# ADAPTIVE SOLAR PANEL CANOPY FOR VINEYARD MICROCLIMATE CONTROL

TEAM 87
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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, which can reduce crop yield and quality. Grapevines are particularly sensitive during key growth stages, where excessive solar exposure can cause leaf burn, reduced photosynthetic efficiency, and uneven ripening. These conditions can 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, this 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. Therefore, developing localized and efficient methods for protecting crops from heat stress while conserving water is an important engineering problem with real-world relevance.

This proposal describes 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, motorized actuation, and a passive moisture-capture layer. The remainder of this proposal presents the system design, design verification process, project costs, and final conclusions including ethical considerations and future work.

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# 2. Design

This chapter describes the overall system architecture and the major design decisions made to implement an adaptive canopy for microclimate regulation. The system is organized into several subsystems including environmental sensing, sun tracking, canopy actuation, and user control. The design is intended to function autonomously for extended periods while also supporting user override for testing, debugging, and operational flexibility.

## 2.1 System Overview

The system 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. The canopy also includes a moisture-capturing layer beneath the shading surface to absorb ambient moisture when humidity is high and release it when conditions become drier.

Two major design complexities were added to improve functionality and demonstrate advanced control capabilities:

1. **Directional sun tracking using four light sensors**
2. **Manual and automatic operating modes**

These features improve system realism and allow the prototype to better simulate real agricultural usage scenarios.

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## 2.2 Directional Sun Tracking Subsystem

Rather than relying on a single light sensor threshold, the system implements directional sun tracking using four light sensors mounted around the canopy in a quadrant layout:

- North sensor
- South sensor
- East sensor
- West sensor

This arrangement allows the controller to determine not only whether light intensity is high, but also the direction from which the strongest light is arriving. By adjusting canopy tilt based on directional input, the system can produce more effective shading and improve temperature reduction performance.

The controller computes error signals such as:

- Horizontal error = East − West
- Vertical error = North − South

These error values are used to 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 and sensor averaging. This ensures that the canopy only moves when the light imbalance exceeds a minimum meaningful amount.

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## 2.3 Manual and Automatic Operating Modes

In addition to autonomous operation, the system supports a manual override mode. This reflects realistic agricultural deployments where growers may want to override automation during maintenance, testing, calibration, or unusual weather conditions.

The system operates using a mode-based control structure:

- **AUTO Mode:** canopy adjusts based on sensor readings and sun tracking logic
- **MANUAL Mode:** canopy responds only to user commands

In manual mode, sensor-driven actuation is disabled, preventing unexpected movements. Manual commands allow direct control of canopy tilt and height. This mode also supports debugging by allowing the system to be tested without relying on environmental conditions.

Manual commands are issued through a laptop interface over USB serial or a simple UI input system. The current operating mode is displayed to the user at all times to avoid confusion and reduce safety risk.

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## 2.4 Microclimate and Moisture Retention Subsystem

When conditions become harsh, 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 exposure, supporting healthy growth. Height control is used as an additional method of managing local humidity conditions, where the canopy may be raised or lowered to trap or release moisture near the plant.

In addition to shading, the system includes a moisture-capturing layer beneath the canopy. This layer uses a hydrophilic foam medium combined with a moisture-absorbing material (calcium chloride, $CaCl_2$) to capture humidity when ambient moisture is high and release it gradually when conditions become drier. By pairing sensor-driven actuation with passive moisture management, the system aims to improve plant-level microclimate stability and reduce unnecessary irrigation.

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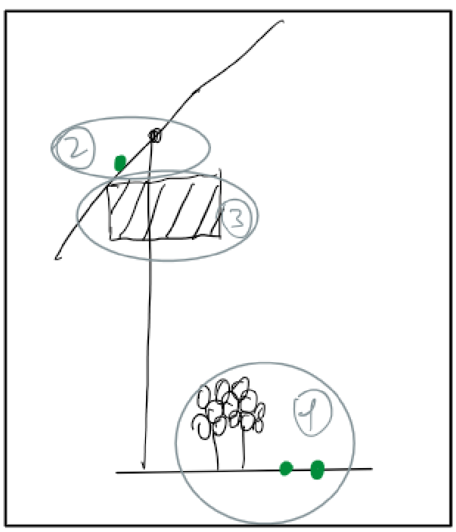
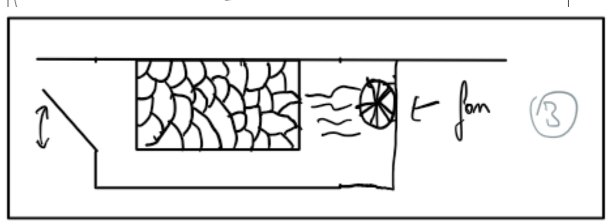
## 2.5 Visual Aid

A context diagram for this project shows a small potted plant or soil container placed beneath a motorized canopy structure. A bright overhead lamp (representing sunlight) illuminates the setup. Sensors are mounted near the plant to measure light intensity, temperature, humidity, and soil moisture. The canopy consists of a rigid shading surface with a moisture-capturing layer beneath it.

