ECE 445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

A Remote Microwave Environmental Monitoring System: Automation and Power Management

Team #24

BOYAO WANG
(boyaow2@illinois.edu)
JIAHENG WEN
(jwen14@illinois.edu)
QIUSHI LIU
(qiushi3@illinois.edu)
HAORAN JIN
(haoranj4@illinois.edu)

TA: Zhijiao Cao

April 14, 2025

Contents

1 Introduction

1.1 Problem

In the field of remote microwave environmental monitoring, data collection at various angles is essential for comprehensive signal analysis. Currently, this process involves two separate software systems that require constant manual intervention: one controlling the rotation platform (pan-tilt mechanism) and another managing the Vector Network Analyzer (VNA) for S-parameter measurements. The existing workflow requires an operator to:

1. Manually set the rotation angle in the platform control software
2. Switch to the S-parameter measurement software
3. Initiate measurements and wait for completion
4. Save the collected data with appropriate angle information
5. Return to the rotation control software to set a new angle
6. Repeat this process for each measurement angle

This manual process is time-consuming, labor-intensive, and prone to human error. Furthermore, the current power management approach requires manual activation and deactivation of AC power through the DJIHome software, which is inefficient and requires human presence even after measurements are complete.

1.2 Solution Overview

Our solution is to develop an integrated automation system that coordinates between the rotation platform control software and S-parameter measurement software, creating a seamless measurement workflow without human intervention. The system will:

1. Allow users to define measurement patterns (e.g., angles from 0° to 360° in 10° increments)
2. Automatically position the rotation platform at each specified angle
3. Wait for platform stabilization before initiating measurements
4. Automatically save collected data with filenames indicating the measurement angle
5. Proceed to the next angle until the entire measurement pattern is complete
6. Initiate computer shutdown after measurements complete to reduce power consumption before manual AC cutoff

This automation eliminates the need for continuous human monitoring and intervention, significantly improving efficiency and reducing the potential for human error in the data collection process.

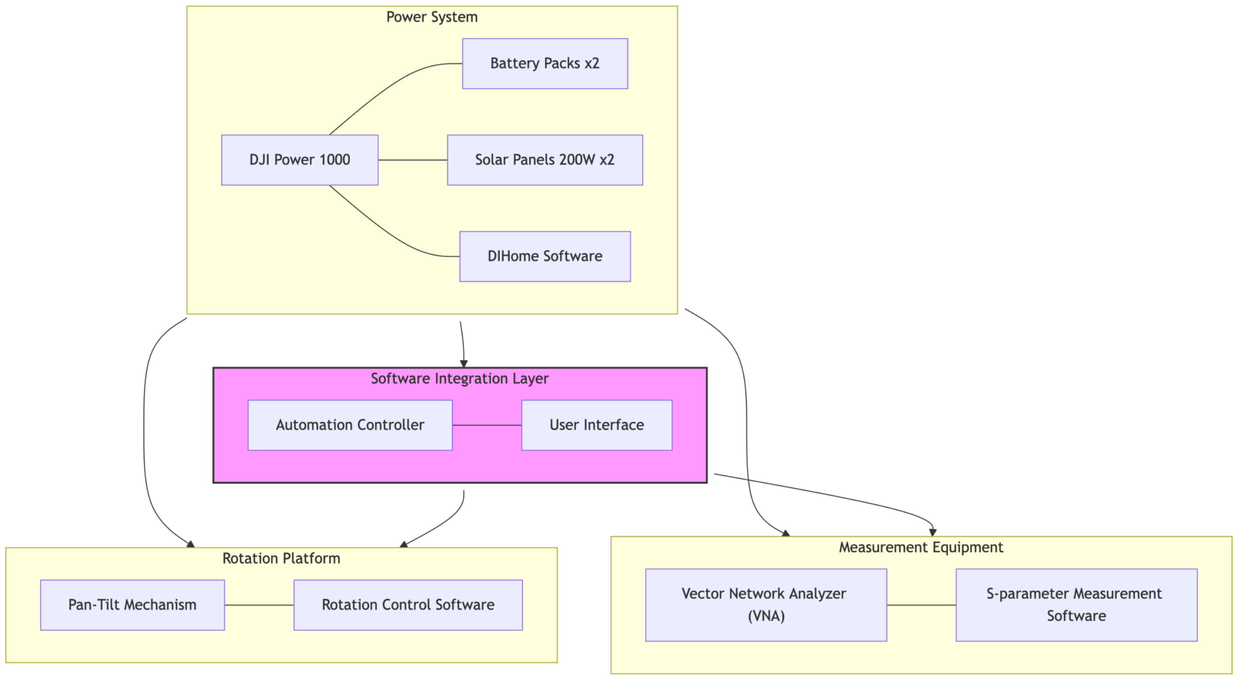

Figure 1: Overview of the automated microwave environmental monitoring system showing the integration between rotation platform, measurement hardware, and software components.

1.3 Existing Hardware

Our solution builds upon existing hardware components:

1. **Power System**: DJI Power 1000 unit supplemented with two battery packs and two 200W solar panels, controlled through DJIHome software
2. **Rotation Platform**: Pan-tilt mechanism capable of adjusting both azimuth (horizontal) and elevation (vertical) angles
3. **Measurement Equipment**: Vector Network Analyzer (VNA) for S-parameter measurements
4. **Control Computer**: Running both rotation control software and S-parameter measurement software

The hardware consumes approximately 130W during normal operation, with a small additional power required during active measurements. After the computer shutdown, the idle system draws only about 5W before the AC output is manually deactivated through DJIHome.

1.4 High-Level Requirements

To successfully address the identified problems, our system must meet 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 any human intervention. Success criterion: Complete measurement pattern execution with correct data files saved for each angle.

2. **Intelligent Power Management**: After completing all measurements, the system must automatically initiate computer shutdown, reducing power consumption to $\leq$5W to minimize energy use before manual AC deactivation. Success criterion: Verified power reduction to $\leq$5W after measurement completion.

3. **Precise Rotation Control**: The rotation platform must position the sensor with sufficient precision to ensure measurement accuracy across all specified angles. Success criterion: Positioning accuracy within ±X degrees of the commanded angle for both azimuth and elevation adjustments.

