# Antenna/Radar Positioning System for Enhanced Military Communication

**By**

| | |
|---|---|
| Asma Kausar | 01-133222-011 |
| Aneela Kousar | 01-133222-009 |

**Supervised By**

Dr. Nadia Sultan

**Co-Superviser Bahria University**

Dr. Adil Ali Raja

**Co-Superviser NESCOM**

Dr. Syed Haider

Session 2022-26

A Report is submitted to the Department of Electrical Engineering, Bahria University, Islamabad.

In partial fulfillment of requirement for the degree of BS(EE).

# CERTIFICATE

We accept the work contained in this report as a confirmation to the required standard for the partial fulfillment of the degree of BS(EE).

Head of Department

Supervisor

Internal Examiner

External Examiner

# DEDICATION

We are dedicating this to our beloved parents who have offered unending support and sacrifices to us and whose encouragement has been the pillar of our academic life. This achievement has been made possible by their faith in our capabilities, which has been a source of strength and inspiration.

We thank our esteemed supervisors, Dr. Nadia Sultan, Dr. Adil Ali Raja, and Dr. Syed Haider, who provided us with invaluable guidance, insightful feedback, and support along with this project.

Special and warm recognition is given to our supervisor, Dr. Nadia Sultan, whose outstanding dedication, continuous motivation and relentless effort were crucial in the development of this work. Her encouragement was much more than we expected and we are so grateful that she was with us through it all and giving us good advice.

Lastly, we devote this work to everyone who is making contributions to the sphere of defense communications, whose contributions to the development of technology and the increase of security keep inspiring innovation and improvement.

# ACKNOWLEDGMENTS

To begin with, it is our utmost gratitude to Almighty Allah, whose inmost mercy, direction, and blessings made us come out of this project successfully. This would not have been achieved without the aid of His.

We wish to show our deepest appreciation to our supervisors, Dr. Nadia Sultan, Dr. Adil Ali Raja and Dr. Haider who have been supportive, expert and encouraging to us in this project. Their input and suggestions played a significant role in the development of this work.

We are grateful to the Department of Electrical Engineering, Bahria University, which helped us with the required resources and laboratory equipment. We also want to thank NESCOM who funded this project and offered technical assistance.

We would like to recognize the help of our colleagues and lab personnel that helped to complete this project successfully. Lastly, we appreciate our families in their patience, understanding and moral support in this academic venture.

# ABSTRACT

Reliable communication is a fundamental requirement in modern military operations, particularly in dynamic and unpredictable battlefield environments where mobility, obstruction, and environmental interference severely degrade signal quality. Conventional static antenna systems are often unable to maintain optimal alignment under such conditions, leading to reduced signal strength, unstable connectivity, and limited operational effectiveness. To address these challenges, this project presents the design and implementation of an Adaptive Antenna Positioning System based on Infrared (IR) sensing for enhanced communication reliability. The proposed system employs a two-axis motorized antenna mount capable of automatic azimuth and elevation control. Instead of relying on RF signal strength estimation, the system utilizes Infrared (IR) transmitter–receiver modules to determine directional alignment with the signal source. The IR-based sensing mechanism continuously detects the intensity and directionality of incoming infrared signals, enabling the system to identify the optimal orientation for maximum alignment accuracy. A microcontroller-based control unit processes real-time IR sensor data and dynamically adjusts the antenna position using high-precision stepper motors, ensuring smooth and accurate tracking performance. To evaluate system performance under controlled dynamic conditions, a custom-built moving IR signal source mechanism is developed to simulate mobility scenarios. The hardware architecture integrates IR sensing modules, an Arduino-based control system, motor driver circuits, and a wireless monitoring interface for real-time observation and testing. This integrated design allows effective validation of tracking behavior in both static and dynamic environments.

Experimental results demonstrate that the proposed IR-based system achieves improved directional accuracy, stable alignment, and reduced signal deviation compared to conventional fixed antenna setups. The system shows reliable tracking capability under simulated movement conditions, confirming its suitability for controlled short-range adaptive communication applications.

Overall, the project contributes to the development of intelligent antenna positioning systems by integrating IR sensing technology with embedded control and electromechanical actuation. The resulting framework offers a cost-effective, lightweight, and scalable solution that can serve as a foundation for further advancements in adaptive communication and tracking systems.

# ABBREVIATIONS

| | |
|---|---|
| **RF** | Radio Frequency |
| **RSSI** | Received Signal Strength Indicator |
| **IR** | Infrared |
| **MCU** | Microcontroller Unit |
| **ADC** | Analog-to-Digital Converter |
| **DAC** | Digital-to-Analog Converter |
| **PWM** | Pulse Width Modulation |
| **GPS** | Global Positioning System |
| **IMU** | Inertial Measurement Unit |
| **LOS** | Line of Sight |
| **NLOS** | Non-Line of Sight |
| **SNR** | Signal-to-Noise Ratio |
| **BER** | Bit Error Rate |
| **Arduino** | Microcontroller Development Platform |
| **IR Sensor** | Infrared Sensor Module |
| **DC Motor** | Direct Current Motor |
| **SM** | Stepper Motor |
| **Servo** | Servo Motor |

| | |
|---|---|
| **H-Bridge** | Motor Driver Circuit |
| **PCB** | Printed Circuit Board |
| **CAD** | Computer-Aided Design |
| **GUI** | Graphical User Interface |
| **Hz** | Hertz |
| **kHz** | Kilohertz |
| **MHz** | Megahertz |
| **GHz** | Gigahertz |
| **dB** | Decibel |
| **dBm** | Decibel-milliwatts |
| **PID** | Proportional-Integral-Derivative (Control Algorithm) |
| **DOF** | Degrees of Freedom |
| **FOV** | Field of View |
| **UAV** | Unmanned Aerial Vehicle |
| **AI** | Artificial Intelligence |
| **IoT** | Internet of Things |

