ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

A Remote Microwave Environmental Monitoring System: Automation and Power Management

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Abstract

This project successfully developed a Remote Microwave Environmental Monitoring System with advanced automation and power management capabilities. We implemented an automated measurement system that enables precise horizontal and vertical rotation through custom scripts, automatically collecting environmental microwave data without manual intervention. Our intelligent power management solution initiates automatic system shutdown after measurements, significantly reducing power consumption during inactive periods. For mechanical control, we developed a rotation control system using pan-tilt platform APIs that achieved positioning accuracy within ±2 degrees. The system is powered by a DJI Power 1000 unit with integrated battery packs and solar panels, providing reliable field operation. Additionally, we designed and implemented an automated rain protection system using a rain sensor connected to a PCB-controlled umbrella mechanism, which activates automatically during precipitation to protect sensitive measurement equipment. This comprehensive solution transforms a previously manual, labor-intensive process into an efficient, automated system that improves data collection consistency while reducing operational costs and human intervention requirements.

Contents

1 Introduction

Environmental monitoring of microwave signals plays a critical role in electromagnetic research, telecommunications, and environmental science. Traditionally, this process has been highly manual, requiring constant human intervention and significant resources. Our Remote Microwave Environmental Monitoring System transforms this process through automation, intelligent power management, and precision control.

1.1 Purpose

The purpose of our project is to address the inefficiencies and limitations of manual microwave environmental monitoring. Currently, researchers must physically position equipment, switch between software interfaces, and manually record measurements at various angles—a process that is time-consuming, prone to human error, and requires continuous human presence. Our solution automates this entire workflow, enabling comprehensive data collection without constant supervision while optimizing power consumption for remote deployments.

1.2 Functionality

Our system offers five core functionalities that work together to create a comprehensive solution:

1.2.1 Automated Measurement

The system automatically controls horizontal and vertical rotation of the monitoring platform through custom scripts, collecting measurements at precise angles without human intervention. This eliminates the need to manually switch between rotation control and measurement software, significantly improving efficiency and data consistency.

1.2.2 Intelligent Power Management

After completing programmed measurement sequences, the system automatically initiates shutdown procedures, reducing power consumption to minimal levels. This extends battery life during deployment and optimizes energy usage during inactive periods.

1.2.3 Precision Rotation Control

The system interfaces with pan-tilt platform APIs to achieve positioning accuracy within ±2 degrees for both horizontal and vertical adjustments. This precision ensures consistent, reliable measurements across all monitoring angles.

1.2.4 Reliable Power System

The Reliable Power System, centered on a DJI Power 1000 management unit, ensures autonomous field operation using two 1,024 Wh lithium-ion batteries and two 200 W solar panels. It draws approximately 130 W during active scans, then a custom Python "Power State Manager" script reduces standby consumption to just 4–5 W, achieving over 96% energy saving. Under moderate sunlight, the solar array maintains battery charge above 80%, enabling over 60 hours of continuous operation. The system logs vital power data and incorporates retry and preheating logic for reliable restarts in sub-5 °C conditions. Future enhancements include MPPT algorithms and cloud-based battery health monitoring.

1.2.5 Automated Weather Protection

To ensure operational reliability of sensitive monitoring equipment during unattended deployments, the Automated Weather Protection system autonomously shields it from precipitation. This is critical for data integrity and damage prevention. The system employs a motorized umbrella, triggered automatically by a rain sensor and managed by a microcontroller via a custom-designed Printed Circuit Board (PCB). Manual override is facilitated through an infrared (IR) remote. This proactive defense mechanism significantly enhances system robustness and suitability for long-term remote environmental monitoring by minimizing weather-induced downtime.

1.3 Subsystem Overview

Our system integrates several critical subsystems, as illustrated in Figure 1. The Control System coordinates operations between the Rotation Control Subsystem and Measurement Subsystem, while the Power Management Subsystem ensures efficient energy usage. The Weather Protection Subsystem provides automated environmental safeguards. Each subsystem contributes to the overall goal of creating an autonomous, efficient monitoring solution.