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

2 Design

2.1 Block Diagram

The system design integrates existing hardware components with new software interfaces to create an automated measurement system, which could satisfy the high-level requirements. Figure 2 shows the high-level block diagram of our design.

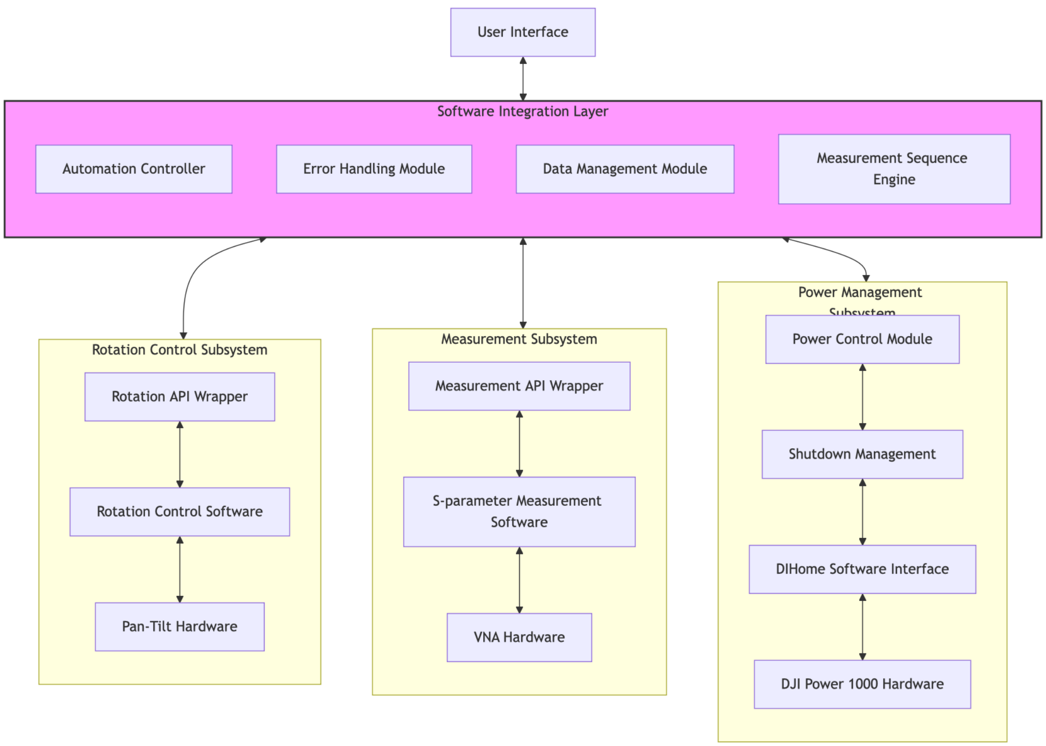

Figure 2: System block diagram showing major subsystems and their interactions. The Software Integration Layer serves as the core of our design, connecting the Rotation Control Subsystem with the Measurement Subsystem.

2.2 Physical Design

The physical components of our system are largely existing hardware, with our design focusing on software integration and control. Figure 3 illustrates the physical arrangement of the major components.

2.3 Subsystem Overview

Our design consists of four main subsystems:

1. Power Management Subsystem
2. Rotation Control Subsystem

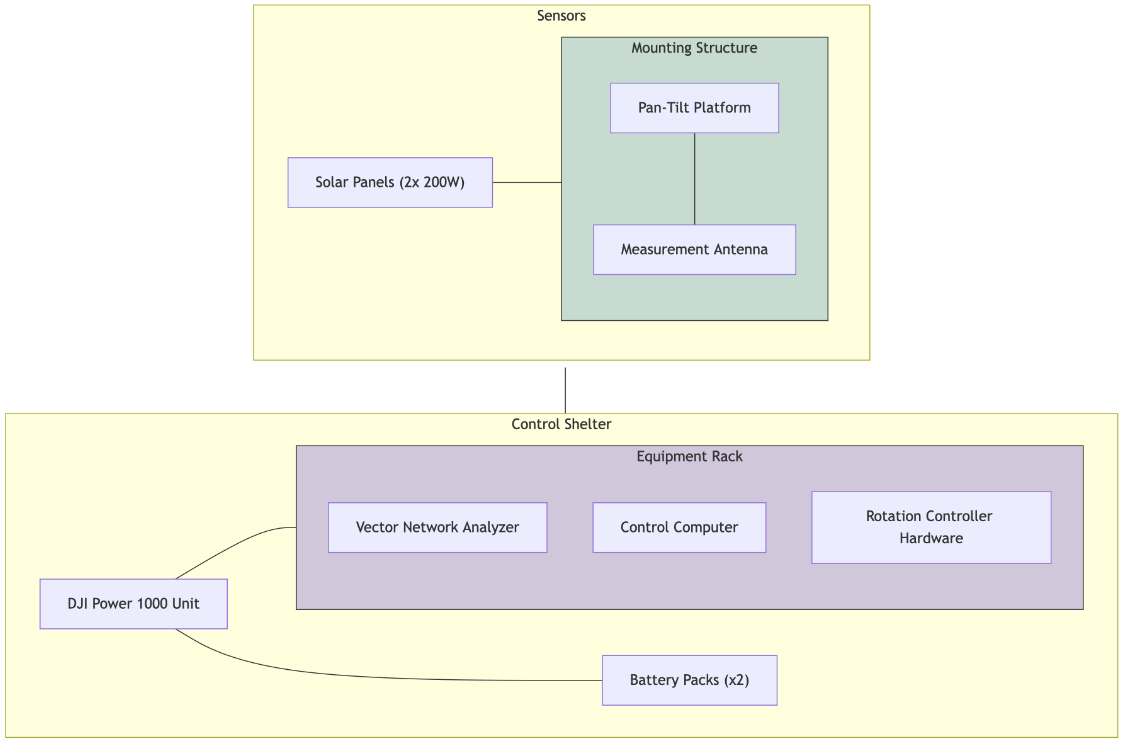

Figure 3: Physical arrangement showing the rotation platform with pan-tilt capability, VNA equipment, and control computer setup.

3. Measurement Subsystem
4. Software Integration Layer

The Software Integration Layer represents our primary design contribution, facilitating communication between existing software components to enable automation.