# Contents

# List of Figures

# List of Tables

# Chapter 1

# INTRODUCTION

## 1.1 Project Background

The ability to precisely locate, track and keep pace with a signal source has ceased to be an optional feature, but a basic working requirement in modern communication and sensing systems. This is essential especially in unsteady situations where both the sender and receiver are moving and are exposed to constant changes in orientation, distance, and the conditions around them. When this occurs, it is necessary that optimum alignment is preserved to promote signal integrity, reduce losses and maintain a reliable system behavior. The newest uses such as military communication, autonomous systems, wireless surveillance, and robot sensing systems have a need of real-time flexibility in the signal acquisition and alignment. The traditional antenna positioning systems however are mostly fixed or semi-manual and are therefore not applicable in situations where there is need of fast and continuous optimization. Even where automation is present, the sensing mechanisms that underlie it tend to be limited to limit overall performance.

In the past, antenna tracking and positioning systems have been highly dependent on Radio Frequency (RF)-based methods, especially the Received Signal Strength Indicator (RSSI) measurements. The principle of operation of these systems is to estimate the direction of a signal source by measuring the change in received power as the antenna orientation is varied. Although these techniques are good in long-range communication and the overall signal collection, they are highly limited in the context of high-precision tracking in dynamic or cluttered conditions. Among the main issues related to the RF-based tracking is the problem of multipath propagation, where the signals bounce off the surface of a building, terrain, or obstacle to the receiver. This causes more than one path of the signal to reach the receiver with varying phases and amplitudes, producing signal variability which is not a true reflection of the actual direction of the source. Also, RF signals are vulnerable to electromagnetic interference, noise, and congestion especially in a setting where several devices are working in close frequency ranges. Signal attenuation and dispersion is another important constraint. With RF propagating in space, power reduces on an inverse square law and other environmental conditions like humidity conditions, obstructions and atmospheric conditions also deteriorate the quality of signals. These effects create uncertainty in the RSSI-based measurements, such that it is hard to produce stable and accurate directional tracking. Moreover, RF systems can also be susceptible to deliberate jamming or interference in sensitive applications, which makes them less reliable in mission-critical situations. In the early stages of this project, the RF-based course was also on the list of approaches and partly tested. Nonetheless, experimental results and analytical evaluation showed that the changes in RSSI were not consistent and very sensitive to environmental factors, resulting in unstable tracking behaviors. The system had problems like oscillations, inaccurate choices of alignments, and slow movement towards the optimal direction. These results illuminated a critical weakness: RF signal strength per se cannot be a reliable enough parameter to accurately direct tracking in short range, high accuracy scenarios. These difficulties also triggered a radical reevaluation of the sensing mechanism and caused a strategic change in the system design away away an RF-based tracking system to an Infrared (IR)-based sensing system.

IR technology has a radically different propagation behavior than RF signals. IR waves lie within a higher frequency range and have line-of-sight properties, i.e. the transmission of signals is more direct and less influenced by reflections and diffraction. This leads to a better predictive and stable relationship between signal strength and alignment, which is necessary to have accurate tracking. High directional sensitivity is one of the main merits of the IR-based systems. In contrast to RF signals which can easily spread and propagate in various directions, the IR signals can be directed to small beams, which allows them to measure the alignment angles with accuracy. This renders IR especially appropriate in the applications where an angular resolution and precise positioning are demanded.

Furthermore, by nature, the IR systems are less susceptible to electromagnetic interference since they are not in the common RF communication spectrum. This minimizes the effects of noise and external disturbances resulting in more dependable signal measurements. The localized transmission of IR can also improve the security of a system and minimize unwanted signal leakage, which may be beneficial in a controlled or sensitive setup. Nevertheless, implementation of IR technology brings about considerations as well. IR signals need line-of-sight to transmit, and ambient light sources can cause noise. These issues need to be addressed by designing systems carefully that should incorporate signal filtering, controlled sensing conditions, and robust feedback controls. These considerations were put into mind when developing the proposed system.

This project is built on the basis of these insights and thus aims at designing and implementing an Adaptive IR-Based Antenna Positioning System. The system will be designed to automatically identify the direction of an IR signal source and constantly change its position to ensure the best alignment. This is done by a closed-loop control architecture in which real-time feedback in form of signal is employed to control mechanical movement.

The proposed system incorporates several subsystems, such as:

- IR sensing sensor to detect the signal.
- Microcontroller unit to process and make decisions.
- Mechanical positioning motor driver and actuators.
- Adaptive alignment feedback control algorithm.