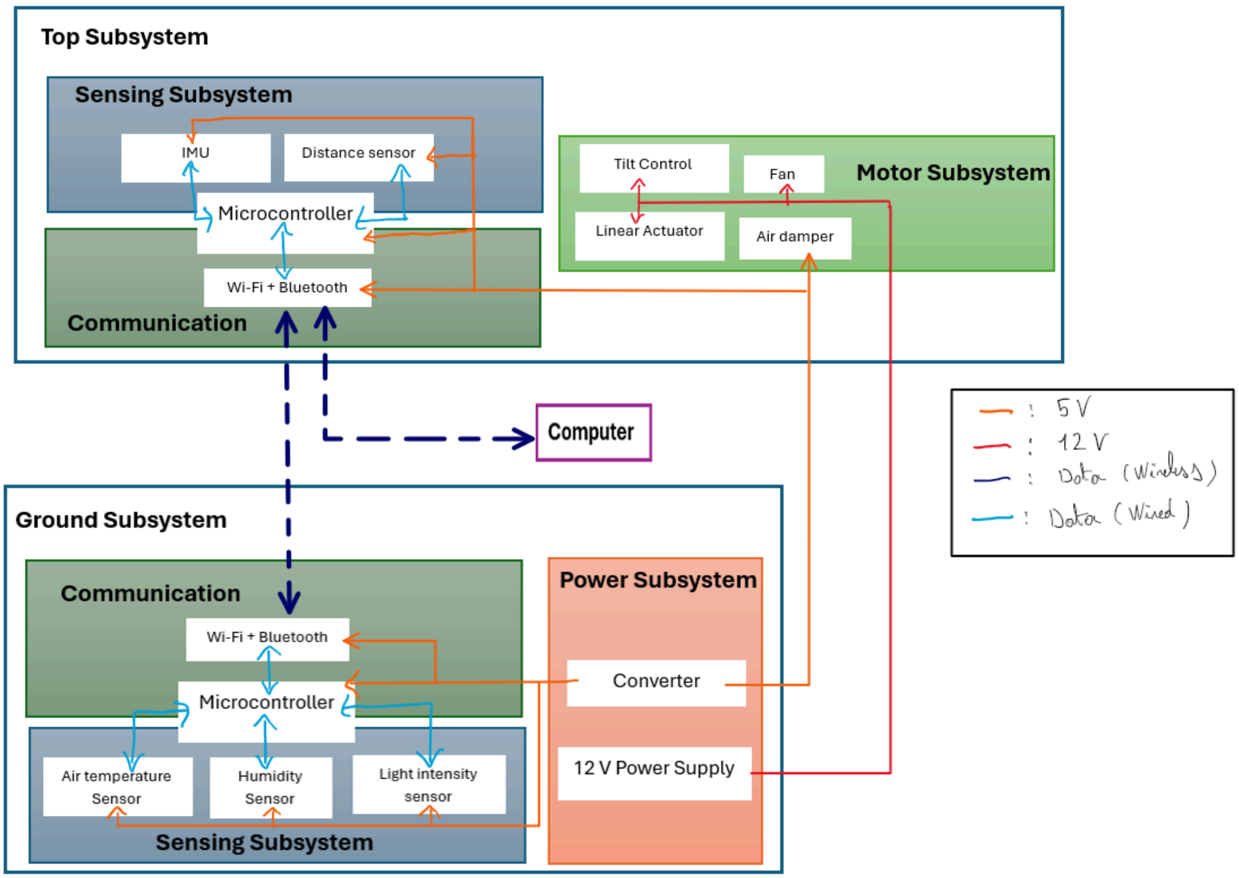
Four light sensors are mounted around the canopy in a quadrant configuration to enable directional sun tracking. A microcontroller reads sensor inputs and controls the canopy motion using a linear actuator for height adjustment and a stepper motor for tilt adjustment.

A laptop displays live sensor readings, system mode (manual/auto), and actuator states for debugging and validation. In manual mode, the laptop interface can also send commands to adjust the canopy tilt and height directly.



## 2.6 Block Diagram




# 3. High-Level Requirements

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

- **Directional Sun Tracking:** The system shall use four light sensors to determine the dominant direction of light exposure and adjust canopy tilt accordingly.

