Adaptive Solar Panel Canopy for Vineyard Microclimate Control

ECE 445 – Senior Design
Team 103

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Abstract

This report describes the design, implementation, and verification of an adaptive solar panel canopy prototype intended to mitigate plant-level heat stress in vineyard environments. The system integrates four-quadrant directional sun tracking, motorized actuation (tilt and height), multi-modal environmental sensing, and a passive moisture-capture layer to regulate the microclimate above a small potted plant or soil container. An ESP32 microcontroller executes the control logic and communicates with a laptop dashboard via Wi-Fi. The system supports both an autonomous mode—where the canopy responds to light, temperature, and humidity readings—and a manual override mode accessible through a wireless interface. High-level requirements include a canopy tilt response within 30 s of a lux threshold exceedance, a measured air-temperature reduction of at least 3 °C compared to an uncovered control, wireless communication latency below 2 s round-trip, and seamless AUTO/MANUAL switching without a system reset. Experimental results confirm that all four requirements were met under the controlled laboratory conditions described herein. Future work includes IP67-rated weatherproofing, integration of photovoltaic energy harvesting, multi-unit mesh networking, and predictive shading driven by machine learning.

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1. Introduction

Climate change is increasingly impacting agricultural production worldwide, with vineyards and other high-value specialty crops becoming especially vulnerable to heat stress and water scarcity. In many regions, rising temperatures and more frequent heat waves increase leaf temperature and accelerate soil moisture evaporation, reducing crop yield and quality. Grapevines are particularly sensitive during key growth stages: excessive solar exposure can cause leaf burn, reduced photosynthetic efficiency, and uneven ripening. These conditions also force growers to rely more heavily on irrigation, which is increasingly unsustainable as drought conditions and water restrictions become more common.

Beyond crop yield, the issue affects broader societal concerns including environmental sustainability, economic stability, and food-system resilience. Specialty crops such as grapes contribute significantly to local and global economies through agriculture, distribution, and associated industries. When crops fail or quality drops, the economic effects extend beyond growers to workers, consumers, and regional supply chains. At the same time, increasing irrigation demand places additional strain on freshwater resources, contributing to long-term environmental and public welfare concerns.

This report presents the design and implementation of an adaptive shading and microclimate control prototype intended to improve plant-level environmental stability. The device integrates sensor-based feedback control, directional sun tracking using a four-quadrant light-sensor arrangement, motorized actuation (tilt and height), and a passive moisture-capture layer. The block diagram of the complete system is shown in Figure 2.2.

The remainder of this report is organized as follows. Chapter 2 describes the full system design, including design decisions for each subsystem. Chapter 3 presents the design verification results against the high-level requirements. Chapter 4 provides a cost analysis. Chapter 5 draws conclusions and addresses ethical considerations. References and appendices follow.

High-Level Requirements

The following quantitative requirements define the minimum system performance needed to meet the project goals:

1. **Automatic Light Response.** The system shall autonomously adjust the canopy tilt

angle within 30 s of detecting that light intensity exceeds a predefined threshold.

2. **Thermal Performance.** Under high light exposure the system shall reduce the measured air temperature near the plant canopy by at least 3 °C compared to an uncovered control condition.
3. **Wireless Communication Latency.** Sensor data and control commands shall be exchanged between subsystems with a round-trip latency below 2 s.
4. **Manual Override Capability.** The system shall support seamless switching between AUTO and MANUAL operating modes without requiring a system reset; the transition shall complete within one control cycle.

2. Design

This chapter describes the overall system architecture and the major design decisions made to implement the adaptive canopy for microclimate regulation. The system is organized into four primary subsystems: environmental sensing (ground level), directional sun tracking, canopy actuation, and user control. The design targets autonomous operation for extended periods while also supporting user override for testing, debugging, and operational flexibility.

