Design Document

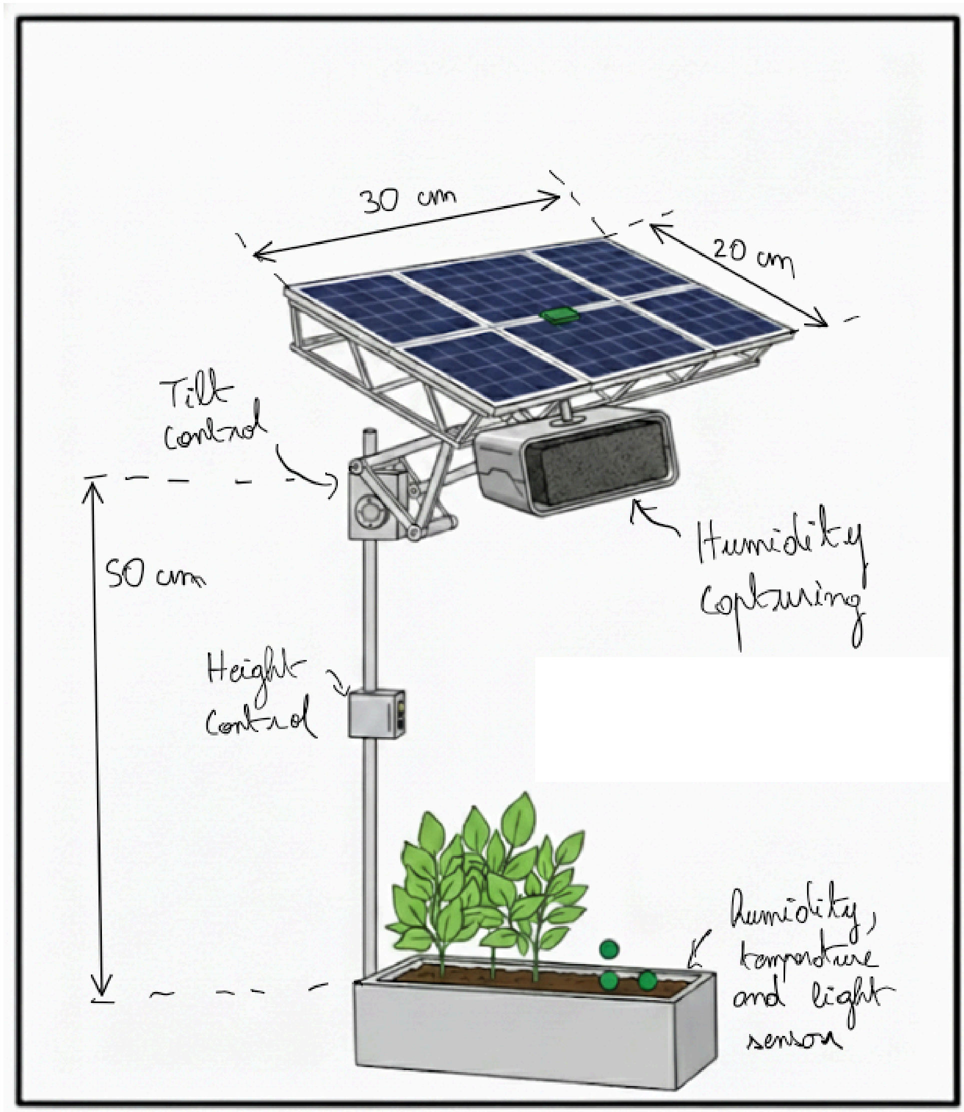
1) Introduction

1.1) Problem and Solution

Climate change is increasingly impacting agricultural production, particularly for specialty crops such as grapes that are highly sensitive to excessive heat and solar exposure. Rising temperatures and more frequent heat waves increase leaf temperature and accelerate soil moisture evaporation, which can reduce photosynthetic efficiency, cause leaf burn, and lead to uneven ripening. These effects not only reduce crop yield and quality but also increase dependence on irrigation, placing additional strain on freshwater resources. Existing shading solutions are typically static, manually adjusted, or implemented at large agricultural scales, making them inefficient for localized plant-level microclimate control. There is a need for an adaptive, low-power, and autonomous shading system that responds dynamically to environmental conditions while minimizing water usage and manual intervention.

