltage of 6V for the final op-amp which was an astable multivibrator which blinked a red LED. The transistors chosen were the 2N3055 [7] which are intended for high power switching applications and could handle the minimum 2.1A for charging the battery. A BC327 PNP BJT [8] was used for turning on the green charge indicator LED as it was not going to handle significant current or voltage as the other transistors. Finally, as the solar panel has a low resistance and could be damaged by battery flow back into the semiconductor cells, a high power blocking diode was used to prevent this from occurring. The BYV79E-200,127 [9] was selected for its low forward voltage drop (approximately 0.9V) and ruggedness which was necessary for use in power applications.The circuit schematic is shown in Figure B.2 of Appendix B.

2.2.2 Microcontroller Supply Circuit

The next part of the power subsystem designed was the supply for the microcontroller which required a steady 5VDC. This was accomplished by adding a linear regulator to the output of the battery charging circuit which allows for either the solar panel or battery to power the microcontroller. The L7805 [10] was chosen due to its stability at a wide range of input voltages. Figure 2.7 shows the schematic of the circuit as referenced in its datasheet.

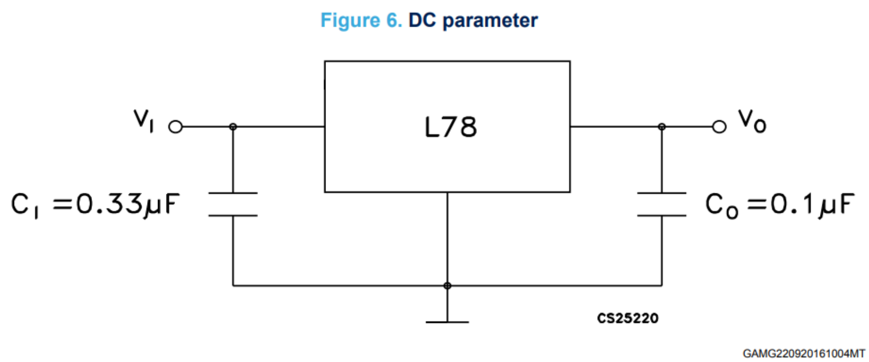

Figure 2.7: L7805 datasheet schematic of the regulator circuit

Capacitors C_i and C_o are smoothing capacitors to assist in stabilizing V_i if the regulator is located far from the supply filter and V_o to improve the transient response if the power draw fluctuates frequently. This circuit was fairly simple as V_i was connected to the battery output trace and V_o was connected to the 5V supply pin on the microcontroller. The ground was connected to the ground plane as all the circuits share the same ground through the solar panel connections.

2.2.3 Subsystem Supply Circuits

To simplify the circuit and to minimize losses through additional voltage conversion, the Control and Cleaning Subsystems are powered via previously established supply circuits. The relay modules (both SPDT and DPDT) are powered through the 5VDC linear regulator which is sufficient as they both draw under 50mA when powered. The wiper motor is powered through the output of the battery and its associated charging circuit through labeled terminal blocks as shown in Figure B.3 of Appendix B. Figure 2.10 in Subsection 2.3.3 also shows how the relay common terminals were connected as the 5VDC and 12VDC are sourced off of the PCB.

2.2.4 Current Meter

In order to initiate cleaning of the solar panel, the output power had to be monitored in a way which reliably varied with panel irradiance but also did not impact its performance. To do this, a hall effect sensor was used to measure the current output which was then collected by a secondary microcontroller and transmitted to the main microcontroller wirelessly.

$$J = Jsc - Jo\,(e^{qV/kT} - 1)[11] \tag{2.3}$$

When considering the hall sensor setup we needed to take into consideration that we needed the hall sensor to be able to be anywhere on the cable output of the solar panel and be able to read. With this in mind we decided to go with a loop current sensor that we would send the cable through and be able to be anywhere on the cable. We also wanted to get one that could interface easily with a microcontroller so a simple output would be optimal. The next consideration that we took in was the current output of the panel and what the max current was. As shown in Figure 2.8 the current output of the panel will be at most 6.5A and other currents determined by current density, equation (2.3), which means we need a hall sensor to read slightly more than this to not deal with accuracy issues.

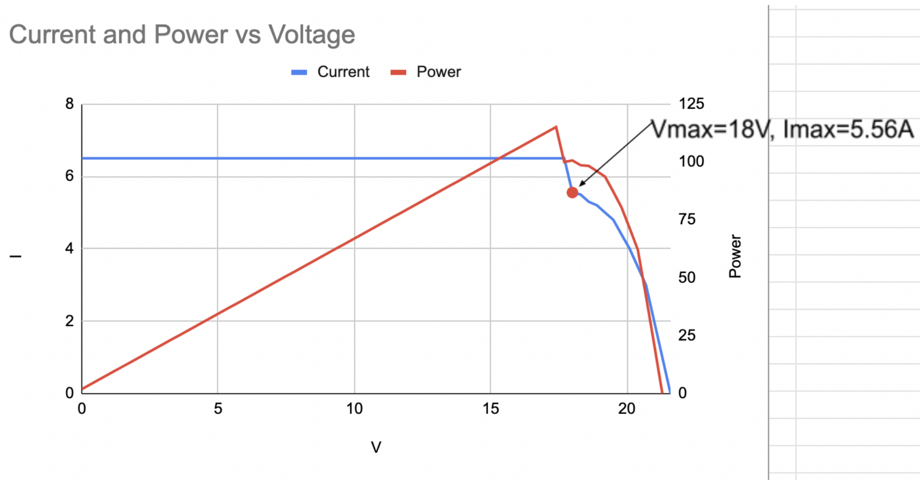

Figure 2.8: Solar panel current output compared to voltage

With these possible currents we decided to go with the bayite Ammeter Gauge with Hall Effect Sensor Transformer, which has a current range from 0A-100A and an accuracy of .3A.

2.3 Control Subsystem

2.3.1 Overview

The control subsystem acts as the brain of the overall system as it determines if the power subsystem can activate the cleaning subsystem for a set period of time. This subsystem consists of the main microcontroller and the relay modules which are connected to the wiper and sprayer motors. When considering the microcontroller, we were keen on finding one which has fast computing power. The ESP32 module offers an extra CPU core compared to its predecessors and has the options between WiFi, Bluetooth, and Bluetooth Low Energy. These communications options were important to our group when deciding upon the board since distance and transmission speed were imperative aspects of our project.

Because the distance between the user and the main microcontroller can vary significantly, we decided to utilize the WiFi capability of the module to send real-time notifications to the user when cleaning is needed. As for communication between the current sensor and the main microcontroller, we used the proprietary communication protocol called ESP-Now as this provides easy and fast communication between two ESP-based modules.