The fundamental working principle is on the principle of the constant tracking of the intensity of received signals. The system gradually changes its orientation and measures the signal strength it achieves, enabling the system to approach the direction of peak intensity. This is done to make sure that the system is flexible to changes in the position of the source or environmental changes.

Another priority of this project is to demonstrate a practical, cost-effective, and reliable alternative to traditional tracking systems as well as the development of a functional prototype. Through the deterministic nature of the IR signals, as well as by using the deterministic behavior of the IR signals with effective control strategies, the system will focus on achieving high accuracy at low complexity. Moreover, this project concentrates on engineering validation by experimentation, so that the design decisions are backed by practical observations and not only by theoretical assumptions. The RF to IR conversion, the choice of the components, and the construction of the control logic are all based on the iterative testing and performance assessment.

Overall, the project fills a gap in the current positioning systems as it suggests that it is:

- Dynamic environment adaptive.
- Directional tracking is accurate.
- Stable to interference and instability.
- Cost- and implementation-efficient.

The resulting system demonstrates how careful selection of sensing technology, combined with intelligent system design, can significantly enhance the performance of antenna positioning mechanisms in modern applications.

## 1.2 Problem Statement

The capability to retain a good level of correct proximity between a transmitter and a receiver is a very important but unfinished engineering problem in present-day communication and sensing settings. This problem is much more complicated in dynamic situations when the constant motion, disturbances in the environment, and differences in signals influence the work of the systems. Traditional positioning systems tend to be restricted by the fixed set-up or manual adjustment, and are inadvisable in applications where dynamism is needed. Even automated systems often depend on the difference in signal strength which is determined by the environmental factors, not actual directional alignment and this leads to a less accurate and stable system. One of the challenges is the uncertainties surrounding the propagation of signals in the real world. Interference, attenuation, and environmental noise among other factors contribute to fluctuations which make it difficult to correctly determine the direction of a signal source. Consequently, a lot of the current systems are characterized by:

- Inconsistent alignment performance
- Delayed response to positional changes
- Oscillatory or unstable tracking behavior
- Reduced efficiency in short-range precision applications

Moreover, high-precision positioning systems, though useful, are usually complex, have high computing requirements, and expensive, which restricts their availability and realistic use.

Thus, there is a definite necessity of a system that can:

- Consistently identify the direction of a signal source.
- Adapt constantly to new circumstances.
- Work very precisely and consistently.
- Be economical and feasible.

This project meets this requirement by emphasizing on the creation of an adaptive positioning system anchored on infrared sensing, which is capable of attaining precise and real time alignment in a controlled and efficient way

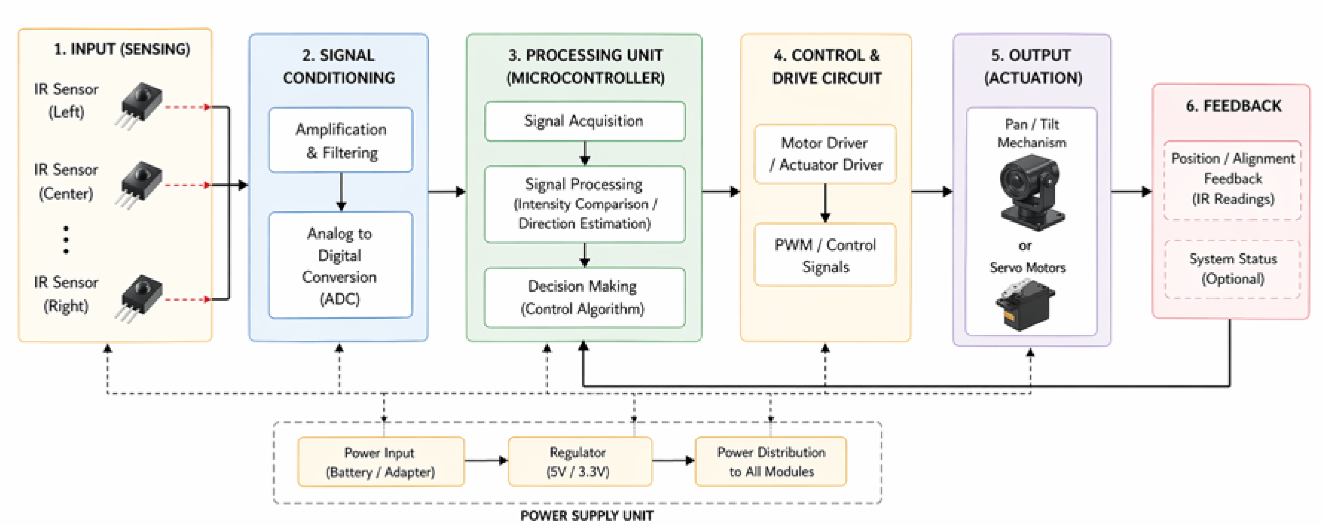


Figure 1.1: Block Diagram of IR based Adaptive Positioning System

## 1.3 Motivation

This project is driven by the fact that there is a growing need to have intelligent and autonomous systems able to work effectively without constant human supervision. In numerous real-world applications, it is important to have very accurate alignment with a signal source to guarantee system performance, reliability, and efficiency. Conventional methods are usually ineffective in dynamic applications because they are not able to react fast and correctly to signal direction changes. This introduces a disconnect between system requirements and available solutions especially in applications where accuracy and responsiveness are paramount.