To address this problem, our project proposes an adaptive microclimate control system consisting of a motorized canopy structure controlled by distributed ESP32-based subsystems. The bottom subsystem monitors environmental conditions including temperature, humidity, soil moisture, and light intensity. The top subsystem controls canopy tilt and height using motorized actuation and incorporates a four-light-sensor sun-tracking system to determine directional solar intensity. The system supports both automatic and manual operating modes, allowing autonomous sensor-driven control or user override via wireless communication. This distributed architecture improves modularity, scalability, and reliability compared to static shading solutions. The integration of real-time sensing, closed-loop actuation, and wireless communication represents a novel improvement over passive agricultural shading techniques.

1.2) Visual aid



1.3) High-Level Requirements

The system must autonomously adjust canopy tilt within 30 seconds when light intensity exceeds a predefined lux threshold. The system must reduce plant-level air temperature by at least 3°C under high-light conditions compared to an uncovered control setup. Wireless communication between subsystems must maintain data latency below two seconds. The system must support seamless switching between manual and automatic operating modes without requiring a system reset. Failure to meet any of these requirements would prevent the system from effectively solving the stated problem.

2) Design

The overall system is divided into modular subsystems: the environmental sensing subsystem, the sun-tracking and actuation subsystem, the power subsystem, and the wireless communication subsystem. The bottom subsystem is responsible for collecting environmental data and transmitting it wirelessly to the top subsystem. The top subsystem processes sensor inputs and controls the mechanical motion of the canopy using motor drivers, a stepper motor for tilt control, and a linear actuator for height adjustment. Both subsystems are powered by regulated voltage supplies derived from a 12V source, with appropriate conversion to 5V and 3.3V for logic components.