2.4 Subsystem Design

2.4.1 Power Management Subsystem

Description The Power Management Subsystem leverages the existing DJI Power 1000 unit with two battery packs and two 200W solar panels. Our design adds automatic shutdown capability to reduce power consumption after measurements are complete, preparing the system for manual AC power deactivation through DJIHome.

Interface

- **With DJIHome**: Monitors AC output status (on/off)
- **With Control Computer**: Sends shutdown command when measurements complete

- **With other subsystems**: Supplies power to all hardware components

Requirements and Verification The requirements and verifications table could be found at 1.

Requirement	Description	Verification
PWR-1	The system must automatically initiate computer shutdown after completing the measurement sequence, reducing power consumption to $\leq 5W$ before manual DJIHome AC deactivation.	Connect power meter to system output. Complete a full measurement sequence and verify system initiates shutdown. Measure power consumption after shutdown and confirm it is $\leq 5W$.
PWR-2	The power management system must support unattended operation for at least 48 hours on a full charge with solar supplement under typical conditions.	Simulate a 48-hour measurement campaign with predefined measurement sequences. Monitor battery levels throughout the test period to verify the system maintains sufficient power.
PWR-3	The system must reliably restart and resume normal operation when AC power is reactivated through DJIHome after a shutdown period.	Perform 10 consecutive power cycles via DJIHome software. Verify system boots properly and is ready for measurement operations each time.

Table 1: Power Management Subsystem Requirements and Verification

2.4.2 Rotation Control Subsystem

Description The Rotation Control Subsystem utilizes the existing pan-tilt platform capable of adjusting both azimuth (horizontal) and elevation (vertical) angles. Our design focuses on creating an API wrapper that allows our Software Integration Layer to command the platform to specific positions and receive confirmation when positions are reached. A detailed flow chart could be found at 5.

Interface

- **With Software Integration Layer**: Receives positioning commands and returns status updates
- **With Power Management**: Receives power from the system

Requirements and Verification The requirements and verifications table could be found at 2.

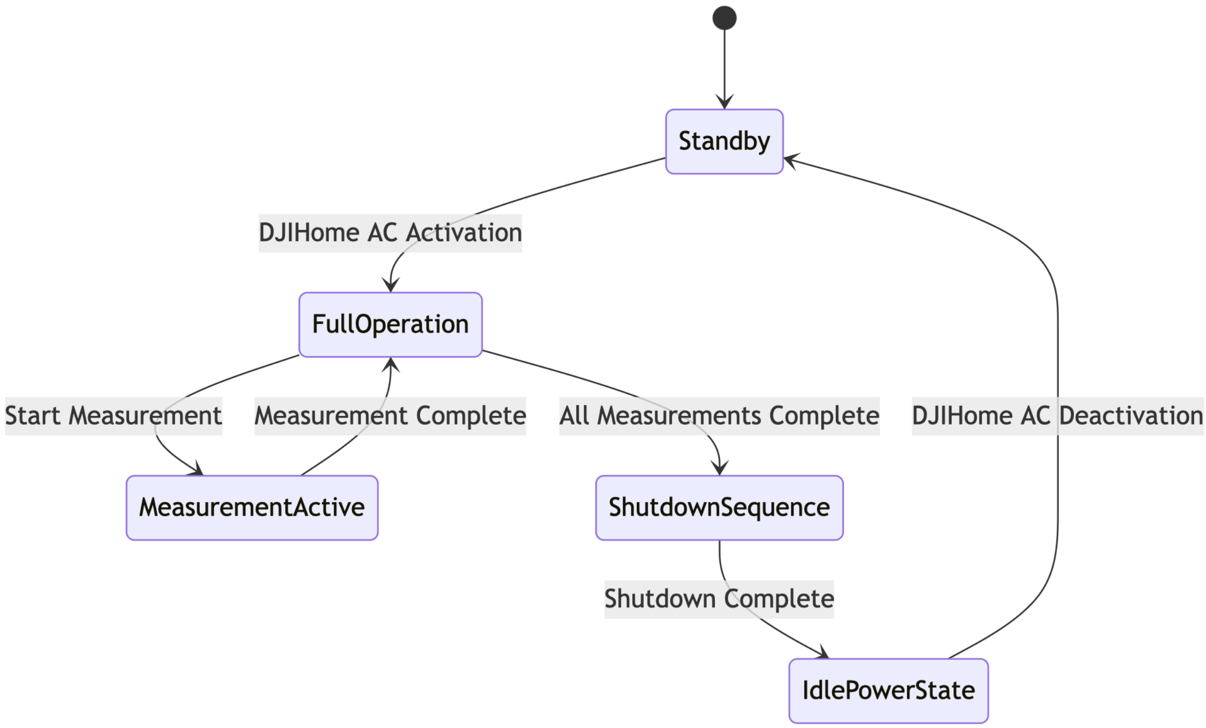

Figure 4: Power Management State Diagram showing transitions between operating states and power consumption at each state.

2.4.3 Measurement Subsystem

Description The Measurement Subsystem interfaces with the existing Vector Network Analyzer (VNA) and its S-parameter measurement software. Our design creates an API wrapper that allows our Software Integration Layer to initiate measurements with specific parameters, monitor measurement progress, and automatically save results with appropriate filenames. A detailed flow chart could be found at 6.

Interface

- **With Software Integration Layer**: Receives measurement commands and returns data status
- **With VNA Hardware**: Controls measurement hardware and receives raw data
- **With Power Management**: Receives power from the system

Requirements and Verification The requirements and verifications table could be found at 3.

Requirement	Description	Verification
ROT-1	The rotation control API must position the platform to commanded angles with precision of ±2 degrees in both azimuth and elevation.	Command the platform to 10 different positions throughout its range of motion. Use calibrated angle measurement tool to verify actual position is within ±2 degrees of commanded position for all test points.
ROT-2	The rotation control API must provide position confirmation to the Software Integration Layer within 5 seconds of reaching the commanded position.	Command the platform to 10 different positions. Use timer to measure delay between physical positioning completion and software confirmation signal. Verify all delays are under 5 seconds.
ROT-3	The rotation control API must support predefined measurement patterns including linear sweeps (e.g., 0° to 360° in 10° increments) and user-defined angle sets.	Program three different measurement patterns: (1) linear sweep, (2) nonlinear increment sequence, (3) randomized angle set. Verify platform correctly executes all patterns without error.