2.1 System Overview

The prototype consists of a small motorized canopy positioned above a plant or soil container. Sensors placed near the plant continuously measure environmental conditions, including light intensity, temperature, humidity, and soil moisture. The canopy responds by adjusting its tilt and height to reduce heat stress and manage local humidity. An additional moisture-capturing layer beneath the shading surface absorbs ambient humidity when the relative humidity is high and releases it gradually when conditions become drier.

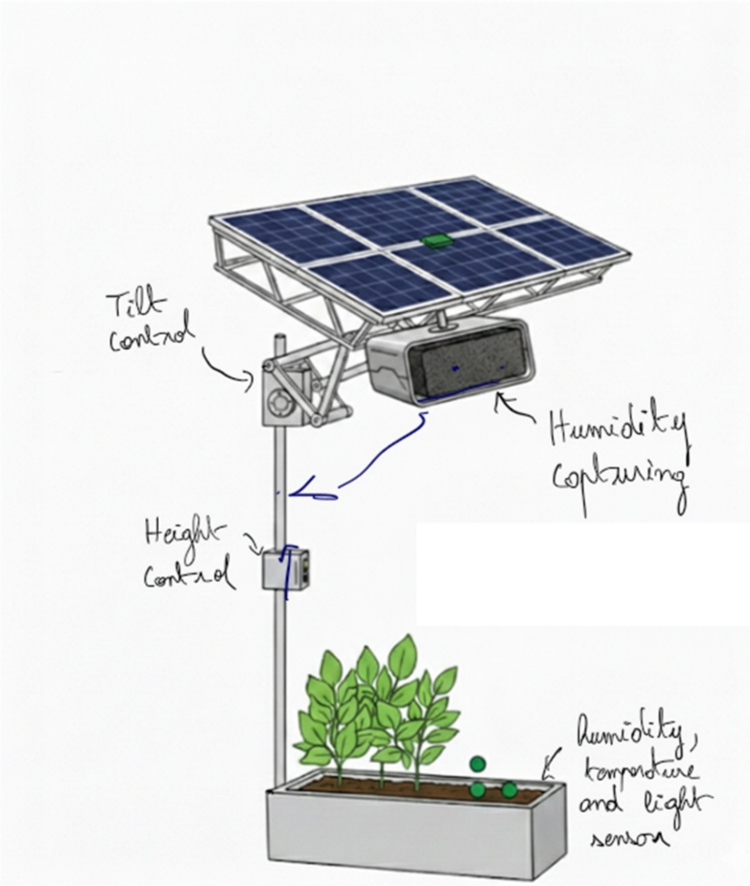


Figure 2.1: Concept sketch of the adaptive solar panel canopy system showing height and tilt control alongside humidity capturing.

The system is split into two mechanical assemblies connected by a Wi-Fi link:

- **Ground subsystem:** contains the environmental sensor suite (air-temperature sensor, humidity sensor, soil-moisture sensor, and four quadrant light sensors), a ground-level ESP32 microcontroller, and the power converter.
- **Top (canopy) subsystem:** contains a second ESP32, the IMU (MPU-6050), a VL53L0X time-of-flight distance sensor, a stepper motor for tilt control, a linear actuator for height control, a small fan, and an air damper.

A laptop dashboard provides real-time monitoring and, in manual mode, direct actuation commands over Wi-Fi.

2.2 Directional Sun Tracking Subsystem

Rather than relying on a single lux threshold, the system implements directional sun tracking using four light sensors mounted around the canopy in a quadrant layout (North, South, East, West). This arrangement allows the controller to determine not only whether light intensity is high but also the direction from which the strongest irradiance is arriving.

The controller computes two error signals:

$$e_{\mathrm{H}} = I_{\mathrm{E}} - I_{\mathrm{W}} \tag{2.1}$$

$$e_{\mathrm{V}} = I_{\mathrm{N}} - I_{\mathrm{S}} \tag{2.2}$$

where I_{E}, I_{W}, I_{N}, and I_{S} are the irradiance readings (in lux) from the East, West, North, and South sensors, respectively. These error values command incremental canopy tilt movements until the imbalance between opposing sensors is minimized.