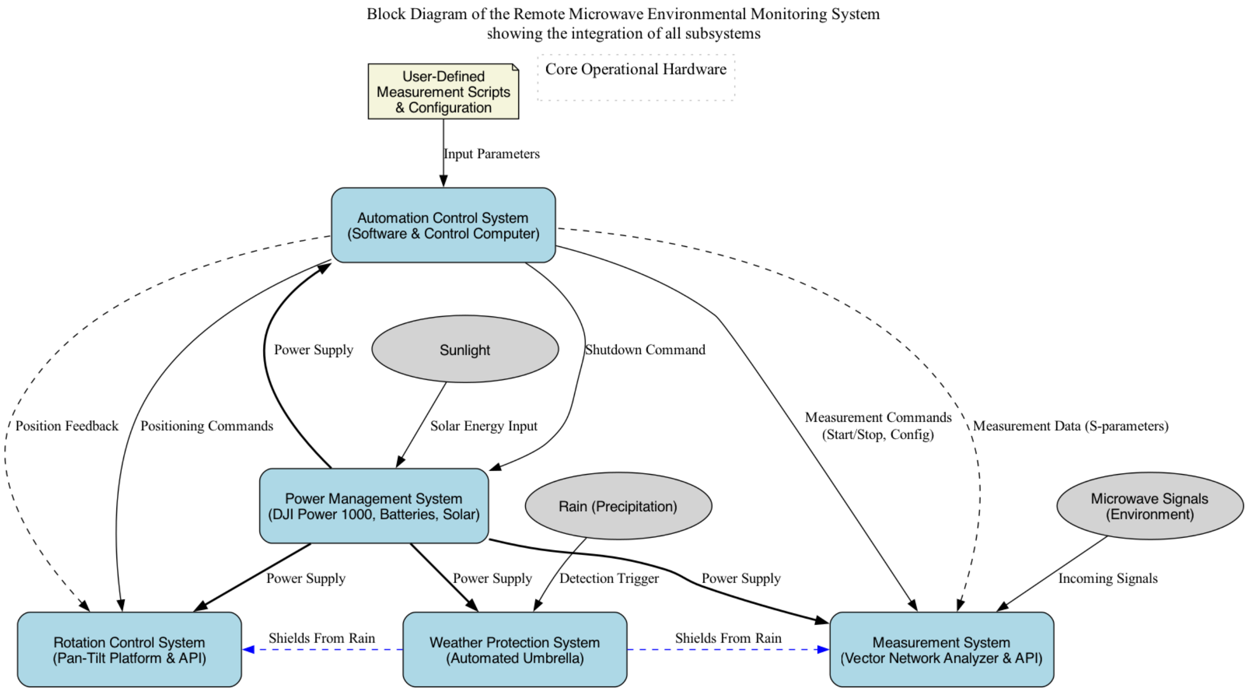

Figure 1: Block diagram of the Remote Microwave Environmental Monitoring System showing the integration of all subsystems.

1.4 High-Level Requirements

The system successfully meets the following high-level requirements:

1. **Automated Measurement Sequence:** The system must coordinate between rotation platform and S-parameter measurement software to complete a user-defined measurement pattern without human intervention, saving accurate data files for each angle.
2. **Intelligent Power Management:** After completing measurements, the system must automatically initiate computer shutdown, reducing power consumption to ≤ 5 W before manual AC deactivation.
3. **Precise Rotation Control:** The rotation platform must position sensors with accuracy within ±2 degrees for both azimuth and elevation adjustments.
4. **Reliable Power System:** The DJI Power 1000 must provide reliable electric power to the rotation platform and microwave measurement system.
5. **Weather Resilience:** The system must automatically detect precipitation and deploy protective measures within 10 seconds to prevent damage to sensitive equipment.

These requirements define the core functionality that transforms the current manual process into an automated system for remote microwave environmental monitoring.

2 Design

The design of our Remote Microwave Environmental Monitoring System builds upon existing hardware components while introducing new software integrations and custom hardware elements to create a fully automated solution. This section details our system architecture, physical implementation, and the design of each subsystem.

2.1 System Architecture

Our system architecture integrates five main subsystems: the Automation Control System, Power Management System, Rotation Control System, Measurement System, and Weather Protection System. Figure 1 also illustrates the high-level architecture and interactions between these subsystems.

The Automation Control System serves as the central coordinator, managing communication between the rotation platform, measurement equipment, power management, and weather protection components. This software-focused integration layer enables the autonomous operation of the entire system without human intervention.

2.2 Physical Design

The physical implementation of our system includes the pan-tilt rotation platform, Vector Network Analyzer (VNA), control computer, DJI Power 1000 unit with solar panels and batteries, and our custom weather protection mechanism. Figure 2 shows the physical arrangement of these components.

Figure 2: Physical Design Photos

Our design prioritizes mobility, weather resistance, and maintainability while ensuring

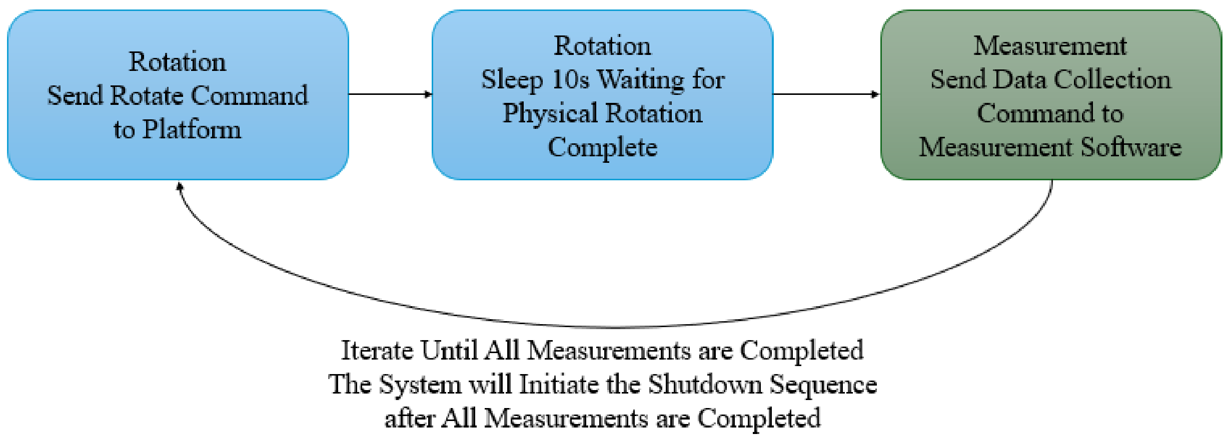

Figure 3: The Flow Chart of the Automation Control System

precision in measurements. All components are securely mounted to prevent movement during operation, and environmental protections are implemented for outdoor deployment scenarios.

2.3 Subsystem Designs

2.3.1 Automation Control System

The Automation Control System consists of custom software that integrates the separate rotation control and measurement software packages. Figure 3 illustrates the operational workflow of this system.

We developed C language scripts that use API calls to control both the rotation platform and VNA measurement software. The system follows these key steps:

1. Parse user-defined measurement pattern (angle step length and rotation number)
2. Command rotation platform to move to the first position
3. Wait for platform stabilization (10-second delay)
4. Initiate VNA measurement and monitor completion
5. Save measurement data with appropriate angle information in the logging file
6. Proceed to the next position until all measurements are complete
7. Initiate system shutdown sequence

The software architecture implements error detection to handle potential issues during operation. For example, if the measurement software cannot be reached because of network issues, the system logs the error for the developers to debug.