2.3.2 Data Collection and Analysis

Collecting and analyzing current sensor data is a key component of our project, and the microcontroller that is connected to the hall sensor contains the logic for doing so.
In essence, the microcontroller continuously polls the hall sensor output and stores those values into memory. Once a specified number of samples are reached, the max value in the set of samples is determined (outliers are attenuated via bypass capacitors and the tune of sampling periods). The subsequent samples are then compared with the max to see if there is a substantial degradation. If there is, the rest of the samples are still scanned to see if that degradation holds or if a temporary fluctuation exists. If the degradation is consistent, the main microcontroller is contacted in order to initiate the cleaning process. We recorded voltage output from the hall sensor overtime with a manual current drop to illustrate this process.

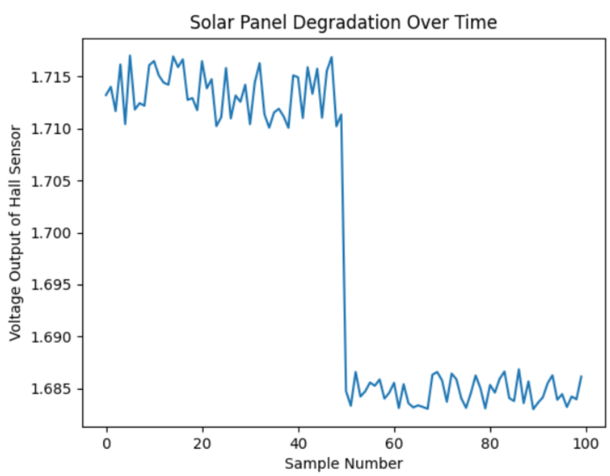

Figure 2.9: Solar Panel Consistent Degradation

As shown in Figure 2.9, the massive dip in voltage output corresponds to debris accumulation or cloud coverage. The fact that this dip holds for about 50 samples shows that its likely debris accumulation. The sensor analysis algorithm will detect the halfway dip and holding pattern. The flowchart for this process is explained in Appendix E.

2.3.3 Relay Modules

Once the hall sensor based microcontroller detects consistent degradation, the main microcontroller receives a notification for cleaning. As an additional check, the main module contacts a weather API to check cloud cover percentage. If the cloud cover percentage is below a specific threshold, the microcontroller will send the appropriate voltage signals for the wiper motor and the sprayer motor to clean the panel. The flowchart for this process is also explained in Appendix E.

The relays are powered by the output of the DC-DC converter in the power subsystem. The sprayer used a single pole relay while the wiper motor needed a double-pole double-throw (DPDT) relay. The sprayer relay simply acts as a switch controlled by the microcontroller to open and close the connection from the DC-DC converter. The design choice for the wiper motor was made since the wiper has to travel down the solar panel and back up to its rest position. The DPDT relay allows the microcontroller to send one set of voltage signals to the relay as it will automatically reverse polarity when there is no digital high signal to send the wiper back up until it hits the limit switch.

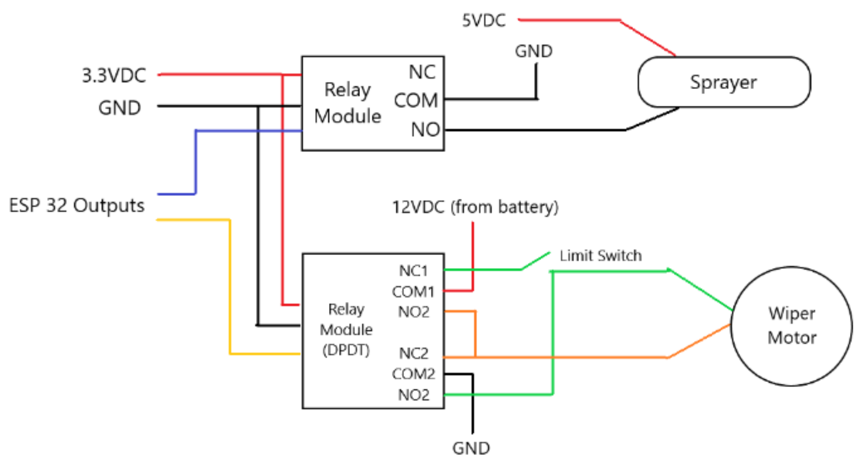

Figure 2.10: Control Subsystem Relay Connections

Figure 2.10 shows the lower level connections between the relay modules for the sprayer and wiper with the rest of the system. The PCB provides 12VDC for the wiper motor, the linear regulator provides 5VDC to the microcontroller and the sprayer motor, and 3.3VDC from the microcontroller is used to power the relays themselves. Concerning the DPDT relay module, the contacts switch the common (COM) from normally closed (NC) to normally open (NO) when the microcontroller sends a high voltage signal to the relay. This will move the wiper down. The contact will switch from normally open to normally closed when the microcontroller stops sending a high voltage signal to the relay. This will reverse the polarity and will cause the wiper to run upwards.

3 Verification

3.1 Cleaning Subsystem

The verification of the motor and sprayer was to determine the current that they would require while running at their respective voltages, as well as how long they would need to run. For the 40 rpm motor that we incorporated into our final design we applied 12VDC to determine how long it would take to run the entire panel. With the length of the panel that needs to be cleaned being 30 inches we ran the motor for 2 inches to determine the total time that would need to be taken to go down the panel by just multiplying it by 15. After testing we determined that the wiper needs only 30 seconds to run the 2 inches and therefore will need 7 minutes to run down the entire panel. The wiper motor will then need to run for a total of 15 minutes, 7 minutes to go down and around 8 minutes to go back up. The time to go back up is slightly longer since it is going against gravity to go back up. For the sprayer we applied 5VDC to determine the length of time that we would need to run it and saw that to get the panel properly wet we only needed to spray for 5 seconds.

Another part of the verification for the cleaning system was to determine the power time that was used for a cleaning cycle and determine if it worked well with the power drop we wanted for cleaning. In our case we were trying to be sure that the power gained from cleaning would be greater than the power used from cleaning. The reason that we worked towards this is that we did not want to contradict what our goal was of getting the panel back to its best efficiency. If we were to use more power to clean than what we would have gained from cleaning we would hurt the efficiency as we would have to use more outside power than wanted.

Table 3.1: Voltage and Current usage of Cleaning cycle

	Motor	Pump
Voltage	12VDC	5VDC
Current	≤200mA	≤700mA

As seen in Table 3.1 we see that the motor has a max current usage of 200mA at 12VDC which gets us to 2.4 Watts and multiplied by the 15 minutes that the motor will have to run we get .6 Watt-hours used by the motor in a cleaning cycle. The sprayer current shown in Table 3.1 has a max current of 700mA at 5VDC which will result in 3.5 Watts and multiplied by the 5 seconds we will have it running we get .004 Watt-hours used by the sprayer in a cleaning cycle which is well within the design specifications as it is significantly less than the 25 Watt gain from cleaning due to power loss.

3.2 Power Subsystem

Our initial verification of the power subsystem is to check if the current meter could accurately measure the solar panel output and send that information to the main microcontroller. To check this, the HP 6332A DC Digital Power Supply was connected to the Agilent 6060B DC Electronic Load set to draw 4.2A which simulates the solar panel output. As shown in Table C.1 in Appendix C we take the voltage output of the hall sensor across a 1kOhm resistor as shown in Figure C.1 in Appendix C. We did this from 4.2A down to 0A in increments of .3A to characterize the sensor and have a table of voltage outputs from the sensor recognizing different currents. The laboratory setup is shown in Figure 3.1. Fluctuations in the current were measurable in the hall sensor output voltage which showed that our meter would work for the project. Tables and schematics of the Hall sensor findings are in Appendix C.