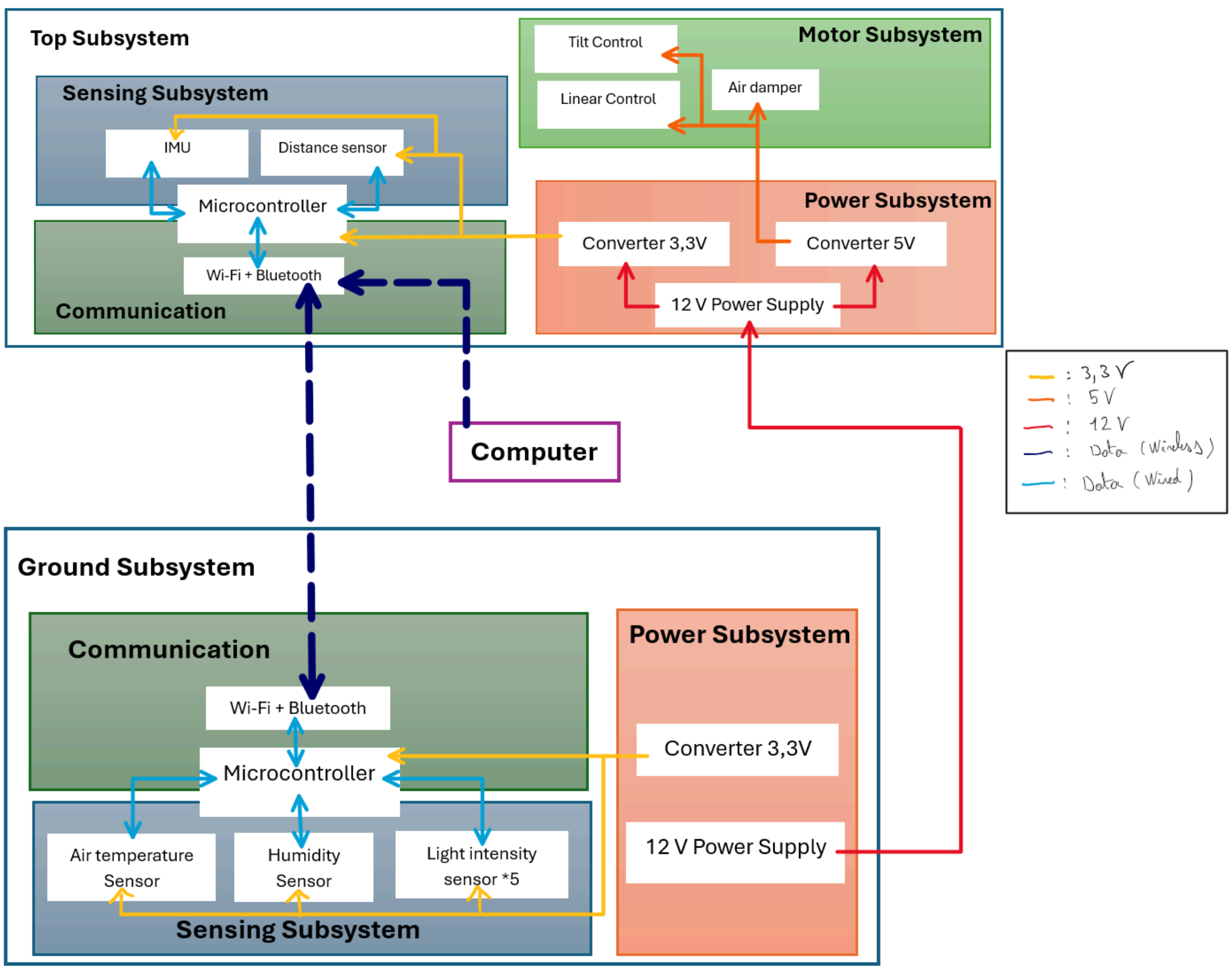
The environmental sensing subsystem consists of an ESP32 microcontroller interfaced with digital sensors over I^2C communication. A light intensity sensor measures ambient solar exposure, while temperature and humidity sensors monitor microclimate conditions near the plant canopy. Soil moisture sensing provides additional feedback for evaluating water retention improvements. These sensors operate at 3.3V logic levels and communicate using a 100 kHz I^2C bus to reduce wiring complexity and ensure reliable data transfer. The ESP32 was selected due to its integrated WiFi and Bluetooth capabilities, sufficient GPIO availability, and dual-core architecture, which allows concurrent communication and control processing.

The sun-tracking subsystem introduces one of the primary technical complexities of the project. Four light sensors are arranged in a quadrant configuration to measure directional differences in incident light. By comparing intensity values between opposing sensors, the system computes a differential light vector that indicates the direction of maximum solar exposure. When the measured lux difference exceeds a predefined threshold, the canopy tilt is adjusted to balance the light distribution. This approach allows dynamic angular correction rather than simple threshold-based shading. The use of four sensors enables more accurate directional tracking compared to single-sensor systems and ensures responsive canopy alignment.

The actuation subsystem includes a stepper motor for canopy tilt adjustment and a linear actuator for vertical height control. Motor drivers interface between the ESP32 logic-level outputs and the higher current requirements of the motors. An inertial measurement unit (IMU) provides tilt angle feedback to verify angular positioning, while a distance sensor measures vertical displacement of the canopy. This creates a closed-loop control system in which positional error can be minimized. The design targets a tilt accuracy within ±3 degrees and height accuracy within ±1 centimeter. Motor torque requirements were calculated based on canopy mass and moment arm distance to ensure sufficient mechanical capability with an appropriate safety margin.