The solution to this problem is the IR-based sensing because of its directional sensitivity and predictable propagativeness. In contrast to more general signal propagation approaches, IR sensing can provide a more direct correlation between signal intensity and alignment, leading to better control and decision-making.

This work is inspired by the need to:

- Autonomously develop a system that synchronizes with a signal source.
- Enhance accuracy in tracking and stability of the system.
- Minimize human intervention.
- Give a basic, but efficient engineering solution.

The project can be viewed as a real-life practical approach to solving real-life issues by integrating both theoretical knowledge and experimental validation and system-level design.

## 1.4 Objectives

The main aim of this project is to design and develop an adaptive infrared-based positioning system in real time that has the ability to precisely detect and track the direction of a signal source.

To achieve this, the project is guided by the following objectives:

1. **Accurate Signal Detection**

   The primary objective of the system is to develop a reliable infrared (IR) sensing mechanism capable of detecting incoming signals with high precision under varying environmental conditions. In practical scenarios, IR signals are affected by ambient light, reflections from nearby surfaces, sensor noise, and attenuation due to distance.

To address these challenges, the system is designed to ensure that the received signal is not only detected but also filtered and interpreted in a stable manner. This includes improving sensor sensitivity while minimizing false triggering caused by noise. Signal conditioning techniques such as filtering, threshold calibration, and differential comparison are incorporated to enhance detection reliability.

The ultimate goal is to achieve stable signal reception that remains consistent despite variations in lighting conditions, object placement, and environmental reflections, ensuring functionality beyond controlled laboratory environments.

2. **Adaptive Control System**

   This objective focuses on establishing a closed-loop adaptive control system that allows the system to dynamically respond to changes in the measured IR signal. Unlike open-loop systems, which operate on fixed responses, this system continuously monitors feedback and adjusts its behavior accordingly.

   The control system minimizes positional error by comparing real-time sensor input with a reference condition and generating corrective actions. This enables the system to respond based on actual operating conditions rather than predefined motion rules.

   Key performance considerations include minimizing overshoot, reducing oscillations, and ensuring smooth convergence toward the target direction. The adaptive nature of the control system enhances robustness, particularly when signal strength varies or when temporary disturbances affect signal detection.

3. **Efficient Decision-Making Algorithm**

   The system requires a computationally efficient algorithm capable of detecting small variations in signal intensity and translating them into accurate directional decisions in real time.

   The algorithm evaluates relative signal strengths from multiple sensors and determines the direction of the highest signal gradient. Based on this analysis, it generates movement commands that guide the mechanical system toward optimal alignment.

Emphasis is placed on simplicity and speed, enabling execution on microcontroller-based hardware with limited processing capability. At the same time, the algorithm must remain stable, avoiding rapid oscillations or conflicting outputs when signal differences are minimal or noisy.

4. **Mechanical Positioning System**

   This objective involves designing and developing a stable and precise mechanical structure capable of controlled rotational movement. The system must effectively convert electrical control signals into smooth mechanical motion while maintaining accuracy and minimizing backlash or drift.

   The positioning mechanism should support fine angular adjustments to ensure precise alignment with the detected IR source. Important considerations include load handling, torque requirements, friction reduction, and structural rigidity.

   Additionally, the system must demonstrate repeatability, ensuring consistent positioning over multiple operations, while maintaining stability during continuous usage.

5. **Real-Time System Integration**

   Another key objective is the seamless integration of sensing, processing, and actuation into a unified real-time system. This includes combining hardware components (IR sensors, microcontroller, actuators) with software elements (signal processing and control algorithms).

   The system is designed to maintain minimal latency between signal detection and mechanical response, enabling near real-time adjustments. Any delay in this loop can lead to tracking errors or instability, particularly in dynamic environments.

   Proper synchronization of data flow is also essential, ensuring that sensor inputs are processed immediately without buffering delays. The goal is to maintain a continuous and stable feedback loop during operation.

6. **Performance Evaluation**

The final objective is to experimentally evaluate the performance of the developed system using defined metrics such as accuracy, response time, stability, and repeatability.

Accuracy measures how precisely the system aligns with the target signal source under different conditions. Response time evaluates the delay between signal detection and mechanical actuation. Stability analysis ensures that the system does not oscillate or drift during tracking.

Testing is conducted under varying environmental conditions, including changes in distance, lighting, and potential interference sources. The results are analyzed to assess how effectively the system meets its design objectives and to identify areas for future improvement.

| **Objective** | **Focus Area** | **Expected Outcome** |
|---|---|---|
| Accurate Signal Detection | IR sensing and filtering | Stable reception of signals under varying conditions |
| Adaptive Control | Closed-loop feedback | Smooth and stable convergence toward target direction |
| Efficient Algorithm | Lightweight decision logic | Real-time response with minimal computational delay |
| Mechanical Precision | Motor-driven positioning | Fine angular control for accurate antenna alignment |
| System Integration | Hardware + software | Unified real-time operational system |
| Performance Evaluation | Testing metrics | Accuracy and stability verification |

Table 1.1: Design Objectives and Expected Outcomes

## 1.5 Scope of the Project

The project focuses on designing, developing, implementing, and experimentally evaluating a prototype adaptive positioning system. The primary goal is to create an efficient system capable of detecting an infrared (IR) signal source and adjusting its orientation accordingly using a controlled mechanical mechanism.