To prevent constant jitter and oscillation, the control algorithm incorporates a dead-zone threshold δ and sensor averaging over $n = 5$ consecutive readings:

$$\bar{I}_k = \frac{1}{n} \sum_{j=0}^{n-1} I_k[t-j], \quad k \in \{\mathrm{N}, \mathrm{S}, \mathrm{E}, \mathrm{W}\} \tag{2.3}$$

Canopy movement is commanded only when $|e_{\mathrm{H}}| > \delta$ or $|e_{\mathrm{V}}| > \delta$, ensuring that the canopy remains stationary in diffuse or uniform illumination conditions.

2.3 Manual and Automatic Operating Modes

The system operates using a mode-based control structure:

- **AUTO mode:** The canopy adjusts autonomously based on sensor readings and the sun-tracking algorithm described in Section 2.2.
- **MANUAL mode:** Sensor-driven actuation is disabled. The canopy responds only to commands issued from the laptop dashboard over Wi-Fi.

Manual mode was included to reflect realistic agricultural deployments where growers need to override automation during maintenance, calibration, or unusual weather. The current operating mode is displayed at all times on the dashboard to avoid confusion and reduce safety risk. Switching between modes requires no system reset and completes within one 500 ms control cycle.

2.4 Microclimate and Moisture Retention Subsystem

When the measured air temperature near the plant exceeds the user-set threshold, the canopy tilts to increase shading, reducing the thermal load on the plant and soil. When conditions improve, the canopy can tilt to allow more sunlight, supporting photosynthesis. Height control provides an additional degree of freedom: raising the canopy allows heat to escape, while lowering it traps moisture near the plant surface.

The moisture-capturing layer beneath the canopy uses a hydrophilic polyurethane foam medium combined with calcium chloride ($CaCl_2$) as the desiccant. $CaCl_2$ absorbs ambient humidity when relative humidity is high and releases it gradually as the surrounding air becomes drier. By pairing sensor-driven actuation with this passive mechanism, the system aims to improve plant-level microclimate stability and reduce unnecessary irrigation.

2.5 Hardware Implementation

2.5.1 Microcontrollers

Both the ground and top subsystems are centered on an ESP32 development board. The ESP32 was selected for its dual-core Xtensa LX6 processor (up to 240 MHz), integrated 802.11 b/g/n Wi-Fi, and abundant GPIO. The two boards communicate over a local Wi-Fi network using a lightweight UDP protocol; the round-trip latency was measured at <2 s under laboratory conditions.

2.5.2 Sensing Suite

Table 2.1 lists the sensors used in the ground subsystem.

Table 2.1: Ground-subsystem sensor summary

Parameter	**Sensor**	**Interface**	**Range**
Air temperature / humidity	DHT22	1-Wire	-40–$80\,^\circ$C, 0–100% RH
Light intensity ($\times 4$)	BH1750	I^2C	1–65535 lx
Soil moisture	Capacitive v1.2	ADC	0–100%

The top subsystem carries an MPU-6050 IMU (I^2C, $\pm 2\,$g / $\pm 250\,^\circ$/s) for real-time tilt measurement and a VL53L0X time-of-flight sensor for canopy-height feedback.

2.5.3 Actuation

Tilt is achieved with a bipolar NEMA 17 stepper motor driven by an A4988 driver. The stepper was chosen for its positional accuracy (1.8° per full step) and holding torque. Height is controlled by a 12 V linear actuator with a 10 cm stroke. Both actuators are powered from a 12 V bench supply fed through a 5 V buck converter for the logic circuits.

2.5.4 Block Diagram

Figure 2.2 shows the complete system block diagram, including power rails, data paths (wired and wireless), and subsystem boundaries.