Table 2: Rotation Control Subsystem Requirements and Verification

2.4.4 Software Integration Layer

Description The Software Integration Layer is the core of our design, orchestrating the interaction between the Rotation Control and Measurement subsystems to create a fully automated workflow. This layer implements the measurement sequence logic, handles error conditions, and manages the overall system state. A detailed diagram could be found at 7 and 8.

Interface

- **With Rotation Control**: Sends positioning commands and processes position confirmations
- **With Measurement System**: Initiates measurements and monitors data collection status
- **With Power Management**: Triggers shutdown sequence upon completion
- **With User**: Provides configuration interface for defining measurement patterns

Requirement	Description	Verification
MEAS-1	The measurement API must support loading of calibration files and configuration of measurement parameters (frequency range, sampling points, etc.) through programmable interface.	Create test script that loads three different calibration files and sets five different parameter configurations. Verify all settings are correctly applied to the measurement software.
MEAS-2	The measurement API must automatically save collected data with filenames that include precise angle information (e.g., "az120_el45_data.s2p" for azimuth 120°, elevation 45°).	Execute measurements at 5 different angle combinations. Verify saved files include correct angle information in the filename and contain valid measurement data.
MEAS-3	The measurement API must provide measurement status updates to the Software Integration Layer, including percent complete and error conditions.	Initiate measurements with different durations. Verify status updates are provided at regular intervals and accurately reflect measurement progress.

Table 3: Measurement Subsystem Requirements and Verification

Requirements and Verification The requirements and verifications table could be found at 4.

2.5 Tolerance Analysis

For our tolerance analysis, we focus on the impact of rotation positioning accuracy on measurement reliability. The positioning accuracy of the rotation platform directly affects the validity of angle-specific measurements, which is critical for creating accurate environmental models.

2.5.1 Mathematical Model

The relationship between positioning error and measurement quality can be modeled as follows:

$$E_{measurement} = |\theta_{error}| \tag{1}$$

Where:

- $E^i_{measurement}$ is the measurement error of the i_{th} rotation

Requirement	Description	Verification
INT-1	The integration layer must coordinate a complete measurement sequence following a user-defined pattern without any human intervention.	Configure a measurement pattern with 10 different angle positions. Initiate the sequence and verify the system completes all measurements, saving properly named data files for each position without any manual intervention.
INT-2	The integration layer must wait for platform stabilization (minimum 3 seconds) after reaching each position before initiating measurements.	Use timer to measure delay between position confirmation and measurement initiation for 10 different position changes. Verify all delays meet or exceed 3 seconds.
INT-3	The integration layer must handle error conditions including positioning failures and measurement failures with appropriate recovery actions or graceful termination.	Simulate 5 different error conditions: (1) position not reached, (2) position timeout, (3) measurement error, (4) file save error, (5) communication loss. Verify system responds appropriately to each condition.
INT-4	The integration layer must provide a user-friendly configuration interface for defining measurement patterns, parameter settings, and file naming conventions.	Have three different operators configure the system for three different measurement scenarios. Verify all operators can successfully configure the system within 10 minutes with minimal assistance.

Table 4: Software Integration Layer Requirements and Verification

- θ^i_{error} is the angular positioning error for the i_{th} rotation, measured by the angle between the intended measuring angle α^i and the actual measuring angle α^i_0.

2.5.2 Analysis

For any given maximal measurement error $E^{max}_{measurement}$ and the known angular velocity ω of the pan-tilt platform, which we assume is constant, we could meet the requirement by setting a time boundary θ^i_t of the i_{th} rotation process, so we have:

$$E^i_{measurement} = |\theta^i_{error}| \tag{2}$$
$$= |\alpha^i - \alpha^i_0| \tag{3}$$
$$= |\omega * t + \alpha^{i-1} - \alpha^i_0| \tag{4}$$

To satisfy each rotation process has an error smaller than the given requirement $E^{max}_{measurement}$, we need

$$\forall i \in \{0, 1, 2, \dots\}, E^i_{measurement} \leq E^{max}_{measurement} \tag{5}$$

that is

$$\forall i \in \{0, 1, 2, \dots\}, \quad -E^{max}_{measurement} \leq |\omega * t + \alpha^{i-1} - \alpha^i_0| \leq E^{max}_{measurement} \tag{6}$$
$$\Rightarrow t \in [\frac{-E^{max}_{measurement} + \alpha^i_0 - \alpha^{i-1}}{\omega}, \frac{E^{max}_{measurement} + \alpha^i_0 - \alpha^{i-1}}{\omega}] \tag{7}$$

According to 7, we could meet the measurement error constraint by adjusting the rotation time with a specific time limit by controlling the signal sent time from the software integration layer, where $E^{max}_{measurement}$ and α^{i-1} is provided for i_{th} rotation, α^i_0 is the user input configuration.