The scope is intentionally limited to a prototype-level implementation to ensure feasibility within academic and laboratory constraints, while still demonstrating key engineering principles of sensing, control, and actuation.

The project includes the development of a real-time tracking mechanism that continuously monitors incoming IR signals and dynamically adjusts system orientation based on signal intensity and direction. This ensures that the system does not remain static but actively responds to environmental feedback.

An infrared-based signal detection subsystem forms a core component of the project. This subsystem captures and interprets variations in IR signal strength, which serve as the primary input for decision-making and control processes. The design prioritizes reliable detection in controlled environments while maintaining sensitivity to directional changes.

The project also involves the design and implementation of a microcontroller-based control architecture. This unit processes sensor inputs, executes decision-making algorithms, and generates control signals for actuation. The architecture is optimized to be lightweight and efficient, suitable for real-time embedded applications.

Figure 1.2: Scope of the Project

The mechanical subsystem is also included within the scope, consisting of motor-driven positioning components responsible for adjusting system orientation. The design emphasizes stability, precision, and smooth motion to ensure accurate alignment with the detected signal source.

System testing is conducted in both controlled and semi-dynamic environments. Controlled conditions provide baseline performance measurements, while semi-dynamic conditions introduce moderate variations to evaluate system adaptability. Key performance metrics include accuracy, response time, stability, and repeatability.

### 1.5.1 Scope Overview

The project is carefully structured with clearly defined scope and limitations, ensuring focus on a specific engineering problem. This approach maintains feasibility within academic constraints while providing meaningful insights into the design and operation of adaptive positioning systems.

The controlled scope enables detailed analysis of system behavior, allowing accurate evaluation and identification of potential improvements for future, more advanced implementations.

## 1.6 Research Challenges

The infrared (IR) signal detection and motor-driven control of an adaptive positioning system offer a variety of technical and practical challenges. These are the challenges because there is the desire to unify sensing, processing, control and mechanical actuation in one real-time system and remain stable, accurate and responsive. All these aspects must be carefully designed, tested, and fine-tuned to enable a stable system functionality.

1. **Signal Variability**

   The invariable variability of infrared signals in the real world is one of the main issues of the system. The intensity of IR signals is extremely sensitive to any environmental conditions (ambient light, surface reflection, color of an object, and distance between the transmitter and receiver). Extraneous noise in an uncontrolled environment and light source like sunlight or artificial lighting may greatly affect the readings, causing the signal to be inaccurate or the signal may also be unstable.

   This heterogeneity complicates the achievement of a uniform and reliable sensor outputs. Consequently, this system has to include proper signal conditioning and filtering procedures to reduce noise and increase signal stability. Sensitivity of sensor thresholds should also be carefully calibrated to make sure that the system is capable of differentiating between significant directional cues and background noise. This variability needs to be managed in order to ensure proper tracking performance.

2. **Real-Time Processing Constraints**

   The necessity of real-time data processing and response is also another important challenge. The system will have to receive sensor inputs, process them, and then implement decision-making logic, and issue control signals to the actuators with no perceivable delay. Any delay in this loop may cause imprecise positioning or unreliable tracking actions.

   Because the system is normally run on a microcontroller which has limited processing power and memory capacity, the design of the algorithms is vital. The control logic should be light such that it can run quickly and at the same time it should be robust enough to maintain the variations in the input data. Real-time constraints require optimization of code structure, minimization of computing overhead, as well as prioritization of important operations.

3. **Mechanical Accuracy**

   Mechanical precision is important part of the system since any slight malfunction with movement can cause a lot of misalignment with the positioning mechanism. The motor-driven system should be able to perform small angular movements, which are controlled, with high repeatability and low deviation.

   Issues are encountered because of gear backlash, friction, motor step resolution and structural vibrations. Such mechanical defects may build up with time and decrease the accuracy of the entire system. Hence, a mechanical design must be carefully planned, actuators well chosen, and meticulously calibrated to be sure that the actual movement is accurately represented by the control signals produced by the system.

4. **Control Stability**

Another important challenge is to ensure stable system behavior, especially in a closed-loop adaptive control environment. The system should be sensitive to the variation of the signal input so that it does not oscillate, overshoot or make constant unnecessary corrections.

In case the control response is excessively aggressive, the system can violate the target position resulting in the instability. Conversely, the system might not be able to handle changes in case the response is too slow. A balanced control response can be achieved by controlling parameters of the control and logic design to give a smooth convergence to the desired alignment point.

The stability of the system under different signal conditions is critical to reliable and predictable performance of the system.

5. **System Integration**

   The combination of several subsystems, such as IR sensors, microcontroller-based processing units, and motor-driven mechanical elements is a challenging engineering problem. All the subsystems have various timing characteristics, response characteristics, and signal requirements, hence synchronization is a key element in the overall system performance.

   A well-designed system architecture is needed to facilitate smooth communication between sensors, processing, and actuation modules. Late or early arrival of signals or information between components may cause intermittent behavior or inaccurate tracking. Thus, the data flow and control signals should be carefully synchronized to ensure system coherence and real-time responsiveness.