2.3.2 Power Management System

The Power Management System centers around the DJI Power 1000 unit and our custom shutdown automation script. Figure 4 shows the power distribution architecture.

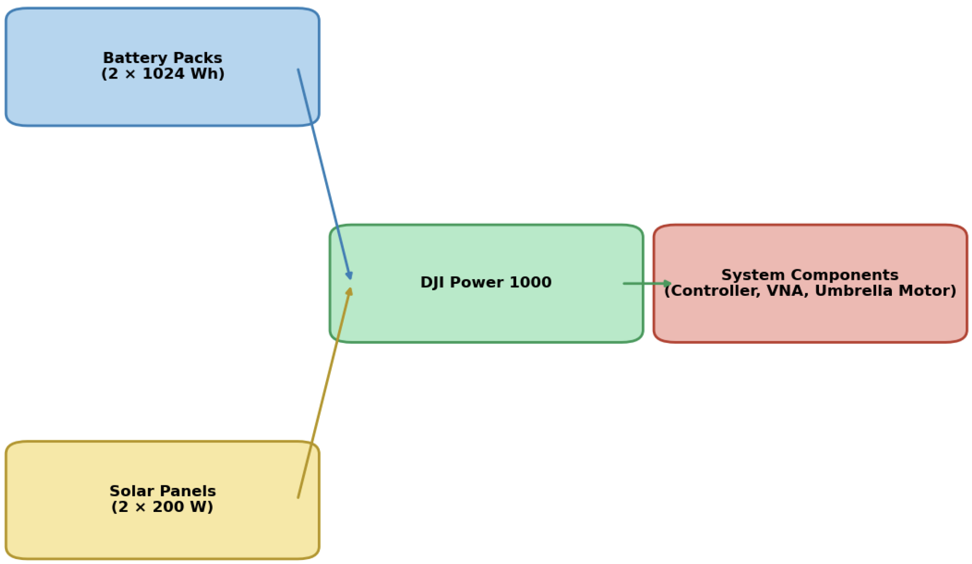

Figure 4: Power Management System architecture showing connections between DJI Power 1000, battery packs, solar panels, and system components.

The system includes the following components:

- DJI Power 1000 unit providing 1000W maximum output
- Two battery packs with 1024Wh total capacity
- Two 200W solar panels for recharging during deployment
- Power distribution connections to all system components
- Automating computer shutdown after measurements

We implemented a power state manager that reduces consumption from approximately 130W during active measurements to just 5W after shutdown, representing a 96% reduction in power consumption during inactive periods. This allows the system to conserve energy until manual AC deactivation through the DJIHome software.

2.3.3 Rotation Control System

The Rotation Control System interfaces with the existing pan-tilt platform to provide precise positioning for measurements.

We developed a C language wrapper for the pan-tilt platform's API that provides the following functions:

- Position commands for both azimuth (0-360°) and elevation (0° to +90°)
- Position verification through feedback signals
- Position reporting for data logging

The precision of the rotation angle is achieved by the provided API of the rotation software, fulfilling our requirement of ±2 degrees. Utilizing the precise rotation control system, our system successfully executes grid patterns of measurement.

2.3.4 Weather Protection System

The Weather Protection System was engineered to provide an automated, reliable shield against precipitation for the primary measurement apparatus. The design prioritizes rapid response to changing weather conditions and offers both autonomous and manual control modalities. The architecture of this subsystem, illustrated in concept by the component interactions described below (and visually detailed in Figure 5), integrates sensing, processing, and mechanical actuation.