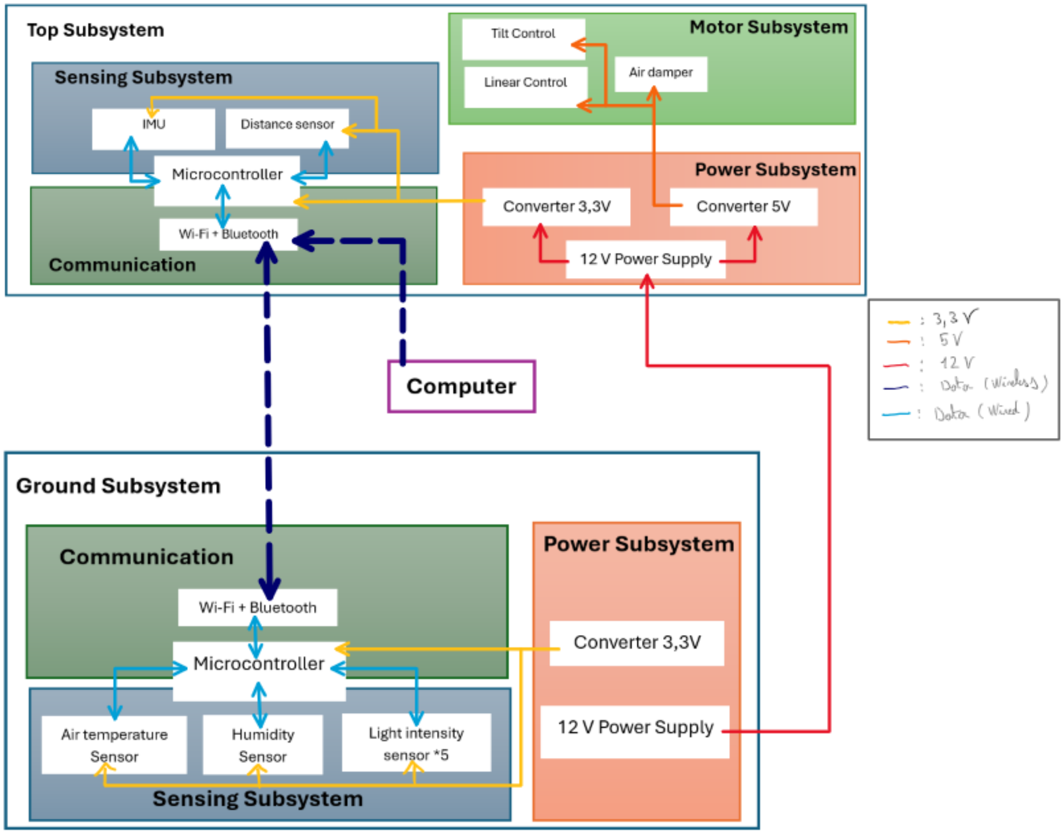
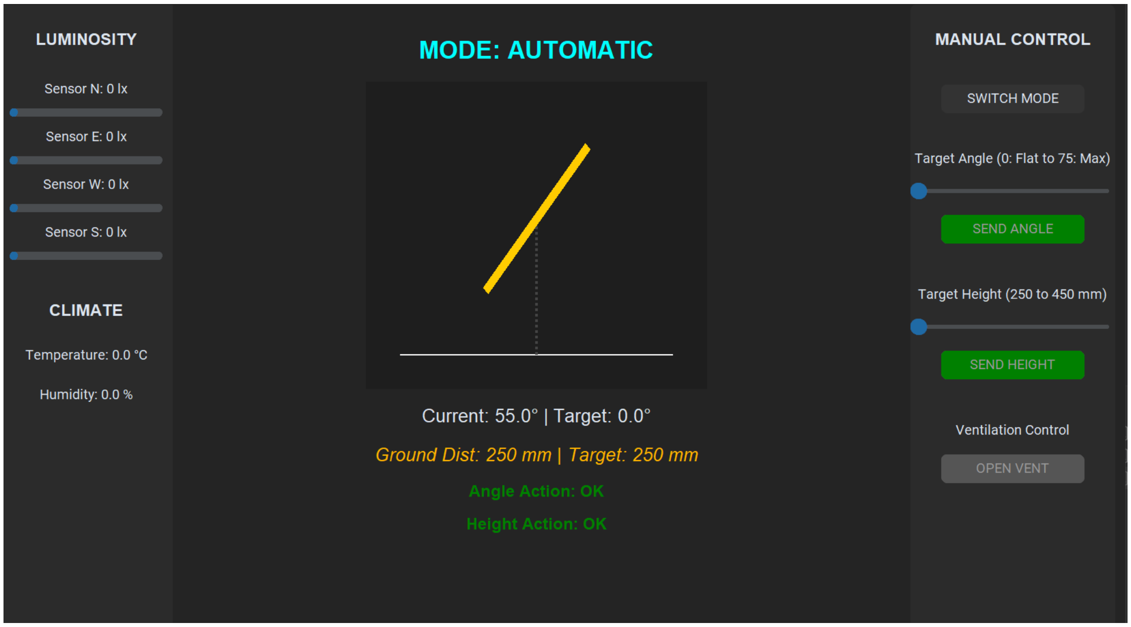