- **Automatic Light Response:** The system shall autonomously adjust the canopy tilt angle within 30 seconds of detecting that light intensity exceeds a predefined threshold.
- **Humidity-Based Height Control:** The system shall autonomously adjust canopy height within 60 seconds of detecting that humidity exceeds or falls below a predefined threshold.
- **Manual Override Capability:** The system shall support both manual and automatic modes, where manual mode disables sensor-driven actuation and allows direct user control of canopy tilt and height.
- **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.

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# 4. Ethical Responsibilities and Professional Conduct

This project addresses climate-driven agricultural challenges and therefore has the potential to influence decisions related to irrigation and crop protection. As a result, it is ethically important to avoid overstating the system's effectiveness or presenting it as a guaranteed solution for real vineyard deployment. The project will be presented as a prototype demonstration system designed for controlled small-scale conditions. Any quantitative results will be reported with clear test conditions, measurement methods, and limitations to avoid unethical misrepresentation of performance.

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## 4.1 Safety Considerations During Development

The system includes moving mechanical components, powered electronics, and moisture-related materials. These introduce several safety risks during prototyping and testing. Mechanical motion poses pinch hazards, especially around actuator joints and rotating components. To mitigate this, the system will be mounted securely, and moving joints will be shielded where possible.

Electrical safety is also a concern, especially because motors can draw significant current and create voltage drops or overheating in wiring. Regulated power supplies, appropriate wire gauge, and motor drivers rated for the expected current will be used. The design will avoid exposed conductive wiring where possible, and all testing will be performed on non-conductive surfaces.

Because moisture is part of the project environment, care will be taken to physically separate wet components from the electronics and power delivery system. The moisture-capturing layer will be isolated from the PCB and wiring using sealed containers and physical barriers.

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## 4.2 Chemical and Material Safety

This project uses calcium chloride ($CaCl_2$) as a moisture-absorbing material. Calcium chloride is commonly used as a desiccant and de-icing agent, but it can cause skin and eye irritation and may become messy when saturated with water. To avoid hazards, $CaCl_2$ will be contained in a sealed or semi-sealed compartment within the moisture layer so that it cannot spill or contact users directly. Handling will be done with gloves when needed, and the material will be stored and disposed of according to appropriate lab procedures.

The polyurethane foam used as a hydrophilic medium will be handled safely and kept away from high heat sources.

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## 4.3 Potential Misuse and Risk Mitigation

Although this project is designed for controlled agricultural applications, misuse could occur if the system were deployed outdoors without adequate weatherproofing or if users relied on it as a replacement for necessary irrigation or safety practices. Improper outdoor deployment could lead to electrical hazards, equipment damage, or inaccurate sensor readings due to rain, dust, or extreme temperatures. To address this, the prototype will be explicitly documented as a proof-of-concept system intended for controlled demonstration conditions. If future iterations were considered for outdoor use, additional safety features such as waterproof enclosures, UV-resistant materials, and redundant sensor validation would be required.

Another misuse risk involves placing the canopy system near unintended areas such as walkways or public spaces where moving components could injure bystanders. This risk is minimized by keeping the prototype small-scale and emphasizing that any real deployment would require additional guarding, safety interlocks, and compliance with applicable mechanical safety standards.

## 4.4 Regulatory and Standards Considerations

While this prototype is not intended for commercial agricultural deployment, the design process will be informed by general electrical and mechanical safety standards. All electrical components will be used within their rated specifications, and wiring practices will follow safe laboratory procedures. Since the project does not involve energy harvesting, connection to building power infrastructure, or high-voltage systems, it avoids many of the regulatory concerns associated with grid-connected systems.

If expanded to real-world agricultural environments, additional regulatory concerns would apply, including weatherproofing, long-term material durability, and agricultural equipment safety. These considerations are out of scope for the current prototype but are acknowledged as future requirements.

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## 4.5 Societal, Environmental, and Economic Impact

This project targets an important global challenge: climate resilience in agriculture. By reducing plant heat stress and improving microclimate stability, this system could help growers maintain crop yield and quality under increasingly harsh environmental conditions. It also supports environmental sustainability by potentially reducing the need for excessive irrigation, helping conserve water resources in drought-prone regions.

Economically, vineyards and other specialty crops are high-value agricultural products, and reducing losses from heat damage can improve financial stability for growers and local agricultural communities. At a broader level, this project demonstrates how embedded sensing and adaptive control can be applied to environmental and agricultural systems. Even as a prototype, it highlights how engineering solutions can contribute to sustainable food production, water conservation, and climate adaptation strategies.