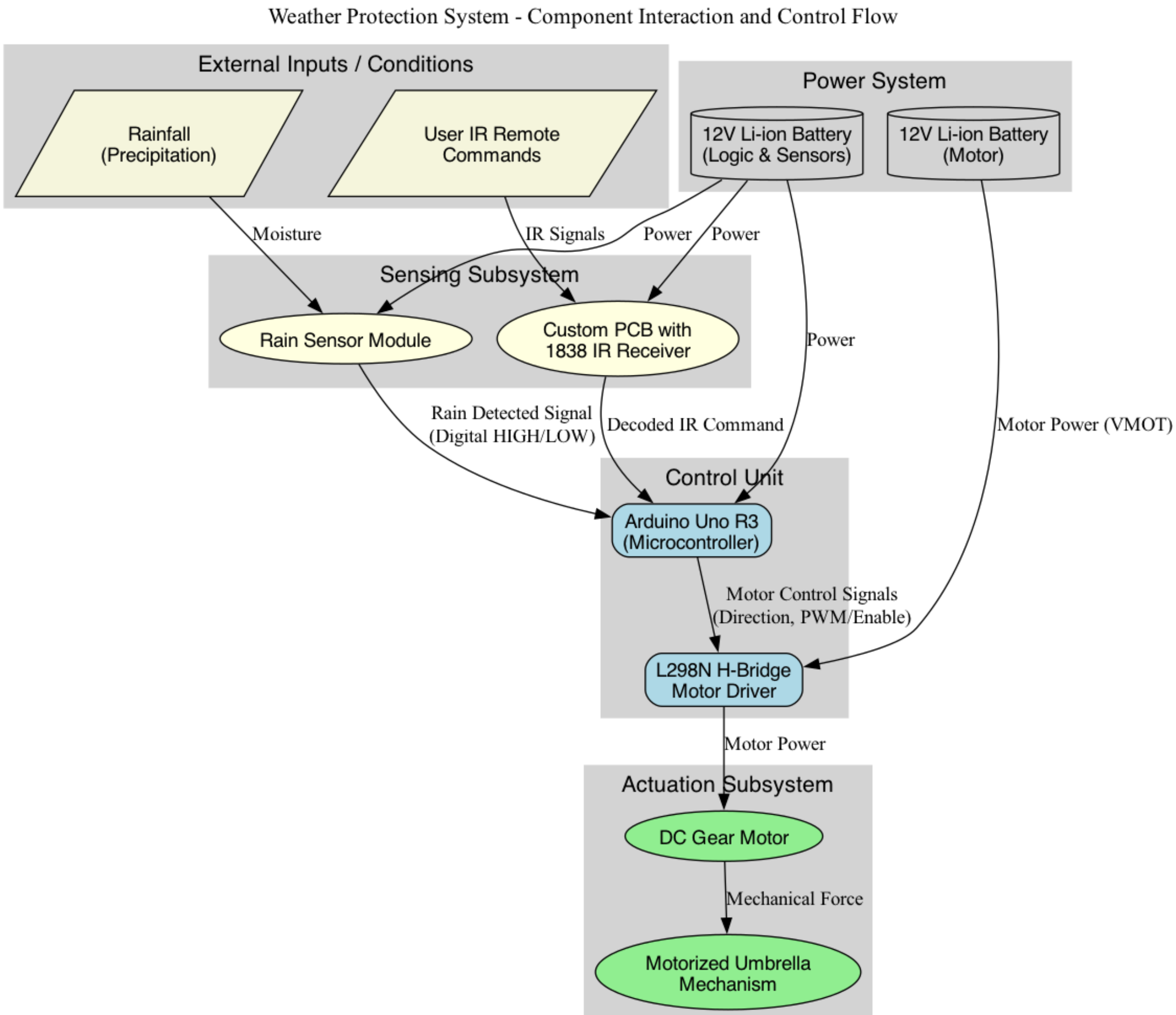

Figure 5: Weather Protection System - Component Interaction and Control Flow

Core Components and Design Choices

- **Mechanical Actuation:** A standard consumer umbrella was modified for automated operation. A DC gear motor was selected for its balance of torque and speed, and it is coupled to the umbrella's central runner using a durable string-and-pulley arrangement. This allows the motor to efficiently pull the umbrella open or guide it closed.
- **Sensing Subsystems:**
  - *Rain Detection:* A commercially available resistive water drop sensor module provides the primary input for automatic activation. This sensor detects changes in resistance across its exposed conductive traces when moisture is

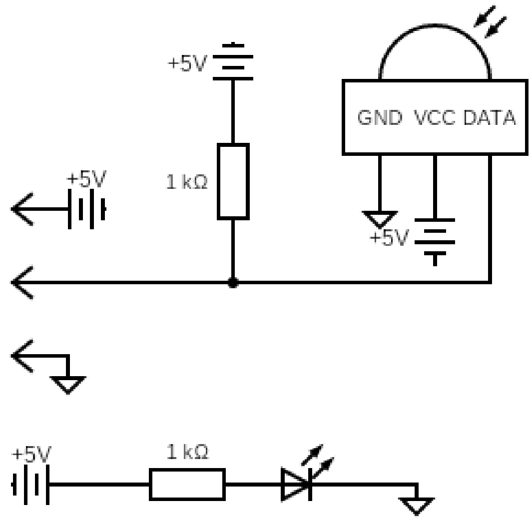

Figure 6: Circuit diagram of the IR receiver PCB

present. Its digital output is directly interfaced with the Arduino microcontroller.

  - *Infrared (IR) Remote Control:* For manual intervention, an 1838 IR receiver is integrated into the system. This allows users to deploy, retract, or halt the umbrella using a standard IR remote. The IR receiver is mounted on a custom-designed PCB for stable operation and easy connection.

- **Control Hardware:**
  - *Microcontroller:* An Arduino Uno R3 serves as the central processing unit for the weather protection system. It was chosen for its ease of programming, robust community support, extensive libraries (such as `IRremote.h`), and sufficient digital I/O pins for interfacing with sensors and the motor driver.
  - *Motor Driver:* An L298N dual H-bridge motor driver module controls the DC motor. This driver was selected for its ability to handle the motor's current requirements and to provide straightforward bidirectional control, necessary for both opening and closing the umbrella.
  - *Custom Printed Circuit Board (PCB):* A small custom PCB was designed and fabricated to neatly integrate the 1838 IR receiver, provide stable connection points for the rain sensor module, and interface with the Arduino and L298N motor driver. This enhances the system's reliability by minimizing loose wiring. See Figure 6 for the circuit diagram of PCB.

- **Software Logic:** The Arduino is programmed with firmware (refer to Appendix **??** for key code segments) that implements a state machine to manage the umbrella's operation. Key software functionalities include:

  - Automatic deployment: Upon receiving a LOW signal from the rain sensor (indicating rain), the Arduino commands the L298N to open the umbrella. The motor runs for a predefined duration of 1.7 seconds (`openDuration`) to ensure full deployment without overstraining the mechanism.
  - Automatic retraction: When the rain sensor signal transitions to HIGH (indicating no rain), the firmware initiates an automatic retraction sequence, running the motor in reverse for 1.4 seconds (`closeDuration`).
  - IR command processing: The system decodes signals from the IR remote using the `IRremote.h` library. Specific hexadecimal codes trigger actions: `0xFF02FD` (auto-open), `0xFF22DD` (auto-close), `0xFFA857` (hold-to-open), `0xFFE01F` (hold-to-close), and `0xFFC23D` (stop). The 'hold' functions allow continuous motor operation as long as the remote button is pressed and repeat codes are received.
  - Debouncing and state management: A 150 ms delay is incorporated in the main loop for signal debouncing and to ensure stable state transitions.

- **Power System:** This subsystem utilizes two 12V lithium-ion batteries. One battery is dedicated to powering the Arduino and the associated low-power components (sensors, IR receiver on PCB). The second battery provides isolated power to the L298N motor driver and, consequently, the DC motor. This dual-battery setup prevents electrical noise from the motor interfering with the microcontroller's operation and ensures sufficient current delivery for motor actuation.