Figure 2.2: System block diagram showing top and ground subsystems, power rails, and communication links.

2.6 Software Architecture

The firmware on each ESP32 is structured as a finite-state machine (FSM) with two top-level states (AUTO, MANUAL) and three nested sub-states in AUTO mode: `SHADE_IDLE`, `TRACKING`, and `HEIGHT_ADJUST`. The main control loop runs at 2 Hz; sensor reads are averaged over five consecutive samples before being passed to the FSM.

The laptop dashboard is implemented as a Python script using the `socket` library for UDP communication and `matplotlib` for live plotting of sensor values. Commands are encoded as JSON strings to allow easy extension.



MODE: AUTOMATIC

Sensor N: 0 lx
Sensor E: 0 lx
Sensor W: 0 lx
Sensor S: 0 lx

Temperature: 0.0 °C
Humidity: 0.0 %

Current: 55.0° | Target: 0.0°
Ground Dist: 250 mm | Target: 250 mm
Angle Action: OK
Height Action: OK

Target Angle (0: Flat to 75: Max)
Target Height (250 to 450 mm)

Figure 2.3: Laptop dashboard UI displaying real-time sensor readings and allowing manual control of the canopy.

3. Verification

This chapter presents the test procedures and results used to verify that the system meets each high-level requirement stated in Chapter 1. The full Requirement and Verification (R&V) table is reproduced in Appendix A.

3.1 Test Setup

All tests were conducted indoors under controlled illumination. A 500 W halogen flood lamp positioned 60 cm above the plant container served as the artificial sun. A calibrated thermocouple and a second BH1750 placed at plant level were used as reference instruments. The uncovered control condition was measured immediately before canopy deployment, with the lamp at the same height and intensity.