A second major system complexity is the implementation of dual-mode operation. In automatic mode, sensor inputs determine canopy movement based on predefined environmental thresholds. In manual mode, a user can override automatic control via wireless communication from a computer interface. Mode switching is implemented in software and must occur without resetting the system. This ensures seamless transitions between autonomous operation and user-directed adjustments. The ESP32 communication subsystem supports WiFi or Bluetooth protocols to transmit sensor data and receive control commands with a target latency of less than two seconds.

2.1) Block Diagram



The system is architecturally divided into two primary physical modules to optimize data collection and mechanical precision.

The Bottom Subsystem is positioned near the crop to capture essential environmental data, including light intensity (LTR-303), soil moisture, and ambient temperature/humidity (AM2302). These parameters define the plant's immediate microclimate and determine the need for shading.

The Top Subsystem focuses on execution and feedback; it houses the three servo motors responsible for movement, along with a VL53L0X distance sensor and an MPU-6050 IMU. This combination allows for high-precision motion control by monitoring the exact tilt angle and the vertical clearance of the canopy.

To ensure system stability, the Power Subsystem implements a dual-rail regulation strategy. The power paths for the ESP32 microcontroller and the three servo motors are strictly separated. By isolating the high-current demands and electrical noise of the servos from the sensitive logic of the MCU, the design prevents voltage sags and electromagnetic interference that could otherwise lead to processor resets or data corruption during canopy adjustments.

2.2) Physical design

The prototype is designed as a compact vertical solution, standing 50 cm in height with a solar canopy footprint of 30 cm x 20 cm. For demonstration purposes, the entire system is housed under a bell jar (cloche) to simulate a controlled greenhouse microclimate.

Passive Humidity Regulation : The system employs a saturated salt-impregnated sponge to maintain a stable microclimate under the 50 cm bell jar, utilizing the principle of hygroscopic equilibrium (Greenspan, 1977). This "Humidity Layer" acts as a passive buffer: the salt-sponge captures excess vapor at night as temperatures drop and releases it during the day as heat increases.

2.3.1) Powers Subsystems (Top and Bottom) :

Requirement	Verification
Provide a stable 3.3V +- 0.1V to the ESP32 and sensors under a constant load of 200mA.	Connect a 16.5 Omega power resistor to the 3.3V rail. Use a DMM to measure voltage over a 60-second interval to ensure it stays within 3.2V - 3.4V.
Provide a 5V +- 0.25V rail to the 3 servo motors capable of handling peak currents of 1.5A without dropping below 4.5V.	Oscilloscope test: Trigger all 3 servos simultaneously. Monitor the 5V rail to ensure voltage sags do not exceed 0.5V.

2.3.2) Sensing Subsystems (Bottom) :

Requirement	Verification
The 4-point light sensor array (LTR-303) must distinguish light intensity differences of +- 10% to determine the sun's vector.	Place a light source at a 45 degree angle. Compare the digital Lux readings from the 4 sensors to verify the vector calculation in the

	serial monitor.
Soil moisture sensor must provide a linear analog response between 1.2V (saturated) and 2.8V (dry) +- 0.2V.	Test the sensor in dry soil, then add measured increments of water (50mL). Measure the output voltage with a DMM at each step.
AM2302 must report temperature within +- 2 celsius degree and humidity within +- 5% compared to a lab-grade reference meter.	Place the sensor and a reference hygrometer under the bell jar. Record values at 3 different intervals and compare.

2.3.3) Top Subsystem Actuation and Precision :

Requirement	Verification
The Pulley/Servo system must adjust the canopy height within a range of 20cm to 50cm with a precision of +- 1cm.	Use a yardstick to measure the height. Command the ESP32 to "Move to 40cm" and verify the distance with the VL53L0X sensor and a manual ruler.
The Tilt Servo must achieve an angular range of 0 degree to 90 degree with a resolution of 5 degree verified by the IMU.	Command the servo in 10 degree increments. Read the MPU-6050 pitch/roll values via I2C and verify they match the commanded angle within +- 3 degrees.
The Humidity Trap Servo must open/close the vent door fully ($90 degree travel) within 3 second of a software command.	Use a stopwatch o to time the interval between the "Open" command sent via Serial and the door hitting the limit.