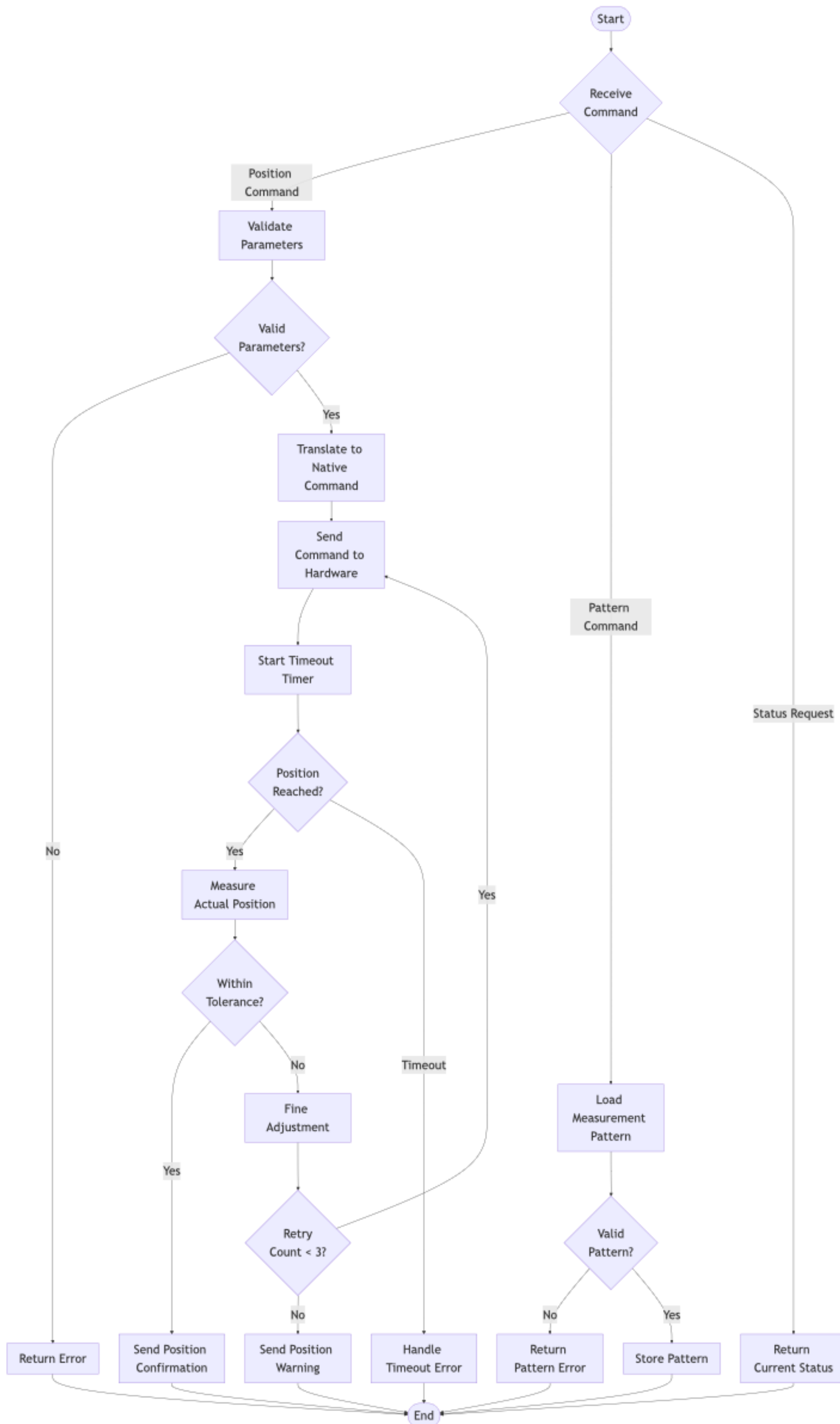

Figure 5: Rotation Control API Flowchart showing command processing and position feedback mechanisms.

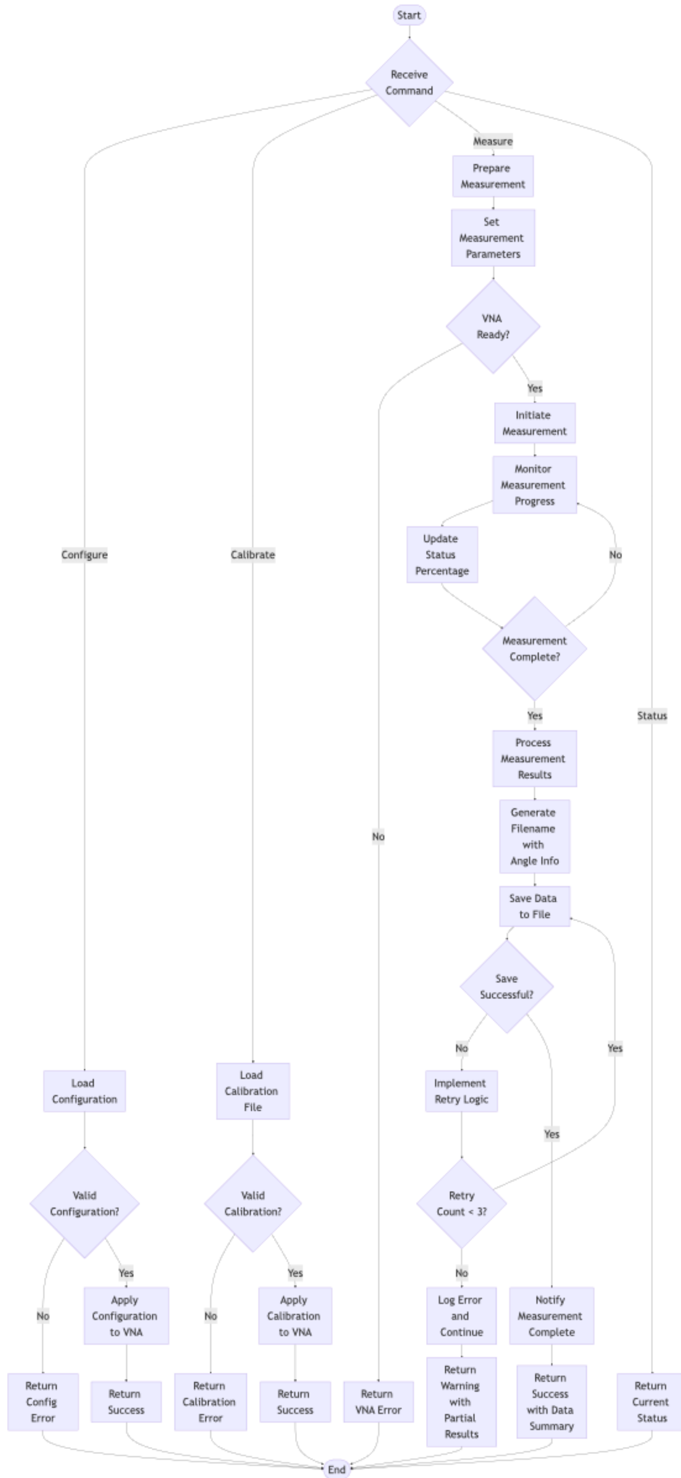

Figure 6: Measurement API Flowchart showing measurement execution and data handling processes.