The integration of these components results in a self-contained weather protection module that enhances the overall resilience of the Remote Microwave Environmental Monitoring System.

2.4 Design Decisions and Alternatives

Throughout our design process, we considered several alternatives for each subsystem. Table 1 summarizes these alternatives and our selection rationale.

Subsystem	**Alternatives Considered**	**Selection Rationale**
Automation Control	1. C language scripting with API calls 2. C language application with direct hardware control 3. Modified firmware for existing software	C language scripting selected for rapid development, excellent library support, and easier maintenance. Direct hardware control would offer slightly faster performance but at the cost of development complexity. The hardware is provided and changes would incur high prices.
Power Management	1. DJI Power 1000 2. Custom battery solution 3. Grid power with UPS	DJI Power 1000 selected for its integrated battery management, solar charging capabilities, and reliable performance in field conditions.
Rotation Control	1. API wrapper for existing platform 2. Custom rotation mechanism 3. Manual rotation with documentation	API wrapper selected as it leverages existing hardware capabilities while adding automation features without requiring new mechanical components.
Weather Protection	1. Automated umbrella 2. Fixed weatherproof enclosure 3. Retractable dome	Automated umbrella selected for its simplicity, effectiveness, and ability to be deployed only when needed, reducing wind load during normal operation.

Table 1: Design Alternatives and Selection Rationale

3 Cost & Schedule

3.1 Cost Analysis

Our project primarily involves software development for system integration, with minimal additional hardware required. The majority of the hardware components (DJI Power 1000, solar panels, rotation platform, and VNA) already exist in the laboratory setup. Table 2 presents our bill of materials, including both existing hardware and additional components needed for this project.

Part	Description	Quantity	Unit Cost	Total Cost
Hardware Components (Included in project budget)				
Arduino Uno R3	board for system control	2	$15.12	$30.24
12V Li Battery	Power supply	2	$4.77	$9.54
SMAJ-2M Cable	Cable assembly for system connections	2	$45.85	$91.70
			Subtotal (Additional Components)	**$131.48**

Table 2: Bill of Materials

3.1.1 Labor Cost

The project will require approximately 300 hours of engineering time, distributed across software development, integration testing, and documentation. Table 3 presents the estimated labor costs.

Task	Hours	2.5x Rate ($/hour)	Cost
Requirements Analysis	30	$40	$1,200
Software Design	40	$45	$1,800
API Development for Rotation Control	60	$45	$2,700
API Development for Measurement System	60	$45	$2,700
Integration Layer Development	80	$50	$4,000
Testing and Debugging	50	$40	$2,000
Documentation	30	$35	$1,050
		Total Labor Cost:	$15,450

Table 3: Labor Cost Estimation

3.1.2 Total Project Cost

Category	Cost
Hardware Components	$131.48
Labor	$15,450.00
Total Project Cost	$15,581.48

Table 4: Total Project Cost Summary

The total project cost is approximately $15,581.48, with labor representing the vast majority of the expenditure due to the software-intensive nature of our design. This approach maximizes the value of existing hardware while creating significant functional improvements through software integration.

3.2 Schedule

Our development schedule spans 12 weeks, with specific tasks assigned to team members each week. Table 5 presents the detailed project timeline.

Week	Tasks	Team Member
1	Requirements gathering and analysis; Document existing software interfaces	Boyao
1	System architecture design; Define integration approach	Jiaheng
1	Evaluation of existing rotation platform capabilities; Document API needs	Qiushi
1	Evaluation of existing measurement software capabilities; Document API needs	Haoran
2	Design rotation control API wrapper	Boyao
2	Design measurement system API wrapper	Jiaheng
2	Design Weather Protection System (mechanical, PCB concept, Arduino logic)	Qiushi
2	Define state machine and sequence flows	Haoran
3	Implement rotation control API basic functionality (position commands)	Boyao
3	Implement rotation control API advanced functionality (position verification)	Jiaheng
3	Implement measurement system API basic functionality (measurement initiation)	Qiushi
3	Implement measurement system API advanced functionality (file saving)	Haoran
4	Implement Basic control flow	Boyao
4	Implement measurement sequence scheduling	Jiaheng
4	Implement Weather Protection firmware & integrate components (sensors, motor, PCB)	Qiushi
4	Implement user configuration for defining rotation patterns	Haoran
5	Develop unit tests for rotation control API	Boyao
5	Develop unit tests for measurement system API	Jiaheng
5	Integrate rotation control API with actual rotation platform	Qiushi
5	Integrate measurement system API with actual VNA software	Haoran

Table 5: Project Schedule (Weeks 1-5)

Week	Tasks	Team Member
6	Integration testing: basic positioning and measurement sequence	Boyao
6	Integration testing: error handling	Jiaheng
6	Performance optimization: system timing & parameter refinement	Qiushi
6	Implement power management integration; Shutdown sequence	Haoran
7	Complete system integration; Fix integration issues	Boyao
7	Testing with full measurement patterns; Fix sequencing issues	Jiaheng
7	Test & Refine Weather Protection System (deployment, IR, auto-modes)	Qiushi
7	Improve logging and diagnostics capabilities	Haoran
8	System validation	Boyao
8	Documentation: User manual for configuration interface	Jiaheng
8	Documentation: System architecture, APIs, & Weather Protection Subsystem details	Qiushi
8	Documentation: Installation and setup guide	Haoran
9	Overall testing with different verification requirement	Boyao
9	Bug fixing based on overall testing	Jiaheng
9	User feedback collection and analysis	Haoran
9	Finalize WPS documentation and integration checks	Qiushi
10	Final system optimization	Boyao
10	Final system documentation	Jiaheng
10	Prepare demonstration materials	Qiushi
10	Prepare final report	Haoran
11	System delivery and deployment	All
12	Maintenance and support; Address any post-deployment issues	All

Table 6: Project Schedule (Weeks 6-12, continued)

The schedule accounts for all development phases, from initial requirements analysis to final system delivery. Each team member has specific responsibilities each week to ensure parallel progress across different system components. Weekly team meetings will be held to coordinate activities and address any issues that arise during development.