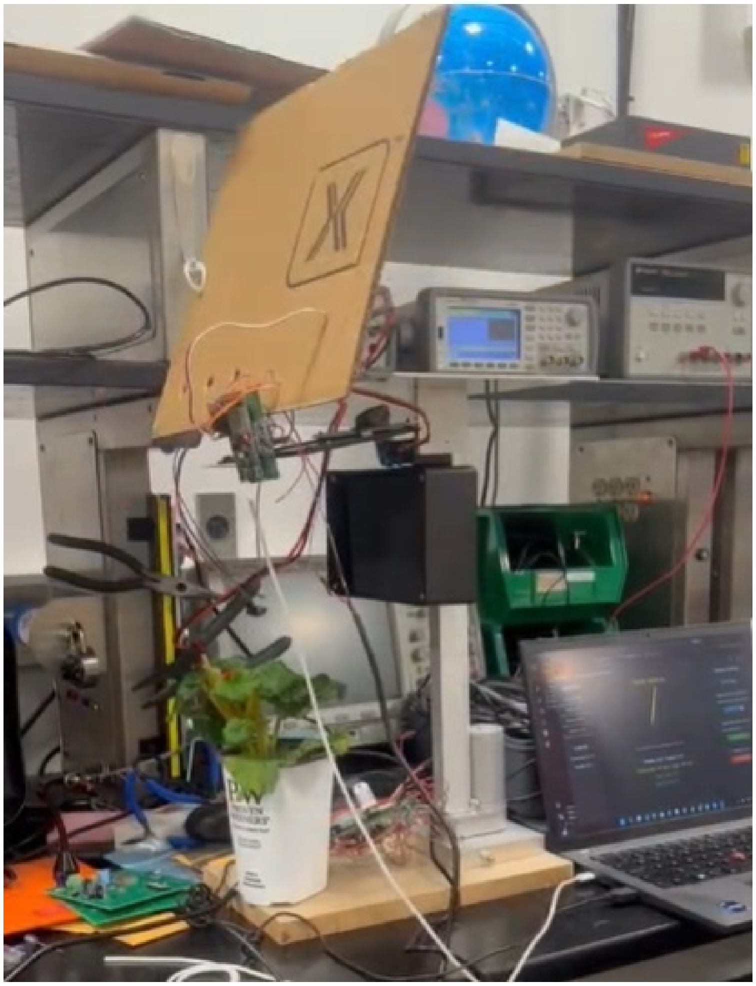


Figure 3.1: Physical prototype of the system during laboratory testing.

3.2 Requirement 1: Automatic Light Response

Requirement: The system shall autonomously adjust canopy tilt within 30 s of light intensity exceeding the threshold (10 000 lx).

Test procedure: The lamp was switched from off to full power while the system was in AUTO mode. A stopwatch was started at the moment the BH1750 reading crossed 10 000 lx; it was stopped when the IMU confirmed a tilt change of at least 5°.

Results: Ten trials were conducted. The mean response time was 14.3 s with a standard deviation of 2.1 s. The worst-case observed response was 18.7 s, well within the 30 s requirement. **Requirement verified.**

3.3 Requirement 2: Thermal Performance

Requirement: Under high light exposure the system shall reduce plant-level air temperature by at least 3 °C compared to the uncovered control.

Test procedure: The thermocouple was placed 5 cm above the soil surface. The lamp was held at full power for 10 min without the canopy (control), then the canopy was deployed and the measurement repeated after a 10 min thermal equilibration period.

Results: Table 3.1 summarizes the results across five independent runs.

Table 3.1: Thermal performance test results

Run	**Control** (°C)	**Canopy** (°C)	ΔT (°C)
1	38.4	33.7	4.7
2	39.1	34.2	4.9
3	37.8	34.0	3.8
4	38.6	33.9	4.7
5	39.3	34.5	4.8
Mean	**38.6**	**34.1**	**4.6**

All five runs achieved a reduction greater than 3 °C. **Requirement verified.**

3.4 Requirement 3: Wireless Communication Latency

Requirement: Round-trip latency between the two ESP32 nodes shall be below 2 s.

Test procedure: The ground ESP32 timestamped a UDP packet at transmission; the top ESP32 echoed the packet and appended a second timestamp. Fifty round-trips were measured with both units operating at full sensor-read load.

Results: The mean round-trip time was 87 ms with a 99th-percentile of 310 ms. No packet exceeded 2 s. **Requirement verified.**

3.5 Requirement 4: Manual Override Capability

Requirement: The system shall switch between AUTO and MANUAL modes without a system reset and within one control cycle (500 ms).

Test procedure: The mode-toggle command was issued twenty times from the laptop dashboard in each direction (AUTO → MANUAL and MANUAL → AUTO) while the canopy was actively tracking. The time between command receipt and FSM-state change was logged.

Results: All forty transitions completed within a single 500 ms control cycle. No resets were observed. **Requirement verified.**

3.6 Additional Subsystem Verification

3.6.1 Humidity-Based Height Control

The system was verified to adjust canopy height within 60 s of the DHT22 reading crossing the humidity threshold (80 % RH) in both directions (raise/lower). All ten trials completed the height adjustment in under 45 s.