To deal with these issues, a systematic and iterative development process with repeated testing, calibration and refinement of hardware and software components was necessary. The system was constantly optimized to become more reliable, more accurate and more responsive.

Finally, the resolution of these issues saw the adaptive positioning system be capable of running successfully in the real world and under semi-controlled conditions, exhibiting a stable performance and stable alignment behavior within the defined scope of the project.

| **Challenge** | **Cause** | **Mitigation Strategy** |
|---|---|---|
| Signal Variability | Ambient light, reflections | Filtering and calibration |
| Real-Time Constraints | Limited MCU power | Lightweight algorithms |
| Mechanical Accuracy | Backlash, friction | Precision motors and calibration |
| Control Stability | Aggressive or slow response | Tuned feedback parameters |
| System Integration | Timing mismatch | Synchronization protocols |

Table 1.2: Research Challenges Summary

## 1.7 Methodological Approach Overview

The approach taken in this project is the closed loop feedback control system of which the adaptive behavior is provided through continuous monitoring and adjustment.

The system works by:

- Measuring signal intensity continuously.
- Incrementally adjusting position.
- Considering the impact of every change.
- Moving towards the point of optimal signal strength.

This approach ensures:

- Stable operation
- Accurate alignment
- Strong reaction to transformations.

The methodology is also simple, which makes it efficient to work on inexpensive hardware platforms.

## 1.8 Constraints of the Proposed System

Despite the effective performance of the proposed system in the scope of its work, it is necessary to consider some additional limitations which inherently influence the performance of the system and its scaling. The main causes of these limitations are the selection of sensing technology, constraints of system complexity, and implementation on the prototype.

Amongst the greatest constraints is that it requires line-of-sight (LOS) to work. As the system is infrared signal detector-based, it assumes that there is a direct or clear enough view between the transmitter and receiver. Any physical barrier between the signal source and the sensor can greatly reduce performance or entirely eliminate signal detection. This limits the use of the system in those environments that contain obstacles or those where tracking of indirect signals is needed.

The other significant weakness is that the system is vulnerable to interference by ambient light. IR sensors are sensitive to environmental light like the sun, fluorescent lamps, and reflecting surfaces. The precision of the signal detection can be compromised by noise or false readings in circumstances where the level of light is high or varying. This can be somewhat alleviated by filtering and calibration methods but within the present design framework it is impossible to eliminate interference.

Also, the system is under a constrained range of operation compared to superior tracking technology like RF based tracking system, radar, or optical tracking systems. Detection IR is commonly only suitable in the short range, limiting its use in the large scale or long range tracking applications. This is mainly limited by the nature of the IR signal propagation and the sensor sensitivity limits.

Another important point that should be mentioned is that the system is implemented on a prototype level, which implies that it is mostly aimed at experimental validation and academic demonstration, although not at an industrial scale. Consequently, long term durability, strict environmental survivability and massive integration have not been well catered to within the scope of the present.

Regardless of these shortcomings, the system also offers a solid base to be developed further. Such limitations point to the obvious improvement directions of enhancement in the future, including the integration of hybrid sensing technologies, enhanced filtering, or sophisticated control strategies to increase the range of operation and robustness.

## 1.9 Expected Contributions

It is anticipated that this project will contribute significantly to the fields of embedded systems, control engineering, and adaptive positioning technologies through the introduction of a practical real-time infrared-based tracking mechanism. The main objective of this work is to bridge theoretical control concepts with a fully functional prototype, demonstrating how sensing, decision-making, and actuation can be successfully integrated into a single system.

1. **Functional Prototype Development**

   The creation of a fully functional prototype of an adaptive positioning system is one of the main contributions of this work. In contrast to theoretical models or simulation-based studies, this project involves a concrete hardware implementation that demonstrates real-time behavior.

   The system integrates infrared sensing, microcontroller-based processing, and motor-driven mechanical movement into a unified structure. This enables observation and evaluation of real-world system behavior, including response to signal variations, directional correction, and continuous feedback-based adjustments. The prototype serves as a practical validation of closed-loop control systems and real-time embedded system concepts.

2. **Practical Engineering Solution**

   This project also contributes by presenting a practical engineering solution that balances performance, simplicity, and cost-effectiveness. While many advanced tracking systems rely on complex hardware and expensive technologies, this system demonstrates that reliable adaptive behavior can be achieved using relatively simple components and efficient design strategies.

The focus on low-cost implementation makes the system suitable for educational, experimental, and small-scale engineering applications. At the same time, essential performance parameters such as responsiveness, stability, and directional accuracy are maintained. This balance enhances its applicability in both academic and prototype development environments.

3. **Improved Tracking Accuracy**

   Another significant contribution is the improvement of tracking accuracy through infrared-based sensing combined with closed-loop control techniques. The system continuously monitors variations in signal intensity and adjusts its position accordingly, enabling closer alignment with the signal source.

   By incorporating feedback-based corrections, the system reduces positional error and enhances alignment precision over time. This adaptive correction leads to smoother tracking performance and minimizes deviation between the target and actual direction, resulting in a more stable and responsive positioning system.