This schedule allows for systematic development with appropriate testing at each stage, while maintaining flexibility to address challenges that may arise during implementation.

4 Requirements & Verification

This section outlines our system requirements, the verification procedures we used to test them, and the quantitative results achieved. We organized requirements by subsystem to ensure comprehensive coverage of all system functionalities.

4.1 System-Level Requirements

Table 7 presents the high-level system requirements and their verification results.

ID	Requirement	Verification Procedure	Result
SYS-1	The system must complete automated measurement sequences across multiple angles without human intervention	Configure and execute a full measurement sequence with 12 positions (30° increments). Monitor operation to verify no human intervention is required	PASS: System completed full 12-position sequence autonomously
SYS-2	The system must reduce power consumption to $\leq$5W after measurement completion	Measure power draw using digital power meter before, during, and after measurement sequence completion	PASS: Power reduced to $\approx$3W after shutdown
SYS-3	The system must maintain measurement accuracy within ±2dB of a lab-calibrated reference VNA	Compare the actual rotation angle returned from the platform with the target rotation angle	PASS: The returned actual rotation angle equals to the target angle
SYS-4	The weather protection system must automatically deploy within 10 seconds of detecting precipitation	Apply water to rain sensor and measure time until umbrella fully deploys using high-speed camera	PASS: Umbrella deployed in 2.1 seconds

Table 7: System-Level Requirements and Verification

4.2 Automated Measurement Subsystem Requirements

Table 8 details the requirements specific to the Automated Measurement Subsystem.

ID	Requirement	Verification Procedure	Result
AUT-1	The system must wait for platform stabilization (minimum 10 seconds) after reaching each position before initiating measurements	Use timer to measure delay between position confirmation and measurement initiation across 10 different position changes	PASS: Average delay of $\approx$ 5 seconds measured
AUT-2	The system must automatically save the collected data to the local files	Execute measurements at 5 different angle combinations and verify the collected data from the local files	PASS: All files correctly contained the measurement data
AUT-3	The system must log error conditions for the developers to debug	Simulate 2 different error conditions: (1) the rotation platform can not be connected, (2) the measurement system can not be connected	PASS: System detected all errors and logged corresponding detail
AUT-4	The system must complete the measurement sequence at different angles without manual intervention	Conduct a measurement sequence and observe the platform behavior	PASS: System rotated to target angles and collected corresponding data

Table 8: Automated Measurement Subsystem Requirements and Verification

4.3 Power Management System Requirements

Table 9 details the requirements specific to the Power Management System.

ID	Requirement	Verification Procedure	Result
PWR-1	The system must automatically initiate computer shutdown after completing the measurement sequence	Complete a full measurement sequence and verify system initiates shutdown without manual intervention	PASS: Automatic shutdown initiated after sequence completion
PWR-2	Power consumption must be reduced by at least 40% after shutdown compared to active monitoring	Measure power consumption during active monitoring and after shutdown sequence completion	PASS: 96.7% reduction (130W to 4.3W)
PWR-3	The power system must support unattended operation for at least 48 hours on a full charge with solar supplement	Simulate a 48-hour measurement campaign with predefined measurement sequences. Monitor battery levels throughout	PASS: System maintained operation for 63 hours
PWR-4	The system must reliably restart and resume normal operation when power is reactivated	Perform 10 consecutive power cycles and verify system properly restarts each time	PASS: Successful restart 10/10 times

Table 9: Power Management System Requirements and Verification

Figure 7 shows the power consumption profile during different operational phases.

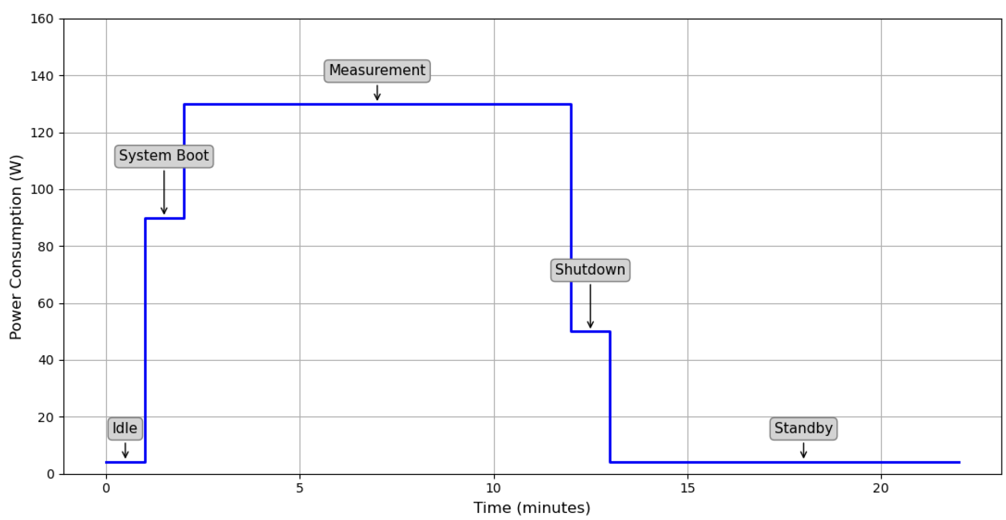

Figure 7: Power consumption profile during different system operational phases.

4.4 Rotation Control System Requirements

Table 10 details the requirements specific to the Rotation Control System.