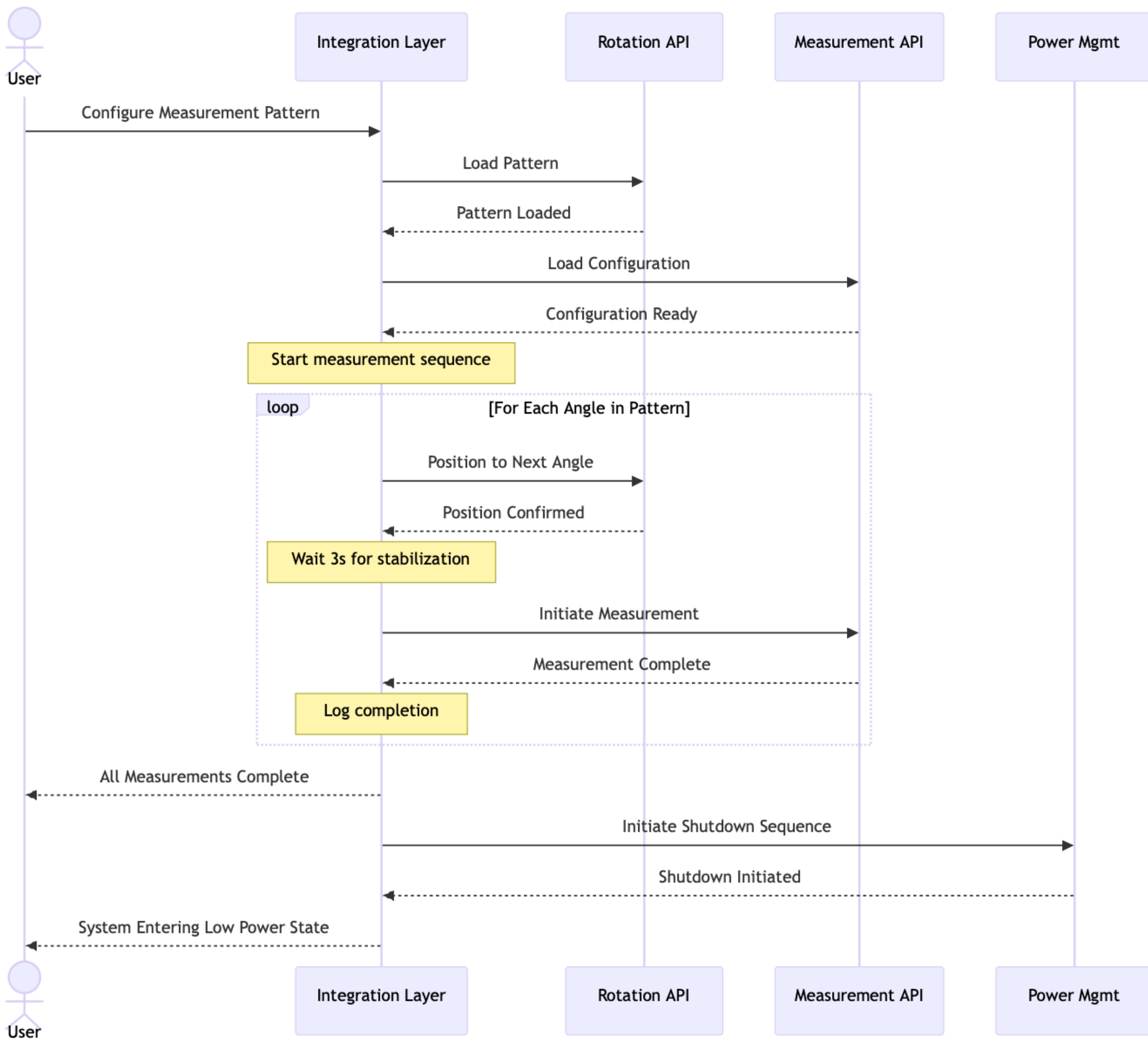

Figure 7: Integration Layer Sequence Diagram showing the coordination between subsystems during a measurement sequence.