2.3.4) Control Subsystem (MCU & Communication :

Requirement	Verification
Maintain a stable WiFi connection to a local access point within a 5-meter range (through the bell jar) with a packet loss < 5\%.	Run a ping test from a connected PC to the ESP32's IP address for 100 packets. Count successful returns.
Latency between a manual "Override" command from the PC and the physical movement of a servo must be < 200ms.	Use the millis() function in the code to timestamp the arrival of a WiFi packet and the initiation of the PWM signal. Output the delta to Serial.

2.4) Tolerance Analysis

The most critical mechanical requirement of the system is the torque necessary to rotate the canopy structure. The required torque is determined by the product of canopy weight and the perpendicular distance from the rotation axis. Assuming a canopy mass of approximately 0.8 kg and a moment arm distance of 0.15 meters, the required torque is approximately 1.2 N·m. A selected stepper motor must exceed this requirement with at least a 25% safety margin to ensure reliable operation under varying environmental loads such as wind or mechanical friction. This analysis demonstrates the feasibility of the actuation subsystem and justifies the motor selection.

3) Cost and Schedule

3.1) Cost Analysis :

Description	Manufacturer	Part #	Quantity	Unit Cost	Total Cost
Microcontroller (ESP32)	Espressif	ESP32-WROOM-32	2	$6.00	$12.00
IMU (Tilt Sensor)	InvenSense	MPU-6050	1	$5.50	$5.50
Temp/Hum Sensor	Aosong	AM2302 (DHT22)	1	$9.00	$9.00
Light Sensor	Lite-On	LTR-303ALS-01	4	$2.50	$10.00
Distance Sensor	STMicroelectronics	VL53L0X	1	$8.00	$8.00
Soil Moisture Sensor	Generic	Capacitive v1.2	1	$4.50	$4.50
Servo Motors	TowerPro	SG90	3	$4.00	$12.00
Pulley & Cable Set	Generic	3D Printed/Nylon	1	$15.00	$15.00
Bell Jar (Cloche)	Generic	Glass/Acrylic	1	$25.00	$25.00
Structural Materials	Local Hardware	30x20cm Panel/Rod	1	$20.00	$20.00
Electronic Components	Various	Resistors/Caps/PCB	1	$15.00	$15.00
Machine Shop Labor	ECE Shop	3D Printing/Laser	4 hrs	$50.00	$200.00
Total Parts					$336.00

Name	Hourly Rate	Overhead Multipl	Total Hours	Total Labor Cost
Partner 1 (Zikora)	$40.00	2.5	150	$15,000
Partner 2 (Titouan)	$40.00	2.5	150	$15,000
Total Labor			300	$30,000

So the grand total is $30,336.00

3.2) Schedule :

- Week 1: System Architecture & Electrical Schematics
    - Finalize complete electrical schematics.