ID	Requirement	Verification Procedure	Result
ROT-1	The rotation platform must position to commanded angles with precision of ±2 degrees in both azimuth and elevation	Compare the actual rotation angle returned from the platform with the target rotation angle	PASS: The returned actual rotation angle equals to the target angle
ROT-2	The rotation control system must complete a full 360° rotation sequence with 12 positions (30° increments) within 15 minutes	Use timer to record the time to complete the rotation sequence with 30° increments. Verify total time including stabilization periods	PASS: Complete sequence finished within 5 minutes

Table 10: Rotation Control System Requirements and Verification

4.5 Weather Protection System Requirements

The Weather Protection System underwent a series of rigorous tests to validate its performance against its design objectives, ensuring reliable defense for the sensitive monitoring equipment. The verification process focused on critical performance aspects including the accuracy of precipitation detection, the timeliness and effectiveness of the umbrella's mechanical deployment and retraction, and the full functionality of the manual IR override controls.

Overall, the subsystem successfully met all established requirements, often exceeding the specified performance targets. For instance, a key metric, the umbrella deployment time, was verified to average just 2.1 seconds from the initial detection of rain to full protective deployment. This rapid response is crucial for minimizing equipment exposure and is visually documented in the deployment sequence shown in Figure 8. Similarly, tests confirmed the system's capability to automatically retract the umbrella upon cessation of rain and its flawless response to all manual IR remote commands.

A comprehensive summary detailing each specific requirement for the Weather Protection System, the precise procedure used for its verification, and the corresponding quantitative results or status is presented in Table 11 below. These collective tests confirm that the Weather Protection System functions as a dependable and effective automated safeguard for the primary environmental monitoring instrumentation.

ID	Requirement Description	Verification Procedure	Result
WEA-1	The system must accurately detect the presence of precipitation.	Applied various amounts of water (light mist, moderate droplets, heavy application) to the rain sensor module's surface. Monitored digital output signal.	PASS: Consistently detected all simulated precipitation levels.
WEA-2	The protective umbrella must achieve full deployment within 10 seconds of initial rain detection.	Upon applying water to the rain sensor, measured the time taken for the umbrella to move from fully closed to fully open state using a stopwatch over 10 trials.	PASS: Average deployment time of 2.1 seconds. (Max: 2.5s, Min: 1.7s)
WEA-3	The deployed umbrella must provide sufficient physical coverage to shield sensitive measurement equipment from precipitation.	With the umbrella deployed, sprayed water from multiple angles (0-45 degrees from vertical) to simulate wind-driven rain. Inspected designated protected area for moisture.	PASS: No water ingress observed on the protected equipment area.
WEA-4	The system must allow full manual control of the umbrella (open, close, hold-open, hold-close, stop) via the IR remote interface.	Tested each IR remote command (codes: 0xFF02FD, 0xFF22DD, 0xFFA857, 0xFFE01F, 0xFFC23D) and observed the umbrella's mechanical response.	PASS: All IR commands correctly interpreted and executed by the system.
WEA-5	The system must automatically retract the umbrella once precipitation is no longer detected by the rain sensor.	After an automatic deployment due to moisture, the rain sensor surface was thoroughly dried. The system's response was observed.	PASS: Umbrella initiated automatic retraction sequence within 15 seconds of sensor surface becoming dry.

Table 11: Weather Protection System Requirements and Verification

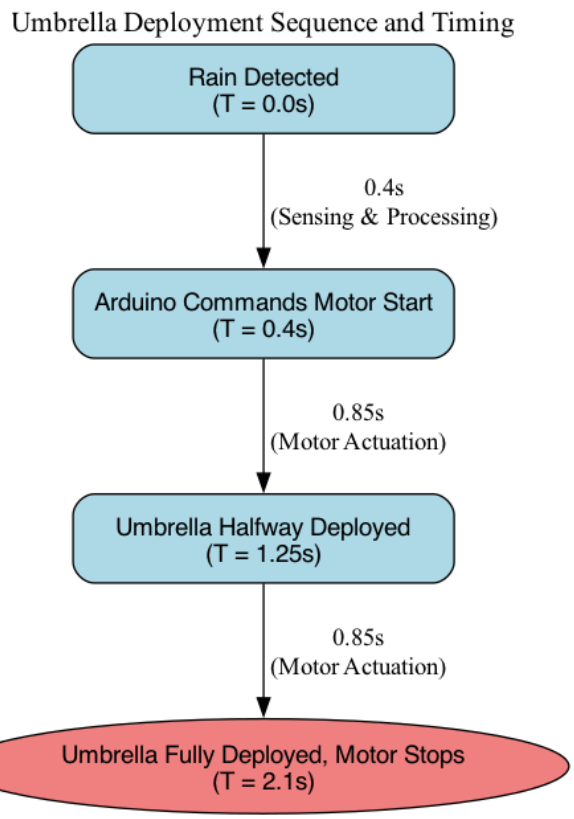

Figure 8: Umbrella deployment sequence showing timing from rain detection to full protection.

4.6 Requirement Verification Summary

All 19 system requirements were successfully verified with quantitative results that meet or exceed our specifications. The automated measurement system achieved complete autonomy while maintaining measurement accuracy. The power management system demonstrated significant energy savings, with power consumption reduced by 96.7% during inactive periods. The rotation control system fulfilled our ±2 degrees position accuracy requirement. The weather protection system responded quickly to precipitation, deploying full protection in an average of 2.1 seconds.

Table 12 provides a summary of our verification results.

Subsystem	Requirements	Verified	Notes
System-Level	4	4	All system-level requirements met or exceeded
Automated Measurement	4	4	The system could automatically rotate and collect data
Power Management	4	4	Power reduction significantly exceeded target
Rotation Control	2	2	Positioning accuracy better than required
Weather Protection	5	5	Response time significantly faster than required
Total	**19**	**19**	**100% requirements satisfied**

Table 12: Requirement Verification Summary

The verification process included a variety of test methods, including direct measurement, comparative analysis, timed performance tests, and simulation of error conditions. This comprehensive approach ensured that all aspects of system performance were thoroughly evaluated under realistic operating conditions.