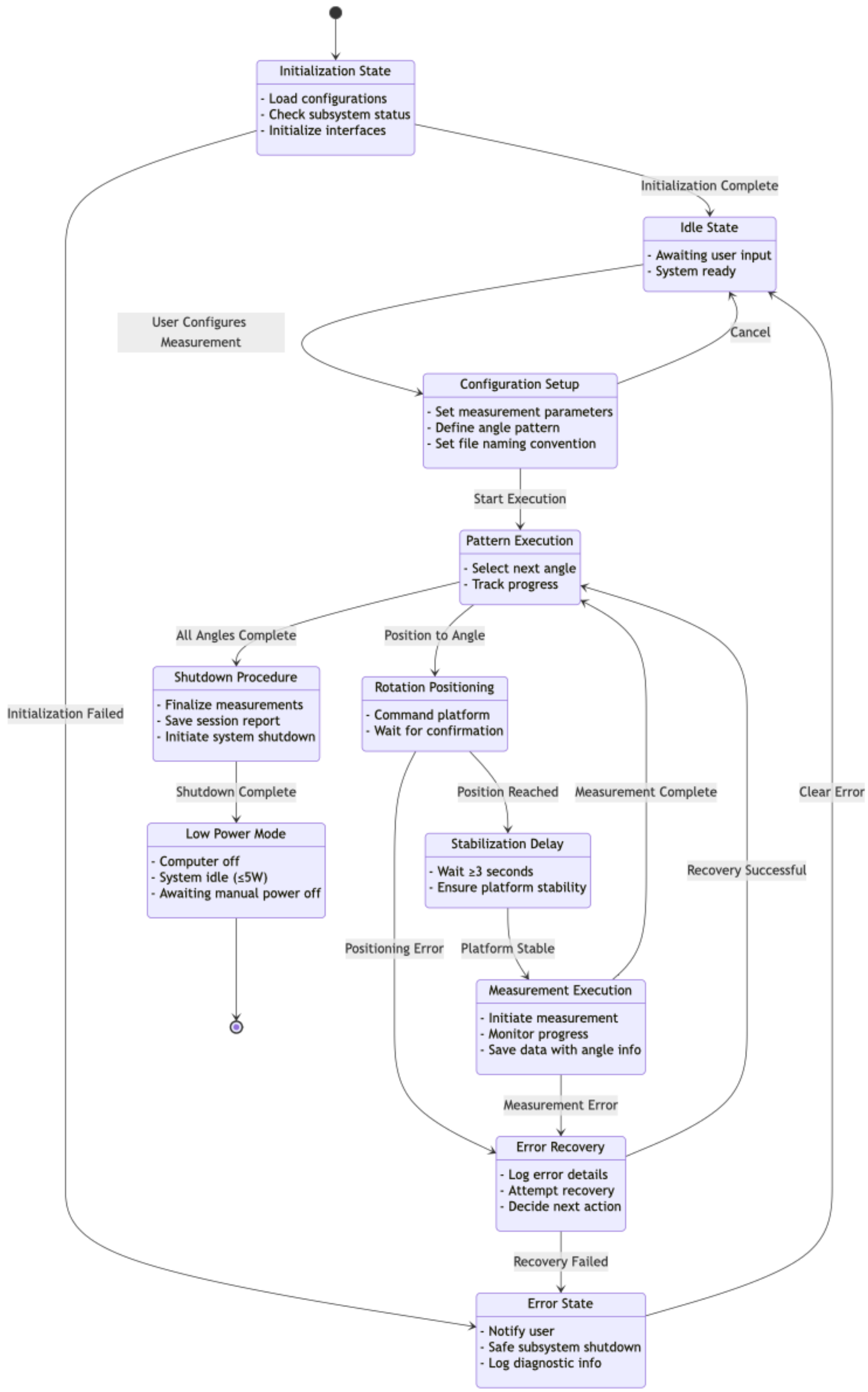

Figure 8: Integration Layer State Machine showing the states and transitions during automated measurement operation.

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 5 presents our bill of materials, including both existing hardware and additional components needed for this project.

3.1.1 Labor Cost

The project will require approximately 350 hours of engineering time, distributed across software development, integration testing, and documentation. Table 6 presents the estimated labor costs.

3.1.2 Total Project Cost

The total project cost is approximately $15,605.00, 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 8 presents the detailed project timeline. Figure 9 gives a clearer roadmap.

Table 8: Project Schedule

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; Create software interface specifications	Boyao

Week	Tasks	Team Member
2	Design measurement system API wrapper; Create software interface specifications	Jiaheng
2	Design integration layer architecture; Define state machine and sequence flows	Qiushi
2	Define error handling strategies; Create error recovery specifications	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 integration layer state machine; Basic control flow	Boyao
4	Implement measurement sequence scheduling; Pattern definition	Jiaheng
4	Implement error detection and handling in API wrappers	Qiushi
4	Implement user configuration interface for defining measurement 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
6	Integration testing: basic positioning and measurement sequence	Boyao
6	Integration testing: error handling and recovery	Jiaheng
6	Performance optimization: timing and resource usage	Qiushi
6	Implement power management integration; Shutdown sequence	Haoran

Week	Tasks	Team Member
7	Complete system integration; Fix integration issues	Boyao
7	Testing with full measurement patterns; Fix sequencing issues	Jiaheng
7	Optimize timing parameters based on field testing	Qiushi
7	Implement logging and diagnostics capabilities	Haoran
8	System validation with extended measurement patterns	Boyao
8	Documentation: User manual for configuration interface	Jiaheng
8	Documentation: System architecture and API specifications	Qiushi
8	Documentation: Installation and setup guide	Haoran
9	Field testing with different environmental conditions	Boyao
9	Performance tuning based on field test results	Jiaheng
9	Bug fixing and stability improvements	Qiushi
9	User feedback collection and analysis	Haoran
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

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.

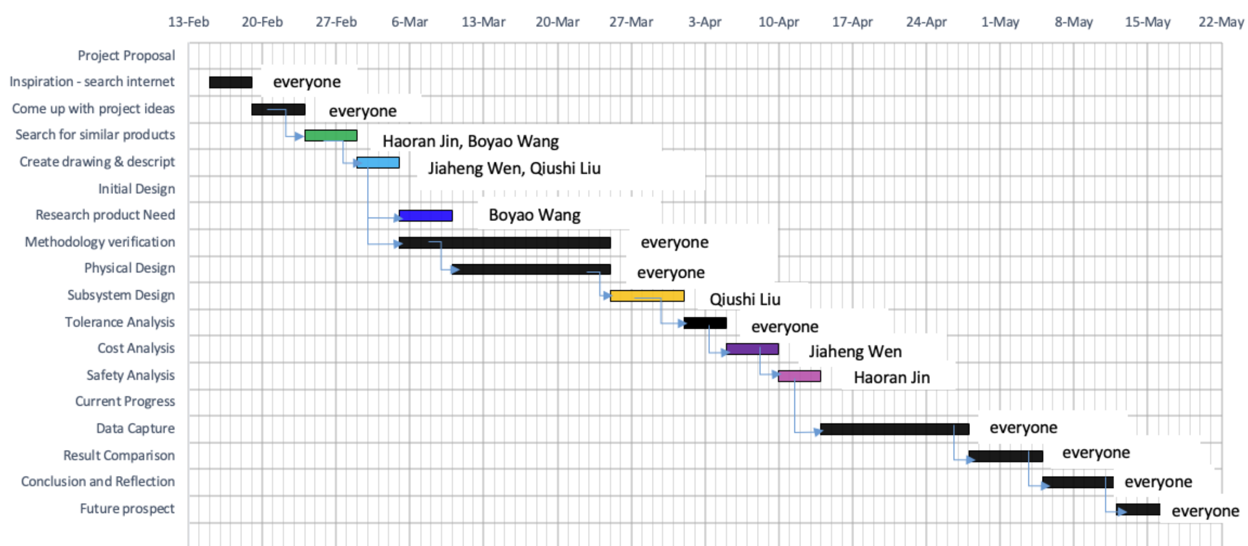

Figure 9: Project Gantt Chart showing task dependencies and timeline.