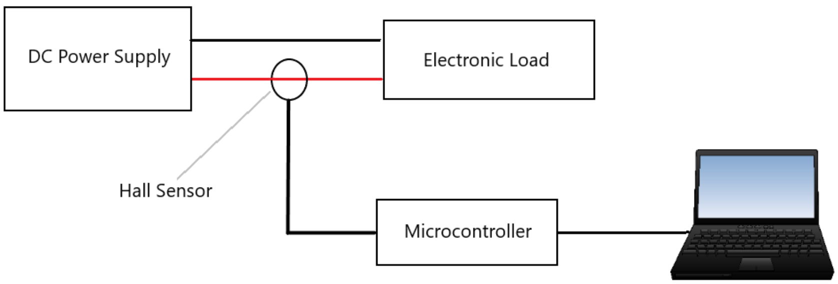

Figure 3.1:Testing and verification of sensing meter in lab

To check the PCB outputs and to power the system indoors, the Keysight E3631A DC Power Supply was used along with the Keysight 34461 A Digital Multimeter. First, the 5VDC linear regulator was tested on a breadboard connected as shown earlier in Figure 2.7 with the power supply sweeping from 11VDC to 17VDC while the output voltage was monitored with the digital multimeter. The output remained constant with a fluctuating voltage in the ten-thousandths. A sample of the measurements taken is shown in Figure 3.2 which shows the necessary voltage for the microcontroller is being provided.

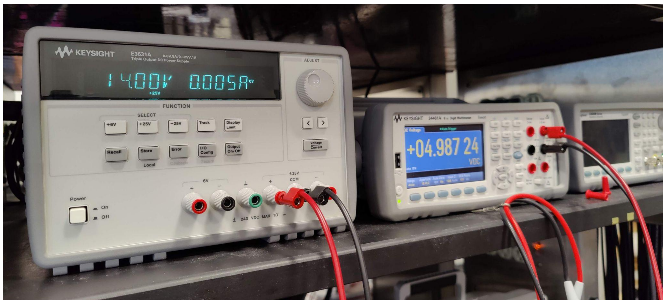

FIgure 3.2: Linear regulator testing in laboratory

Next, we moved onto testing the output of the PCB to other subsystems and found that the PCB was able to provide necessary voltages to the wiper motor and sprayer. Unfortunately, the current limit of the linear regulator meant the sprayer had to be powered via an external supply which is addressed in Section 5.1. Figures 3.3 and 3.4 show the output of the PCB when the input is a steady 18VDC. As expected, the op-amp regulator was able to check and compare the input voltage against the battery and ensure charging was possible.

Figure 3.3: Output of battery charging and power terminals

Figure 3.4: Output of microcontroller supply regulator when mounted on PCB.

Due to failure of the PCB before testing the battery charging circuit abilities, we were unable to verify the functionality of the circuit on a discharged battery. These shortcomings are addressed in Section 5.1 and 5.3.

3.3 Control Subsystem

The main requirements in the control subsystem deal with gathering accurate current/voltage readings from the hall sensor, properly regulating the passage of current through the relays into the wiper and sprayer motors, and ensuring that the user receives notifications about cleaning in a very prompt manner.

Figure 3.5: Voltage Readings Output of Hall Sensor

In Figure 3.5, the voltage readings from the current sensor hover around 1.68-1.69V when dropped to 2.0A, and the module managed to collect readings around 1.71V at 4.2A. This verifies the requirement that the microcontroller can read known voltage and current readings cast from a power supply using the hall sensor.

Requirements dealing with the motor involved measuring the voltage and current needed when the relays are operated and when they are not. One important aspect of this is the current drawn from the wiper motor since the wiper has to run for 14 minutes to go up and down the panel.

Figure 3.6: Current Drawn by Wiper Motor

Figure 3.6 shows the wiper motor was drawing around 0.15~0.2A consistently for the time the wiper was running on the solar panel. The image specifically shows the current to be 0.172A, but fluctuation did exist in the full process. The initial estimate of 0.25A proved to be conservative and now shows the subsystem was not drawing too much power.

In contrast, we wanted to make sure that the relays were not drawing power when cleaning was not needed by the system.

Figure 3.7: Sprayer pump current when not activated

As shown in Figure 3.7, the sprayer will not draw any substantial amount of current when the relay is not activated. Since this occurs, we can verify that the relays will not be in active mode when cleaning is not needed and our system will not consume any excess power.

Notifying the user is very important in our implementation so an important requirement is that the user receives notifications in real-time about the status of the solar panel. The table in Appendix D shows the notification time period when the solar panel needed to be clean. These times were measured from the start of certain flags being set to set up the SMTP server connection to when the actual message was received in the user’s inbox. From these trials, we were able to confirm that the user can receive notifications in real-time, and that our initial estimate was quite conservative.

4 Labor Costs and Schedule

4.1 Parts

Table 4.1: Parts Quantity and Cost for Project

Description	Part Number	Quantity	Cost
Microcontroller	ESP32	1	$4.00
Windshield Wiper	RX30224	1	$9.00
Battery	ML5-12	1	$15.99
Sprayer Module	CMXCAFG190640	1	$8.98
Current Sensor	BYT-VAM-033	1	$18.98
MCU Board (2nd Board)	ESP32-C3-DevKitC-02	1	$9.00
Relay Module	B00LW15A4W	1	$6.79
Limit Switch	ZMSH03130T10SSC	1	$3.53
Solar Panel	HSP100D-L	1	$89.14
Quad Op Amp IC	LM324DR2G	1	$0.55
12v to 5v Regulator	L7805ABV	1	$0.70
5.1V Zener Diode	BZX79C5V1-T50A	1	$0.16
Rectifier Diode	BYV79E-200,127	1	$1.25
Switching BJT	2N3055	2 (Min 5 order)	$9.85
LED BJT	BC327-25-AP	1	$0.40
Battery Filter Cap	25PX1000MEFCT810X16	1	$0.64
Lighting Ckt Diode	1N914MS-ND	2	$1.68
0.1μF Capacitor	FA28X8R1E104KNU06	1	$0.34
0.33μF Capacitor	FA14X8R1E334KNU06	1	$0.48
1μF Capacitor	FA18X8R1E104KNU06	1	$0.38
120Ω Resistor	CFR-12JB-52-120R	1	$0.10
220Ω Resistor	CFR-12JB-52-220R	1	$0.10
470Ω Resistor	CF14JT470R	2	$0.20
2kΩ Resistor	CFR-25JB-52-2K	1	$0.10
2.7kΩ Resistor	CFR-25JB-52-2K7	1	$0.10

5.3kΩ Resistor	CMF555K3000BHEB	1	$1.04
5.6kΩ Resistor	CF14JT5K60	1	$0.10
10kΩ Resistor	CF14JT10K0	5	$0.50
11kΩ Resistor	CFR-25JB-52-11K	1	$0.10
12kΩ Resistor	CF14JT12K0	1	$0.10
33kΩ Resistor	CF14JT33K0	1	$0.10
470kΩ Resistor	RNMF14FTC470K	1	$0.10
820kΩ Resistor	RNV14FAL820K	1	$0.24
Red LED	UR502DC	1	Already Own
Green LED	UR502DC	1	Already Own
Terminal Block	TB007-508-02BE	7	$5.95

4.2 Labor Costs

The average salary (in the 2019-2019 academic year) for an Electrical Engineer graduate from UIUC is $79,714, and the average salary for a Computer Engineer graduate is $96,992. We will use the average of those two values in our calculations which is $88,353.