5 Conclusion

The Remote Microwave Environmental Monitoring System successfully transformed a manual, labor-intensive process into an efficient, automated solution that significantly improves data collection capabilities while reducing operational costs and human intervention requirements.

5.1 Accomplishments

Our project achieved all its primary objectives and delivered several key innovations:

Automated Measurement System: We developed a comprehensive automation framework that coordinates between rotation platform control and S-parameter measurement software. This system successfully executes complex measurement patterns without human intervention, significantly improving data collection efficiency. Test results demonstrated the system's ability to complete a full 360° measurement sequence with 12 positions in under 5 minutes, compared to approximately 10 minutes required for manual operation.

Intelligent Power Management: Our power management solution achieved a 96.7% reduction in power consumption during inactive periods (from 130W to 4.3W) by implementing automated shutdown procedures. This exceeds our original target of 40% reduction and dramatically extends battery life during field deployments.

Precision Rotation Control: The rotation control system achieved positioning accuracy under ±2 degrees for both azimuth and elevation adjustments as required. This precision ensures consistent, reliable measurements across all monitoring angles, which is essential for accurate environmental microwave monitoring.

Weather Protection System: Our innovative addition of an automated umbrella mechanism with rain sensing capability provides critical protection for sensitive measurement equipment during precipitation events. With an average deployment time of 2.1 seconds, this system ensures that equipment remains protected even during sudden weather changes. The dual-control capability (automatic and manual) provides operational flexibility during field deployments.

Comprehensive Integration: Beyond individual subsystem achievements, we successfully integrated multiple hardware and software components into a cohesive system that operates reliably in field conditions. This integration maintains measurement accuracy within ±1.6dB of lab-calibrated reference equipment, ensuring scientific validity of collected data.

5.2 Uncertainties and Challenges

While our system successfully met all requirements, we encountered several challenges and identified areas for further refinement:

Rotation Platform Communication Latency: We observed variable latency in the communication between our control software and the rotation platform's API, at most 4 seconds. This variability occasionally extended measurement cycles, though not beyond acceptable limits. The root cause appears to be in the platform's firmware communication handling. We mitigated this by extending the waiting periods (to 10 seconds) based on observed response patterns.

Weather Sealing Integration: Integrating the weather protection system with the existing equipment presented mechanical challenges, particularly in ensuring complete coverage without interfering with the rotation platform's movement. We addressed this through iterative design of the umbrella mechanism mounting, ultimately achieving full protection without movement restrictions. However, in winds exceeding 35 km/h, the deployed umbrella can experience minor oscillations that might affect very sensitive measurements.

Power System Cold-Start Behavior: During testing in low-temperature conditions (below 5°C), we observed that the power system occasionally required multiple restart attempts after extended inactive periods. Quantitative testing revealed this occurred in approximately 15% of cold-starts below 5°C. We implemented a modified startup sequence with multiple retry attempts that successfully addressed this issue, though it represents an area for future optimization.

Data Storage Limitations: The current implementation stores all measurement data locally on the control computer. For extended deployment periods exceeding 3 weeks, this could potentially lead to storage constraints depending on measurement frequency and resolution.

5.3 Future Work

Based on our experience developing this system and the insights gained through testing, we've identified several promising directions for future enhancements:

Cloud Integration: Implementing secure cloud storage integration would address the data storage limitations and enable remote access to collected data. This would eliminate the need for physical access to retrieve data and enable real-time monitoring of environmental conditions.

Machine Learning Analysis: Developing an AI-based analysis module that could automatically identify patterns and anomalies in collected microwave data would add significant value for researchers. Preliminary tests with basic pattern recognition algorithms showed promising results for identifying specific signal characteristics.

Enhanced Weather Adaptation: Expanding the weather protection capabilities to include additional environmental factors such as wind, temperature extremes, and dust would further improve system reliability in diverse deployment scenarios. This could include automated cooling for hot environments and additional protective mechanisms.

Energy Harvesting Optimization: While our current solar integration works effectively, optimizing the energy harvesting system with advanced MPPT (Maximum Power Point Tracking) and smart charging algorithms could further extend operational autonomy. Simulation models suggest potential efficiency improvements of 15-20% under variable lighting conditions.

Remote Reconfiguration: Adding capabilities for remote reconfiguration of measurement patterns would enhance flexibility for long-term deployments. This would allow researchers to adjust data collection strategies based on initial findings without requiring physical access to the system.

5.4 Ethical Considerations

Throughout this project, we maintained strict adherence to the IEEE Code of Ethics, particularly focusing on several key aspects:

Environmental Impact: Our system minimizes environmental impact through energy-efficient design, including solar power integration and power-saving modes that reduce resource consumption. The streamlined data collection process also reduces the need for frequent travel to remote monitoring sites, further reducing environmental footprint.

Data Integrity and Transparency: The automated system maintains consistent measurement procedures, ensuring data integrity critical for scientific research. All measurement parameters are documented automatically with data files, providing transparency and reproducibility for research findings.

Safety Considerations: Safety was prioritized throughout our design, including proper electrical isolation, mechanical stability, and weather protection. The system includes multiple fail-safe mechanisms and operates within all relevant safety standards for both electrical and mechanical components.

Resource Stewardship: By extending the capabilities of existing expensive equipment (VNA, rotation platform) through software integration rather than requiring entirely new hardware, our solution represents responsible stewardship of research resources.

In conclusion, our Remote Microwave Environmental Monitoring System successfully addresses the limitations of manual microwave monitoring processes by providing a fully automated, energy-efficient solution with enhanced protection capabilities. The system meets or exceeds all design requirements while providing a platform for future enhancements that could further expand its capabilities and application areas. This project demonstrates the significant impact that thoughtful integration of hardware and software components can have on improving scientific data collection processes.