4. **System Integration Framework**

   The project also provides a structured framework for integrating multiple subsystems, including sensing units, processing modules, and mechanical actuators. One of the major challenges in such systems is ensuring smooth coordination between components with different operational speeds and characteristics.

   This work demonstrates a systematic hardware-software integration approach in which sensor data is processed in real time and directly translated into motor control signals using a microcontroller-based design. This integration ensures coordinated operation, low latency, and stable system behavior.

   Such a structured design approach can serve as a reference model for similar embedded system applications requiring multi-domain integration.

5. **Future Research**

   Finally, the project establishes a strong foundation for future research and development in adaptive tracking and intelligent positioning systems. Although the current implementation is based on rule-based control and infrared sensing, it opens opportunities for further enhancement in both sensing and decision-making capabilities.

Future improvements may include the integration of hybrid sensing techniques such as combining infrared with ultrasonic, camera-based, or RF-based systems to enhance robustness and operational range. Additionally, advanced control strategies, including optimization algorithms or intelligent learning-based methods, can be incorporated to improve adaptability and accuracy.

Thus, the current system serves as a baseline that can be extended into more advanced and intelligent tracking systems applicable in industrial, aerospace, and autonomous domains.

# Chapter 2

# LITERATURE REVIEW

## 2.1 Introduction and Research Methodology

The development of adaptive antenna positioning systems represents a multidisciplinary research domain that integrates principles from wireless communication, control systems engineering, signal processing, and embedded system design[2]. In modern communication environments, particularly those characterized by mobility and uncertainty, the ability to maintain reliable and continuous signal connectivity has become a fundamental requirement rather than an optional enhancement. This is especially critical in applications such as military communication systems, unmanned aerial vehicles (UAVs), remote sensing networks, and autonomous platforms, where communication reliability directly impacts operational effectiveness and mission success[1]. Traditional antenna systems, which are typically fixed or manually oriented, are increasingly inadequate in dynamic environments where the position of the transmitter or receiver changes frequently. Signal degradation due to misalignment, environmental obstructions, multipath propagation, and interference poses significant challenges to maintaining stable communication links. As a result, there has been a growing research focus on the development of intelligent antenna positioning systems capable of automatically detecting, tracking, and aligning with signal sources in real time. These systems aim to optimize signal reception by continuously adjusting antenna orientation based on feedback mechanisms, thereby enhancing communication reliability and efficiency.

This chapter presents a comprehensive and critical review of existing literature related to antenna tracking and positioning systems. Rather than providing a descriptive summary alone, the review adopts an analytical approach that evaluates different methodologies, compares their performance, and identifies inherent limitations[20]. The objective is to establish a clear understanding of the current state of research while highlighting the gaps that necessitate further investigation. The discussion encompasses a wide range of approaches, including RSSI-based tracking techniques, closed-loop control systems, alternative sensing technologies such as ultrasonic and optical methods, and integrated systems utilizing GPS and inertial sensors. In addition to examining technical approaches, this review also considers practical implementation aspects that are often overlooked in academic research. Many proposed systems demonstrate promising results under controlled laboratory conditions but fail to address real-world constraints such as environmental variability, hardware limitations, power consumption, and system robustness. Therefore, particular emphasis is placed on studies that include experimental validation, hardware implementation, and field testing. This ensures that the insights derived from the literature are directly relevant to the design and development of a practical and deployable antenna positioning system.

The research methodology adopted for this literature review is systematic and structured. A wide range of sources has been consulted, including peer-reviewed journal articles, IEEE conference papers, technical reports, and recent research publications. Priority has been given to high-impact and recent studies to ensure that the review reflects current technological advancements[21]. The selection process involved identifying relevant keywords such as "antenna tracking," "adaptive antenna systems," "RSSI-based positioning," and "antenna alignment control," followed by filtering sources based on relevance, credibility, and contribution to the field. Furthermore, the review process includes a comparative analysis of different approaches based on key performance metrics such as tracking accuracy, response time, system complexity, cost, and adaptability to dynamic environments. This comparative perspective enables a deeper understanding of the trade-offs involved in different design choices. In addition, insights from practical experimentation and prototype development are considered to bridge the gap between theoretical research and real-world implementation.

A critical aspect of this chapter is the identification of research gaps. Despite significant progress in antenna tracking technologies, several challenges remain unresolved. These include the lack of cost-effective solutions that balance performance and simplicity, limited focus on real-time adaptability in noisy environments, and insufficient integration of sensing, control, and mechanical subsystems into a cohesive architecture. By systematically analyzing existing work, this chapter establishes the foundation for the proposed system and justifies the need for a novel approach.

In summary, this section sets the context for the entire literature review by outlining the importance of adaptive antenna positioning systems, defining the scope of the review, and describing the methodology used to analyze existing research. The insights gained from this chapter will guide the design decisions and methodological framework presented in the subsequent chapters, ensuring that the proposed system is both technically sound and practically viable.