- $88,353 / (50 weeks*40 hours per week) = $44.18 per hour
- Overhead inclusion: $44.18 per hour * 2.5 = $110.45
- $110.45 * 15 hours per week * 11 weeks = $18,224.25 per Student
- $18,224.25 * 3 students = $54,672.75 for student labor
- Machine Shop Estimated Labor = *15 hours * $59*
- **Total Cost** = Student Labor + Machine Shop Labor = *$83,336.63*

4.3 Schedule

Table 4.2: Finalized schedule for project completion

Week	Austin	Alex	Prudhvie
Week 7	Help with PCB design/ Go in and finalize design with machine shop	Finalize PCB design	Help with PCB and understand how to program ESP Chips
Week 8	Get PV characteristics of the solar panel	Characterize cleaning subsystem components (sprayer, wiper motors) with waveforms.	Test if current sensor is outputting correct readings to secondary board (Use Arduino test kit)
Week 9 (Spring Break)	Document Check	Document check (datasheets)	Document Check

Week 10	Helping with prototyping/ Working on solar output threshold for data transmission	Prototyping for circuit design	Work on setting up web interface; Get current sensor interfacing with secondary board
Week 11	Work with known power source and check outputs of power subsystem	Prototyping for circuit design	Work on interfacing main board with secondary board
Week 12	Start connections with main microcontroller	Finalize testing of cleaning system interactions	Work on processing data and activating relay from microcontroller
Week 13	Connect solar panel with power subsystem and test	Extreme testing for operation conditions	Work on sending data and notification to web application

5 Conclusions

5.1 Results

Operation of the overall project allowed us to determine that autonomous cleaning of the solar panel was feasible and produced a system that was functional. The cleaning subsystem was able to go through an entire cycle and remove debris from the panel at only .604 Watt-hours used which was less than the 25W power loss threshold due to soiling. The hall sensor of the power subsystem allowed us to see if possible degradation occurred and would notify the main microcontroller which we used to check cloudiness. If cloudiness is recognized the main microcontroller will begin a cleaning cycle.

5.2 Ethical Considerations

As our sensing meter and microcontroller rely on wireless communication, we must follow regulations set forth by IEEE [12] and the FCC to prevent interference with networks of equipment nearby. Preferably, our project will use WiFi for the communication standard. Sealed lead-acid batteries will be used to store energy for the project and possibly for a demonstration of connections to larger storage systems. We will need to size [13] our components in the power subsystem as well as the batteries themselves to ensure safe and efficient operation of the project.

As our project was developed with the IEEE Code of Ethics in mind, we needed to consider the implications which involve those lines. Our project looks “to strive to comply with ethical design and sustainable development practices” [14] and “to improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies, including intelligent systems” [14]. Due to moving components that are able to produce significant force, we will need to ensure that there are sensors which monitor equipment status and stop movement if resistance is detected as we need “to hold paramount the safety, health, and welfare of the public” [14]

5.3 Further Work

A concern of the cleaning subsystem is to increase the speed of the wiper motor so the cleaning takes less than 15 minutes. Our current motor runs at 40 rpm which is already a four time increase than the initial choice. If the solar panel is located in a hot, arid region the cleaning solution used could evaporate before the wiper has an opportunity to clean off the soiling. Suggested improvements could be to push cleaning to overnight where temperatures will be lower or to have a faster motor which will increase the power consumption of the system, but also reduces the number of sprays necessary to maintain a damp panel.

In the power subsystem, there were several pitfalls which affected the final implementation of the project. In particular, the linear regulator for the microcontroller had a maximum output of 1.5A which was insufficient to provide power to both the microcontroller and the sprayer pump. While testing the integrations together, the regulator was pushed into shutdown and had to be reset. To get the functionality needed, we had to utilize an external power supply for the sprayer pump through the relay. To remedy this problem, a buck converter should have been used which allows for a higher current output and stronger resilience to fluctuations in load. Another issue was the current meter not having the resolution we expected. The 0.3A resolution is too coarse for fine tracking of panel output that could be sent to the user. Investigating different loop hall sensors could be used to increase resolution for more accurate readings. Finally, the crux which led to our project's demise is protection against reverse current flow on the PCB. While powering the wiper motor with the battery to discharge it, we accidentally sent power backwards through the connection terminals which destroyed the op-amp chip releasing the magic smoke that indicates burning silicon. Careful disconnection of wires would have prevented this from happening, but in actual installation this would need to be considered.

For the control subsystem, we would like to increase our range of debris to snow. Our current system will likely encounter too much resistance while clearing a build-up of snow due to the substantial weight increase from sand/dirt to snow. We will likely need a motor with better torque which will utilize more power from the battery/panel. This trade-off would have to be balanced as the overall power consumption of the system should be lower than the power production increase of the solar panel due to cleaning. A continuous issue we had was devising an accurate and flexible algorithm to detect degradation. In future iterations, utilizing a data structure like a heap can be beneficial for tracking important values in continuous streams of data.

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Appendices

Appendix A: Requirement and Verification Tables

Table A.1: Control Subsystem Requirements and Verification

Requirements	Verification	Verified?
1. Apply 12VDC and 1A through the relay that is connected to the pump and motor and be sure there is 0V and 0A reaching 2. Have 12VDC and 250mA run to the pump and motor for a 30sec to clean the system and make sure nothing goes wrong	1A. Measure with an Oscilloscope that no voltage and current is reaching the pump and motor when cleaning is not needed 2A. Measure that when 12VDC is supposed to be reaching the pump and motor it is and within a +/- 5% using an Oscilloscope. 2B. Read motor specs and determine how long it will need to run to reach the entire length of the solar panel 32.5 inches +/- 3 inches	Yes