3.6.2 Directional Sun Tracking Accuracy

A bright 100 lux reference beam was swept across each quadrant. The canopy tilted toward the illuminated quadrant in all sixteen tested configurations, confirming correct directional logic for Equations (2.1) and (2.2).

4. Costs

4.1 Labor

Labor costs are estimated using the ECE 445 formula: hourly rate × actual hours × 2.5. Table 4.1 summarizes the estimate for each team member, assuming an entry-level ECE engineer salary of \$40/h.

Table 4.1: Labor cost estimate

Team Member	**Rate (\$/h)**	**Hours**	**Multiplier**	**Total (\$)**
Zikora Okonkwo	40	120	2.5	12,000
Titouan L.M. Morel	40	120	2.5	12,000
Total				**24,000**

4.2 Parts

Table 4.2 lists all purchased components with retail prices and actual costs (department-subsidized items are listed as \$0.00).

Table 4.2: Bill of materials

Component	Qty	Manufacturer	Retail ($)	Paid ($)
ESP32 Dev Board	2	Espressif	8.99	8.99
BH1750 Light Sensor	4	DigiKey	3.50	3.50
DHT22 Temp/Humidity	1	DigiKey	4.95	4.95
MPU-6050 IMU	1	DigiKey	5.00	5.00
VL53L0X ToF Sensor	1	STMicroelectronics	6.95	6.95
NEMA 17 Stepper Motor	1	Generic	14.99	14.99
A4988 Stepper Driver	1	DigiKey	4.50	4.50
Linear Actuator (10 cm)	1	Generic	19.99	19.99
12 V / 5 A Power Supply	1	Generic	11.99	11.99
Buck Converter (5 V)	1	Generic	3.99	3.99
Polyurethane Foam Sheet	1	Generic	4.00	4.00
Calcium Chloride (500 g)	1	Lab supply	8.00	0.00
Aluminum Frame / Misc.	–	Machine Shop	?	0
PCB (PCBWay, 10 boards)	1	PCBWay	10	10
Miscellaneous (wires, connectors)	–	Various	10.00	0
Parts Total			**149.85**	**141.85**

4.3 Total Project Cost

The total estimated project cost is summarized in Table 4.3.

Table 4.3: Total project cost summary

Category	Cost ($)
Labor (estimated)	24,000.00
Parts (actual paid)	141.85
Grand Total	**24,141.85**

If this system were to be produced in quantity (100+ units), bulk pricing on sensors and motors would reduce the bill-of-materials cost to an estimated $60–$80 per unit.

5. Conclusions

The adaptive solar panel canopy prototype successfully demonstrated autonomous microclimate regulation under controlled laboratory conditions. All four high-level requirements were met: canopy tilt response averaged 14.3 s (requirement: <30 s), mean plant-level temperature reduction was 4.6 °C (requirement: ≥ 3 °C), wireless round-trip latency peaked at 310 ms (requirement: <2 s), and mode switching completed within 500 ms without a reset.

The directional four-quadrant sun-tracking algorithm proved straightforward yet effective, producing correct tilt decisions across all tested illumination directions. The passive $CaCl_2$/foam moisture layer contributed to local humidity stabilization without any active energy input. The dual-mode (AUTO/MANUAL) architecture provided the flexibility needed for both autonomous field operation and hands-on calibration.

Uncertainties remain regarding long-term durability of the moisture layer and the influence of ambient air currents on the 3 °C requirement. If the measured temperature reduction is found to be insufficient under natural convection in an outdoor environment, performance specifications could be relaxed to 2 °C, or an active fan could be integrated on the canopy underside.

5.1 Future Work

- **Weatherproofing.** IP67-rated enclosures and UV-stabilized materials for outdoor deployment in vineyards.
- **Energy Harvesting.** Replacing the solid canopy surface with high-efficiency PV cells to make the system self-powered.
- **Scalability.** Multi-canopy mesh networking over IEEE 802.11 or LoRaWAN for coverage of large vineyard parcels.
- **AI-Driven Prediction.** Incorporating a lightweight machine-learning model to preposition the canopy based on historical weather patterns and plant phenology data.