Part	Description	Quantity	Unit Cost	Total Cost
Existing Hardware (Not included in project budget)				
DJI Power 1000	Power management unit with battery integration	1	$400.00	$400.00
Solar Panels	200W solar panels for power generation	2	$350.00	$700.00
Battery Packs	Energy storage for DJI Power 1000	2	$400.00	$800.00
Rotation Platform	Pan-tilt platform with control motors	1	$3,200.00	$3,200.00
VNA	Vector Network Analyzer for S-parameter measurements	1	$45,000.00	$45,000.00
Desktop Computer	Control computer for software operation	1	$1,200.00	$1,200.00
Additional Components (Included in project budget)				
USB-GPIO Interface	Interface for additional hardware control signals	1	$45.00	$45.00
Status LEDs	Visual indicators for system operation	5	$2.00	$10.00
Enclosure	Weather-resistant enclosure for interface components	1	$35.00	$35.00
Connectors	Various connectors for interface wiring	1 set	$20.00	$20.00
PCB	Custom PCB for interface circuits	2	$15.00	$30.00
Misc. Components	Resistors, capacitors, etc.	1 set	$15.00	$15.00
			Total Hardware Cost:	$155.00

Table 5: Bill of Materials

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 6: Labor Cost Estimation

Category	Cost
Hardware Components	$155.00
Labor	$15,450.00
Total Project Cost	$15,605.00

Table 7: Total Project Cost Summary

4 Ethics & Safety

4.1 Ethical Considerations

The development and implementation of our automated microwave environmental monitoring system involves several ethical considerations that our team has carefully evaluated in accordance with the IEEE Code of Ethics [1]. We have identified the following key ethical aspects of our project:

4.1.1 Environmental Impact

Our system is designed with environmental sustainability as a core consideration:

- **Energy Efficiency**: By implementing automated shutdown procedures and solar power integration, our system minimizes energy consumption during non-measurement periods, reducing the environmental footprint of long-term deployments.
- **Reduced Resource Usage**: Automation eliminates the need for constant human presence, reducing transportation needs and associated carbon emissions that would otherwise be required for manual data collection.
- **Resource Conservation**: The system maximizes the utility of existing hardware through software integration rather than building entirely new hardware, reducing material consumption and electronic waste.

4.1.2 Research Integrity and Data Quality

Our system directly impacts the quality and reliability of scientific research:

- **Measurement Accuracy**: Automating the data collection process reduces human error and improves consistency, leading to more reliable scientific results. This aligns with IEEE Code of Ethics point 3: ”to be honest and realistic in stating claims or estimates based on available data.”
- **Data Provenance**: Our system automatically includes precise angle information in data filenames, ensuring clear documentation of measurement conditions for future reference and scientific reproducibility.
- **Transparency**: The system’s design and operation are fully documented, allowing other researchers to understand how data was collected and any potential limitations.

4.1.3 Responsible Resource Allocation

- **Cost Effectiveness**: By focusing on software integration rather than new hardware development, our project provides significant functionality improvements at minimal cost, representing responsible use of research resources.

- **Time Efficiency**: Automating data collection frees researchers from mundane tasks, allowing them to focus on data analysis and interpretation, thereby maximizing the value of human expertise.

4.1.4 Potential Misuse Considerations

While our system is designed for scientific environmental monitoring, we have considered potential misuse scenarios:

- **Unauthorized Surveillance**: The technology could potentially be repurposed for monitoring in ways that infringe on privacy. We address this by ensuring our documentation emphasizes appropriate use cases and by not incorporating features that would facilitate surveillance applications.
- **Security Implications**: The remote operation capabilities could potentially be vulnerable to unauthorized access. We implement appropriate authentication and access controls to mitigate this risk.

4.2 Safety Considerations

The safety of users, equipment, and the environment has been a primary concern throughout our design process. We have identified and addressed the following safety considerations:

4.2.1 Electrical Safety

- **Power System Safety**: The DJI Power 1000 and associated battery packs involve high-voltage components. Our system documentation includes clear safety warnings and proper operating procedures in accordance with the National Electrical Code (NEC) standards [2].
- **Overload Protection**: Our power management integration includes monitoring for potential overload conditions and implements appropriate safeguards to prevent damage to equipment or safety hazards.
- **Weather Considerations**: For outdoor deployments, all electrical connections and components are properly sealed and insulated to prevent hazards during adverse weather conditions, following IEC 60529 standards for ingress protection [3].

4.2.2 Mechanical Safety

- **Moving Parts**: The rotation platform contains moving components that could potentially cause injury. Our automated control system includes:
  - Movement speed limitations to prevent rapid, unexpected motions
  - Emergency stop capabilities accessible through the software interface
  - Clear indication when the system is in motion

- **Stability and Mounting**: Documentation includes proper mounting instructions to ensure the system remains stable during operation, preventing tipping or falling hazards.

4.2.3 Operational Safety

- **Safe Operating Procedures**: Comprehensive documentation includes step-by-step procedures for safe system setup, operation, and maintenance.
- **Error Handling**: The software includes robust error detection and handling to prevent unsafe operating conditions, such as:
  - Detection of abnormal power conditions
  - Monitoring for unexpected physical resistance during platform movement
  - Graceful failure modes that bring the system to a safe state
- **User Training**: We recommend appropriate user training before operating the system, with detailed safety information included in the user manual.

4.2.4 Radio Frequency (RF) Exposure Considerations

- **RF Radiation**: The VNA system used for measurements generates RF signals. Our documentation includes appropriate warnings and safety guidelines regarding RF exposure, in accordance with IEEE C95.1 standards for human exposure to radio frequency electromagnetic fields [4].
- **Safe Operation Distances**: Clear guidelines are provided regarding minimum safe distances during operation.

4.3 Standards Compliance

Our system design and documentation comply with the following relevant standards:

- IEEE Code of Ethics [1]
- National Electrical Code (NEC) for power systems [2]
- IEC 60529 for environmental protection [3]
- IEEE C95.1 for RF exposure safety [4]
- ISO/IEC 27001 for information security management [5]

Through careful consideration of these ethical and safety aspects, our team has designed a system that not only achieves its technical objectives but does so in a manner that prioritizes ethical research practices, environmental sustainability, and the safety of users and equipment.

References

[1] *Ieee code of ethics*, IEEE, Accessed: 2025-04-14, 2023. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html.

[2] *National electrical code (nfpa 70)*, National Fire Protection Association, Accessed: 2025-04-14, 2023. [Online]. Available: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70.

[3] *Iec 60529: Degrees of protection provided by enclosures (ip code)*, International Electrotechnical Commission, Accessed: 2025-04-14, 2021.

[4] *Ieee c95.1-2019: Ieee standard for safety levels with respect to human exposure to electric, magnetic, and electromagnetic fields*, IEEE, Accessed: 2025-04-14, 2019. [Online]. Available: https://standards.ieee.org/standard/C95_1-2019.html.

[5] *Iso/iec 27001: Information security management*, International Organization for Standardization, Accessed: 2025-04-14, 2022. [Online]. Available: https://www.iso.org/standard/27001.