Table A.2: Power Subsystem Requirements and Verification

Requirements	Verification	Verified?
1. Determine that the current meter is properly reading 5A of current and sending the correct data with +/- 1% accuracy	1A. Send 12V and 5A through the sensor with a power source in lab to test the ability and accuracy of the current reading of the current sensor +/- 1% accuracy 1B. When the current sensor is correct and the ability is there send the data to the microcontroller and determine if the output remains the same through data transmission	Yes
2. Output of DC-DC Converter is able to supply 12VDC at rated current for cleaning subsystem	2A. Apply steady voltage (18VDC) to input of converter and measure output voltage. 2B. Introduce known load to reach desired rated current (~2A) 2C. Activate all cleaning subsystem	Yes

	components manually and observe supply components with oscilloscope and multimeters to ensure minimal drop	
3. Output of DC-DC converter supplies 5VDC at rated current for microcontroller and relay trigger contacts.	3A. Apply 12VDC to the specified regulator and measure output voltage. 3B. Provide load at minimum of 0.5A to ensure microcontroller will be able to operate 3C: Increase load to max of both relay contacts to ensure the system will not push the regulator into shut-down.	Yes
4. Battery charging is stopped when rated voltage is reached	4A. Place a properly charged 12V battery to output terminals which should not activate the charging circuit. 4B. Place a discharged battery at terminals to activate the charging circuit which will draw a maximum of 3A +/- 1%. 4C. Circuit will turn off green LED and turn on Red LED to signify batteries are fully charged.	No

Table A.3: Control Subsystem Requirements and Verification

Requirements	Verification	Verified?
1. Receives the current readings from current sensor system on the solar panel cables 2. Controls relay and doesn't allow power through when power is not needed in pump and motor 3. Controls relay and allows power to pump and	1A. When we have both the sensor and microcontroller read a known current from a known power source at 6A. 2A. Measure current and voltage, with an oscilloscope, across a resistive load from the output of the relay to be 12V +/- 5% 3A. Measure current and voltage, using an Oscilloscope, across resistive load from the output of the relay to be 0.25A amps and 12V for the motor.	Yes

motor when cleaning is wanted 4. Wirelessly transmit message to App or E-mail	4A. Check if message is received by App or E-mail notification within a period of 3 minutes from when the data was processed on microcontroller	