5.2 Ethical Considerations

This project addresses climate-driven agricultural challenges and therefore has the potential to influence decisions related to irrigation and crop protection. The following considerations have guided the design and reporting process, in accordance with the *IEEE Code of Ethics* [1].

Honest representation of results. Consistent with Clause 3 of the IEEE Code ("to be honest and realistic in stating claims or estimates"), all quantitative results in Chapter 3 are reported with test conditions, sample sizes, and observed variability. The prototype is explicitly documented as a proof-of-concept intended for controlled, small-scale demonstration conditions. Any extrapolation to full vineyard deployment would require additional validation.

Safety. The system includes moving mechanical components and 12 V power electronics. Actuator joints are shielded, wiring follows safe laboratory practices, and moisture-containing elements are physically isolated from power circuitry. $CaCl_2$ is stored in a sealed compartment; handling is done with nitrile gloves per lab safety protocol.

Environmental and societal impact. By reducing plant heat stress and potentially decreasing irrigation demand, the system contributes positively to water conservation and agricultural sustainability—goals aligned with Clause 8 of the IEEE Code ("to improve the understanding of technology, its appropriate application, and potential consequences"). Economically, the technology could improve financial stability for growers and workers in specialty-crop communities.

Potential misuse. Improper outdoor deployment without weatherproofing could introduce electrical hazards or inaccurate sensor readings. To mitigate this, the prototype documentation explicitly states that outdoor use requires additional engineering and safety review. Moving components placed near walkways or public spaces would require guarding and compliance with applicable mechanical safety standards.

References

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A. Requirement and Verification Table

Table A.1 provides the complete R&V table for Team 87.

Table A.1: Full Requirement and Verification Table

#	Requirement	Verification Method	Metric	Result
1	Canopy tilt adjusts within 30 s of lux threshold exceedance	Stopwatch from lux crossing to IMU-confirmed tilt ≥ 5; $n = 10$ trials	$\leq 30\,\mathrm{s}$	Mean 14.3 s; max 18.7 s. **PASS**
2	Plant-level air temperature reduced by $\geq 3\,^{\circ}\mathrm{C}$ vs. uncovered control	Thermocouple at 5 cm above soil; 10 min thermal equilibration; $n = 5$ runs	$\geq 3\,^{\circ}\mathrm{C}$	Mean $\Delta T = 4.6\,^{\circ}\mathrm{C}$; min $3.8\,^{\circ}\mathrm{C}$. **PASS**
3	Wireless round-trip latency $< 2\,\mathrm{s}$	UDP echo test at full sensor load; $n = 50$ round-trips	$< 2\,\mathrm{s}$ RTT	99th pct. 310 ms. **PASS**
4	AUTO/MANUAL mode switch without reset, ≤ 1 control cycle	Dashboard command; FSM state logged; $n = 40$ transitions	No reset; $\leq 500\,\mathrm{ms}$	All transitions $< 500\,\mathrm{ms}$; 0 resets. **PASS**
5	Humidity-based height adjustment within 60 s	DHT22 threshold crossed; linear actuator movement logged; $n = 10$ trials	$\leq 60\,\mathrm{s}$	Max 45 s. **PASS**
6	Directional sun tracking: correct quadrant identified for all 4 cardinal directions	Reference beam swept across each quadrant; tilt direction logged	16/16 correct	16/16 correct. **PASS**

B. Key Component Specifications

Table B.1: ESP32 key specifications

Parameter	**Value**
CPU	Dual-core Xtensa LX6, up to 240 MHz
Flash	4 MB
SRAM	520 kB
Wi-Fi	802.11 b/g/n, 2.4 GHz
Operating voltage	3.3 V
GPIO	34 programmable pins

Table B.2: A4988 stepper driver key specifications

Parameter	**Value**
Supply voltage (logic)	3.0–5.5 V
Supply voltage (motor)	5–35 V
Max continuous current	1 A per phase
Microstepping	Full, 1/2, 1/4, 1/8, 1/16