    - Design the power isolation strategy (separating MCU and Servo power rails).
    - *Responsibility: Both.*
- Week 2: PCB Layout & Component Sourcing
    - Complete the PCB routing and layout.
    - Submit Gerber files for fabrication.
    - Order any remaining specialty sensors.
    - *Responsibility: Both.*
- Week 3: Mechanical Design Consultation with Machine Shop
    - Submit requirements to the Machine Shop.
    - Consult with technicians for the mechanical design of the pulley system and the 30x20 cm panel support.
    - *Responsibility: Both.*
- Week 4: Software Infrastructure & Drivers
    - Develop I2C drivers for the Bottom Subsystem sensors (LTR-303, AM2302).
    - Establish WiFi communication protocols between the ESP32 and the PC.
    - *Responsibility: Both.*
- Week 5: Bottom Subsystem Assembly (Sensing)
    - Receive and solder the PCB components.
    - Verify data acquisition from light and soil moisture sensors.
    - *Responsibility: Both.*
- Week 6: Top Subsystem & Pulley Integration
    - Retrieve the mechanical structure fabricated by the Machine Shop.
    - Install the 3 servo motors and calibrate the 50 cm vertical lift.
    - *Responsibility: Both.*
- Week 7: Closed-Loop Control Logic
    - Integrate IMU and distance sensor data with the servo PWM logic.
    - Test positioning accuracy and tilt precision.
    - *Responsibility: Both.*
- Week 8: Bell Jar Environment Testing
    - Install the full system inside the demonstration bell jar.
    - Deploy the "Salt-Sponge" humidity buffer and monitor microclimate stability.
    - *Responsibility: Both.*
- Week 9: Requirements & Verification (R&V)
    - Conduct final quantitative tests: verify height accuracy ($\pm$1 cm) and solar tracking efficiency.
    - Perform final software bug fixes.
    - *Responsibility: Both.*
- Week 10: Final Report & Demonstration
    - Complete the final design report documentation.
    - Prepare the live demonstration for course instructors.
    - *Responsibility: Both.*

4) Societal Impact, Ethics, and Safety Considerations

This project contributes positively to environmental sustainability by reducing irrigation demand and improving crop resilience to heat stress. By providing localized microclimate control, the system supports more efficient water usage and reduces agricultural resource strain. Economically, improving crop stability benefits growers and associated supply chains. The design aligns with IEEE and course ethical guidelines by promoting public welfare, environmental responsibility, and safe engineering practices.

Electrical safety considerations include proper voltage regulation, current limiting for motor drivers, and adequate decoupling to prevent power instability. Mechanical safety concerns include secure mounting of motors and moving components to prevent unintended motion. The system operates at low voltage (12V maximum) to minimize electrical hazards. All battery handling procedures, if applicable, will follow course safety guidelines. Design decisions prioritize protection of both users and developers from electrical, thermal, and mechanical risks.

The Adaptive Solar Panel Canopy project contributes to public welfare by addressing climate-driven agricultural challenges, such as heat stress and water scarcity, through localized microclimate stabilization that supports economic stability and food system resilience. The design adheres to engineering standards including **IEEE 1621** for power control interfaces, **IEEE 1012** for system verification, and **NEMA** guidelines for enclosure safety to physically isolate electronics from moisture-capturing layers. In alignment with the **IEEE Code of Ethics**, the project emphasizes safety and honesty by explicitly documenting the system as a proof-of-concept for controlled environments and incorporating a manual override to ensure human control during testing or unusual conditions.

Safety concerns are mitigated through rigorous procedures: mechanical pinch hazards from the 50 cm pulley system and 30x20 cm panels are addressed by secure mounting and software dead-zones; electrical risks from the high-current draw of three servos are managed via regulated power supplies and dedicated power rails to prevent ESP32 resets; and chemical risks from the hygroscopic calcium chloride ($CaCl2$) are mitigated by using sealed compartments and protective gloves. Finally, to protect the system under the demonstration bell jar, a software "Protection Mode" has been implemented to level the panels if temperatures exceed 45 degree.

5) Citations

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[4] Espressif Systems, "ESP32 Series Datasheet," v4.1, 2023.

[5] InvenSense, "MPU-6000 and MPU-6050 Product Specification Revision 3.4," Aug. 2013.

[6] STMicroelectronics, "VL53L0X World smallest Time-of-Flight (ToF) ranging sensor datasheet," 2018.

[7] Lite-On Technology Corp., "LTR-303ALS-01 Digital Light Sensor Datasheet," 2013.

[8] Aosong Electronics, "Digital-output relative humidity & temperature sensor/module AM2302 (DHT22) Datasheet," 2015.