Appendix B: Power Subsystem Schematics and PCB Designs

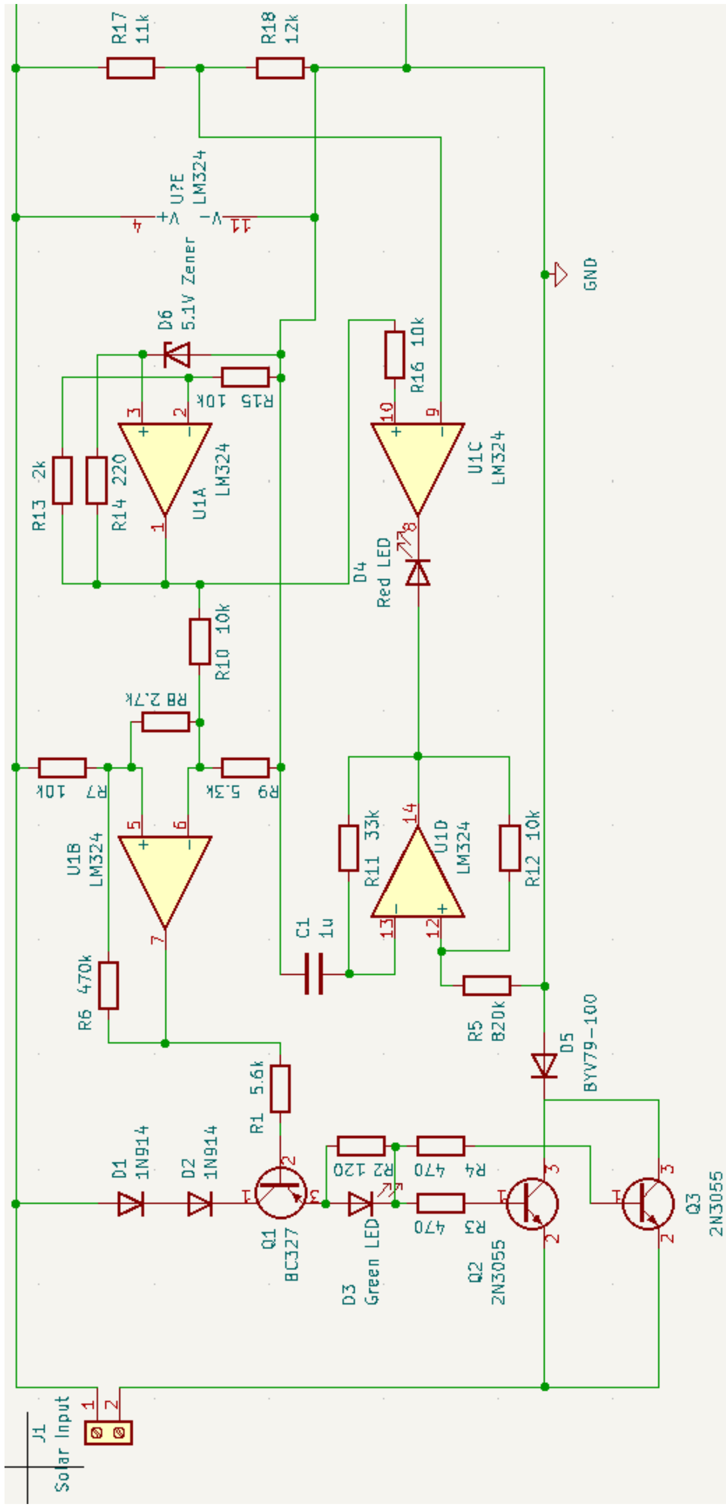

Figure B.1: Op-amp Regulator Circuit

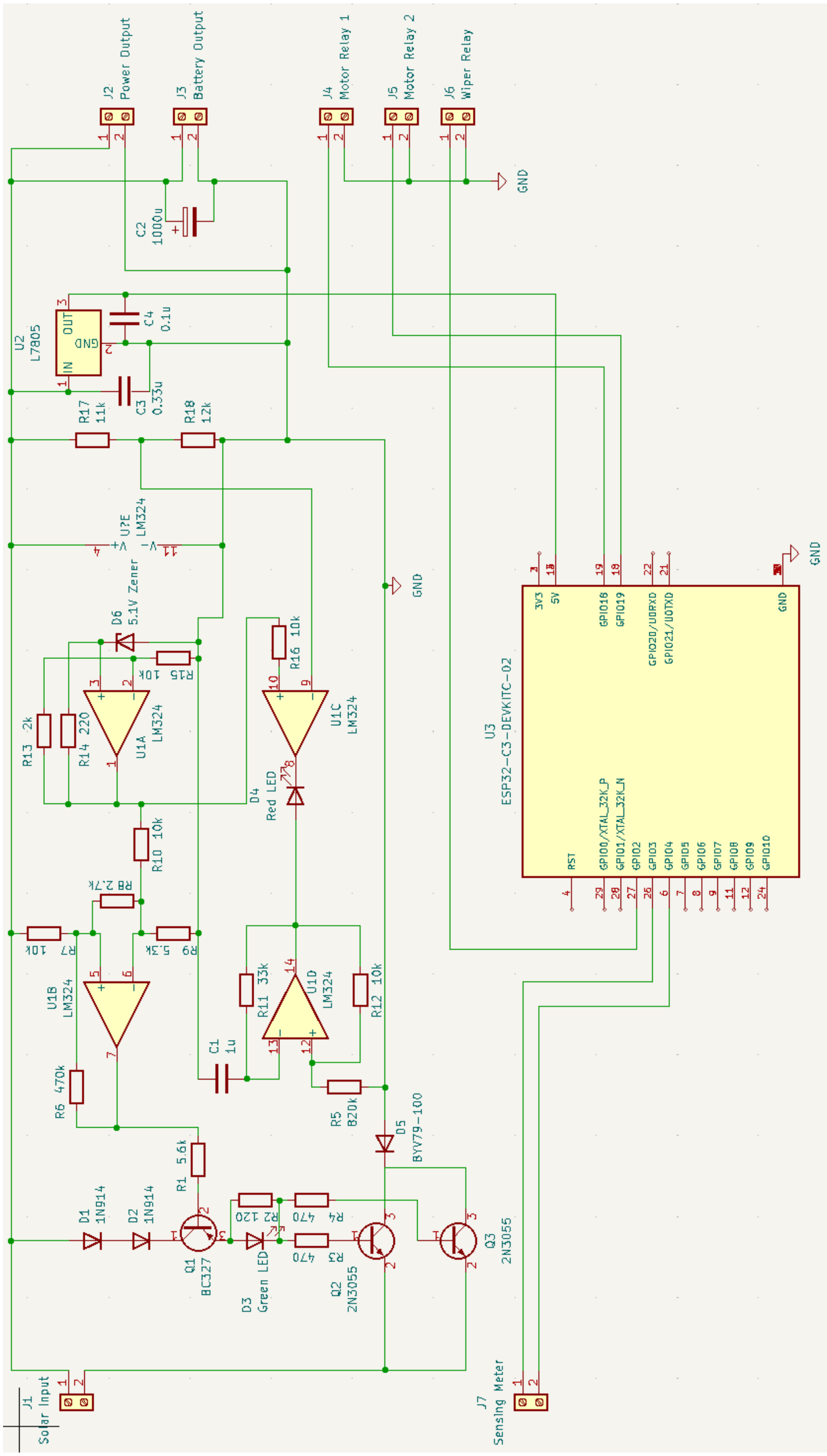

Figure B.2: Full circuit diagram for PCB

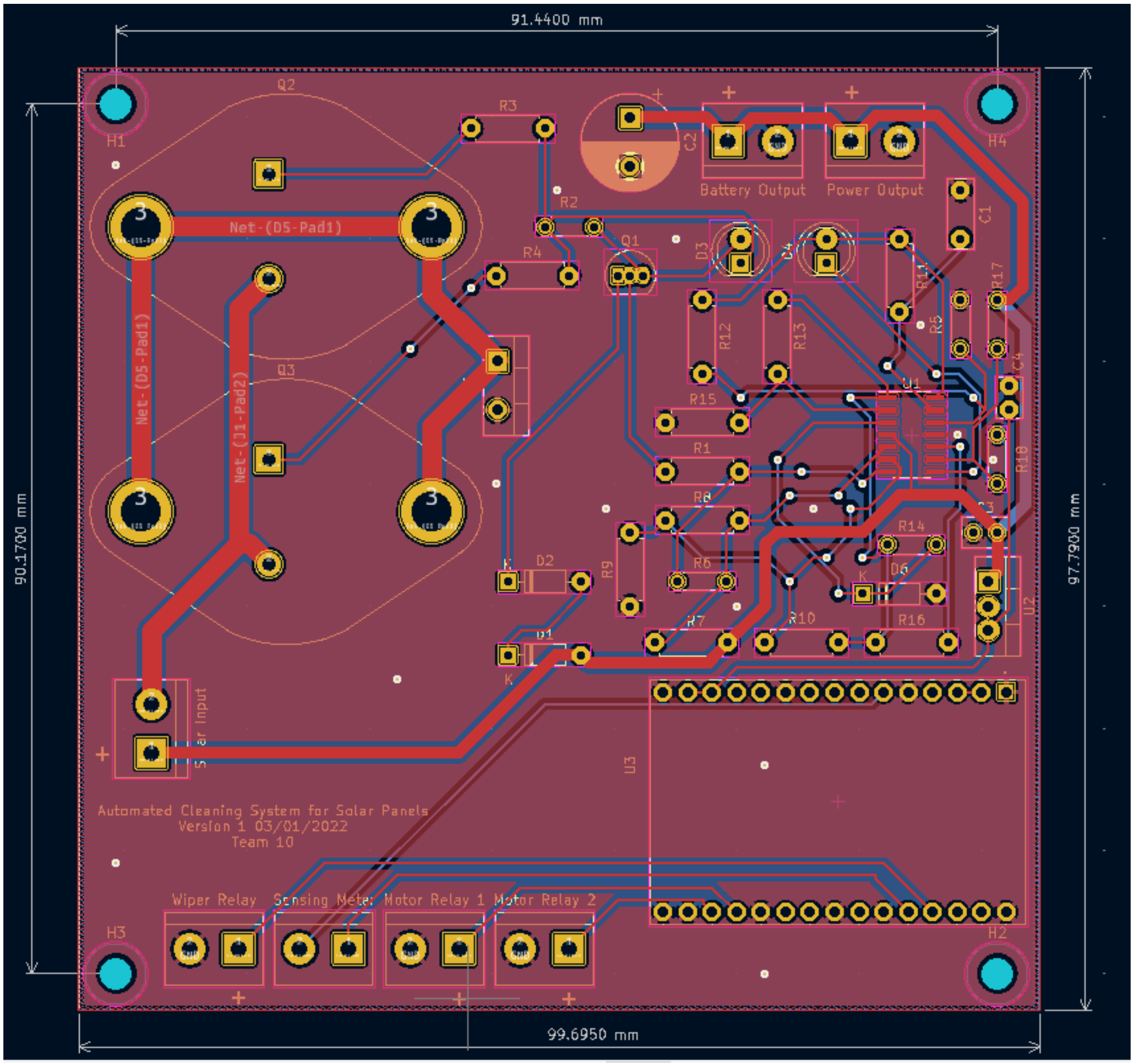

Figure B.3: PCB trace layout and associated footprints

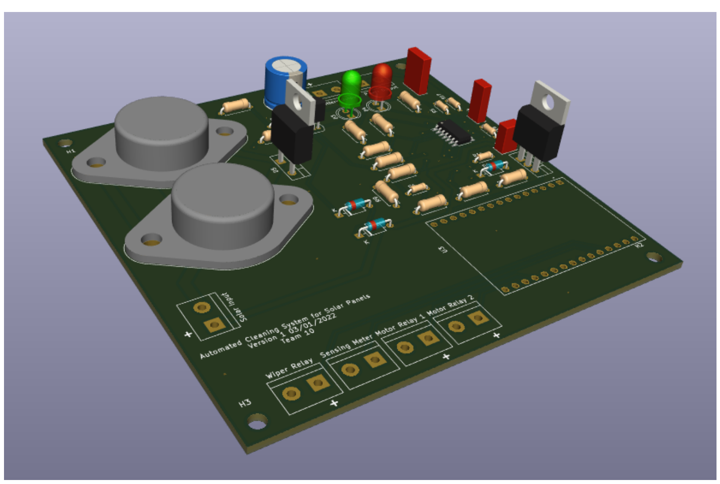

Figure B.4: 3-D rendering of PCB layout

Appendix C: Hall Sensor Verification Table and Schematic

Table C.1: Hall sensor output voltages while sweeping current

Current (A)	Sensor Output (V)
0	1.664
0.3	1.6666
0.6	1.6702
0.9	1.6736
1.2	1.6772
1.5	1.6806
1.8	1.684
2.1	1.6875
2.4	1.691
2.7	1.694
3	1.6978
3.3	1.7012
3.6	1.7046
3.9	1.7082
4.2	1.7115

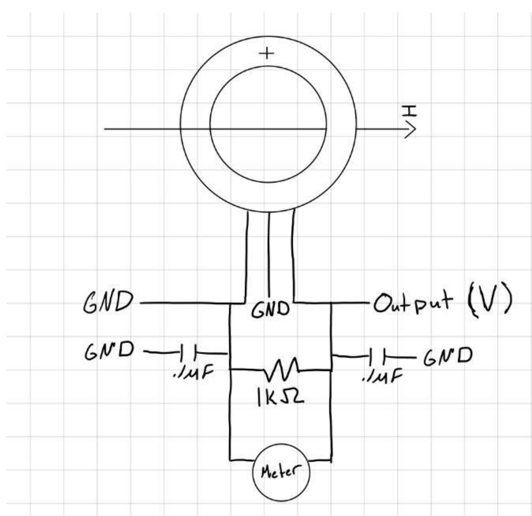

Figure C.1: Schematic of Hall sensor verification circuit

Appendix D: User Notification Verification Table

Trial Number	Time Taken (Seconds)
1	29.85
2	30.38
3	30.42
4	31.15
5	30.12
6	29.78
7	30.54
8	30.89
9	30.55
10	30.23

Appendix E: Control Subsystem Flowcharts

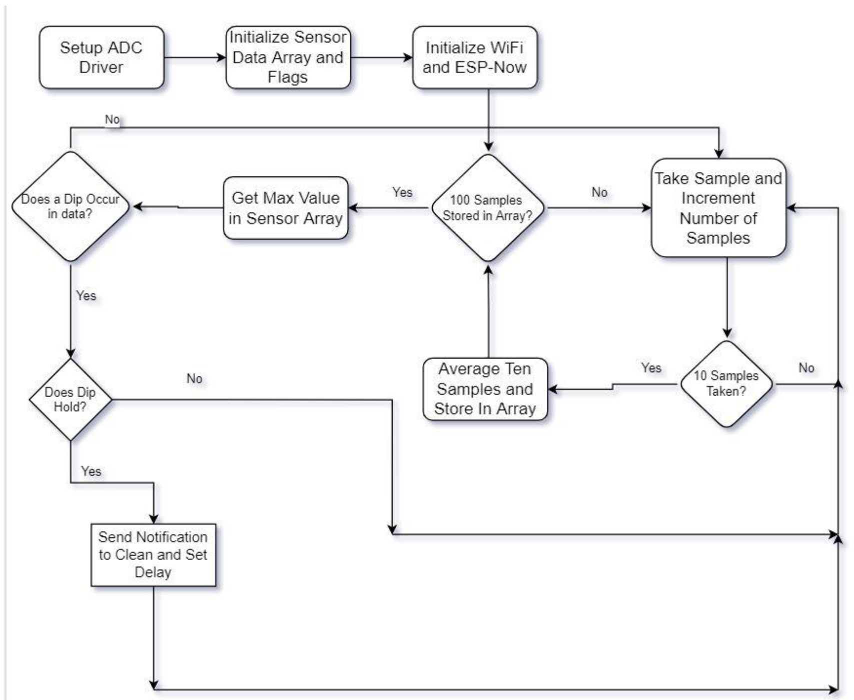

Figure E.1: Transmitter (Current Sensor) Microcontroller Flowchart

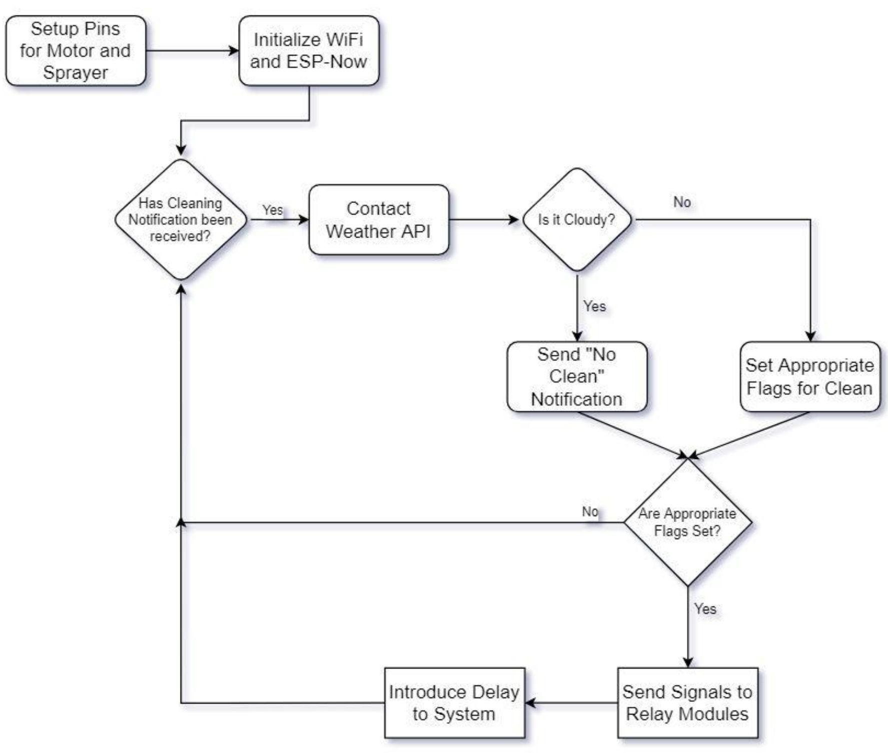

Figure E.2: Receiver (Main) Microcontroller Flowchart

Appendix F: Code Screenshots

```
//configuring wifi access for chip
WiFi.mode(WIFI_STA);
WiFi.begin(SSID, PASSWORD);
Serial.print("Connecting to WiFi");
while(WiFi.status() != WL_CONNECTED) {
  Serial.print(".");
  delay(1000);
}
Serial.println("Connected to WiFi!");

//initializing ESP-Now
if(esp_now_init() != ESP_OK)
  {
    Serial.println("Error initializing ESP-Now. Aborting Setup");
    return;
  }

//register Send Callback function
esp_now_register_send_cb(OnDataSent);
```

Figure F.1: Receiver (Main) Microcontroller WiFi and ESP-Now Setup

```
//register and add peer device
memcpy(peerInfo.peer_addr, transmitterBroadcastAddr, 6);
peerInfo.channel = 0;
peerInfo.encrypt = false;
if(esp_now_add_peer(&peerInfo) != ESP_OK)
  {
    Serial.println("Failed to add peer. Aborting setup");
    return;
  }

//register Receive Callback function
esp_now_register_recv_cb(OnDataRecv);
```

Figure F.2: Receiver (Main) Microcontroller WiFI and ESP-Now Setup (2)

```
//WEATHER API CODE (IN REAL WORLD USE CASE; UTILIZE THIS)
if(WEATHER_FLAG == true)
  {
    WEATHER_FLAG = false;
    String serverPath = "http://api.openweathermap.org/data/2.5/weather?q=" + city + "," + countryCode + "&APPID=" + openWeatherMapApiKey;
    jsonBuffer = httpGETRequest(serverPath.c_str());
    Serial.println(jsonBuffer);
    JSONVar myObject = JSON.parse(jsonBuffer);

    if (JSON.typeof(myObject) == "undefined")
      {
      Serial.println("Parsing input failed!");
      return;
      }

    Serial.print("Temperature: ");
    Serial.println(int(myObject["main"]["temp"]) - 273);
    Serial.print("Cloud Cover: ");
    Serial.println(int(myObject["clouds"]["all"]));
  }
```

Figure F.3: Weather API Contact and JSON Structure Parsing

```
//activate sprayer for 2 seconds and deactivate sprayer
if(SPRAYER_FLAG == true)
  {
    digitalWrite(RELAY_SPRAYER, HIGH);
    Serial.println("Sent voltage signal HIGH to Sprayer Relay");
    delay(5000);
    digitalWrite(RELAY_SPRAYER, LOW);
    SPRAYER_FLAG = false;
    delay(2000); //slight delay between the relays for stabilization purposes
  }

//activate motor for 7 minutes (reverse polarity on motor relay will bring it back up to the limit switch and stop it)
if(MOTOR_FLAG == true)
  {
    digitalWrite(RELAY_MOTOR, HIGH);
    Serial.println("Sent voltage signal to motor!");
    delay(300000);
    digitalWrite(RELAY_MOTOR, LOW);
    MOTOR_FLAG = false;
  }
```

Figure F.4: Sprayer and Wiper Relays Activation

```
ESP_Mail_Session session;
session.server.host_name = SMTP_HOST;
session.server.port = SMTP_PORT;
session.login.email = AUTHOR_EMAIL;
session.login.password = AUTHOR_PASSWORD;
session.login.user_domain = "";

//configuring email message settings
SMTP_Message message;
message.sender.name = "ESP32";
message.sender.email = AUTHOR_EMAIL;
message.subject = "ESP32 Testing Email";
message.addRecipient("gudappr",RECEPIENT_EMAIL);
```

Figure F.5: E-Mail Notification Setup (1)

```
String textMsg = "Panel has noticable power degradation and will be cleaned!";
message.text.content = textMsg.c_str();
message.text.charSet = "us-ascii";
message.text.transfer_encoding = Content_Transfer_Encoding::enc_7bit;

//connect to SMTP session attempt
if (!smtp.connect(&session))
  return;

//Start sending Email and close the session
if (!MailClient.sendMail(&smtp, &message))
  Serial.println("Error sending Email, " + smtp.errorReason());
else
  Serial.println("Mail has been sent!");

EMAIL_FLAG = false;
}
```

Figure F.6: E-Mail Notification Setup (2)

```
esp_adc_cal_get_voltage(ADC_CHANNEL_2, &characteristics, &high_voltage);
esp_adc_cal_get_voltage(ADC_CHANNEL_3, &characteristics, &low_voltage);
CUR_READING = (float(high_voltage) / 1000) - (float(low_voltage) / 1000);
num_samples += 1;
sum += CUR_READING;
if (num_samples == 10)
  {
   Serial.println(sum / 10, 3);
   if(current_ptr <= 99)
    {
    sensor_data[current_ptr] = sum / 10;
    current_ptr += 1;
    }
   num_samples = 0;
   sum = 0;
   delay(1000);
  }
else
  delay(10);
```

Figure F.7: Reading Current Sensor Output and Storing Data

```
if(current_ptr == 100)
  {
    for(int i = 0; i < 100; i++)
      {
        Serial.println(sensor_data[i],3);
      }
    Serial.println("Collected 100 samples!");
    //get max in sensor_data array
    float maxVal = sensor_data[0];
    Serial.print("Initial MaxVal: ");
    Serial.println(maxVal, 3);
    for(int index = 0; index < 100; index++)
      {
        if(sensor_data[index] > maxVal)
          maxVal = sensor_data[index];
      }
    Serial.println("Found Max");
    Serial.print("Maxval: ");
    Serial.println(maxVal, 3);
```

Figure F.8: Finding Maximum Sample in Set of Sensor Data

```
//scan through array again to find if degradation exists
for(int index = 0; index < 100; index++)
  {
    if(maxVal - sensor_data[index] > DEGRADATION_LIMIT)
    {
      REF_VOLTAGE_IDX = index;
      Serial.print("val that broke limit: ");
      Serial.println(sensor_data[index], 3);
      break;
    }
  }
```

Figure F.9: Scanning of Possible Degradation in Acquired Sensor Data

```
if(REF_VOLTAGE_IDX != -1)
  {
    Serial.println("Found Degradation.");
    int new_index = REF_VOLTAGE_IDX + 1;
    int increment = 0;
    while(increment < HOLDING_NUM)
    {
      if(sensor_data[new_index + increment] - sensor_data[REF_VOLTAGE_IDX] > HOLDING_THRESHOLD)
      {
        Serial.println("Found fluctuation point.");
        current_ptr = 0;
        for(int i = 0; i < 100; i++)
        {
          sensor_data[i] = 0;
        }
        break;
      }
      increment += 1;
    }
```

Figure F.10: Scanning of Consistent Degradation in Acquired Sensor Data (1)

```
        }
        if(increment == HOLDING_NUM)
        {
            SEND_FLAG = true;
            current_ptr = 0;
            for(int i = 0; i < 100; i++)
            {
                sensor_data[i] = 0;
            }
        }
    REF_VOLTAGE_IDX = -1;
    }
else
    {
    current_ptr = 0;
    for(int i = 0; i < 100; i++)
        {
        sensor_data[i] = 0;
        }
    }
```

Figure F.11: Scanning of Consistent Degradation in Acquired Sensor Data (2)

```
f(SEND_FLAG == true)
 {
   Serial.println("Sending notification");
   outgoingMessage.current_reading = 32;
   esp_err_t result = esp_now_send(receiverBroadcastAddr, (uint8_t*) &outgoingMessage, sizeof(outgoingMessage));

   if(result == ESP_OK)
   {
   Serial.println("Sent Successfully");
   }

 else
   {
   Serial.println("Not Sent Successfully");
   }

 SEND_FLAG = false;
```

Figure F.12: Transmitter (Current Sensor) Communication Link With Receiver (Main Microcontroller) About Possible Cleaning