## 2.2 Evolution of Antenna Tracking Systems

The evolution of antenna tracking systems reflects the broader advancement of communication technologies and control methodologies[3]. As communication systems transitioned from static and predictable environments to highly dynamic and uncertain operational scenarios, the need for adaptive antenna alignment mechanisms became increasingly evident[10].

| **Method** | **Strengths** | **Limitations** |
|---|---|---|
| RF (RSSI-based) | Long-range communication | Multipath errors, interference, unstable tracking |
| GPS | Global coverage | Low precision indoors, high cost |
| Manual Antenna | Simple setup | Slow, inaccurate, human-dependent |
| Semi-Automated | Partial automation | Prone to noise, limited adaptability |
| Radar | High accuracy | Expensive, complex hardware |
| IR (Proposed) | High angular precision | Requires line-of-sight, sensitive to ambient light |

Table 2.1: Limitations of Existing Tracking System

### 2.2.1 Early Manual and Static Systems

In the initial stages of wireless communication development, antenna systems were predominantly static or manually operated. Directional antennas were physically oriented toward known transmitter locations based on predefined geometrical alignment or operator estimation. This approach was particularly suitable for fixed communication links such as point-to-point microwave communication, where both transmitter and receiver positions remained constant over time.

Manual alignment methods were favored due to their simplicity, low cost, and minimal hardware requirements. In many practical implementations, technicians adjusted antenna orientation using mechanical mounts, often guided by signal strength indicators or predefined alignment procedures. While such systems were adequate for stable and predictable environments, they exhibited significant shortcomings when applied to dynamic scenarios.

The primary limitation of manual systems lies in their dependence on human intervention. Continuous monitoring and adjustment are required to maintain optimal alignment, which is both time-consuming and prone to human error. Furthermore, the response time of manual adjustments is inherently slow, making these systems unsuitable for applications involving rapidly moving transmitters, such as mobile communication units or unmanned aerial vehicles.

Another critical issue is the high probability of misalignment. Even slight deviations in antenna orientation can result in substantial signal degradation, particularly in high-frequency communication systems where directional beams are narrow. In addition, manual systems lack the capability to respond to environmental variations such as obstacles, reflections, and signal fading caused by multipath propagation. The inability of static and manually controlled systems to adapt to changing conditions significantly limits their effectiveness in modern communication environments.

### 2.2.2 RSSI-Based Tracking Systems

The transition from manual to automated antenna tracking systems introduced the use of signal-based feedback mechanisms, with the Received Signal Strength Indicator (RSSI) emerging as one of the earliest and most widely adopted parameters[10]. RSSI represents the power level of a received signal and is readily available in most RF communication modules, making it an attractive choice for low-cost and hardware-efficient implementations[20].

RSSI-based tracking systems operate on a straightforward principle: the optimal antenna orientation corresponds to the direction in which the received signal strength is maximized. By continuously monitoring RSSI values and adjusting antenna position accordingly, these systems attempt to align the antenna with the signal source.

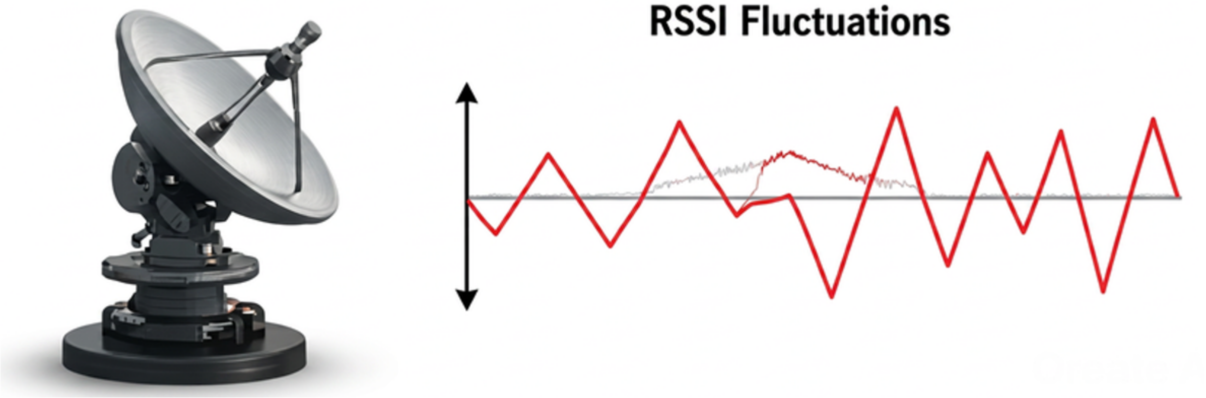


Figure 2.1: RSSI Based Traditional Alignment Method

### 2.2.3 Closed-Loop Control-Based Systems

To address the shortcomings of basic RSSI-based approaches, researchers have increasingly incorporated closed-loop control mechanisms into antenna tracking systems[4]. Closed-loop systems utilize feedback to continuously monitor system performance and adjust control actions in real time, thereby improving accuracy and stability. Among the various control strategies, the Proportional-Integral-Derivative (PID) controller has emerged as one of the most widely used techniques. PID controllers operate by minimizing the error between a desired reference value and the measured output. In the context of antenna tracking, this error is typically defined in terms of signal strength deviation or alignment discrepancy. Khan et al. (2020) demonstrated the effectiveness of PID-based antenna positioning systems, showing significant improvements in tracking performance compared to conventional RSSI-driven methods. By dynamically adjusting antenna orientation based on proportional, integral, and derivative components of the error signal, the system achieves smoother motion, reduced overshoot, and faster convergence to the optimal position.

The advantages of closed-loop PID-based systems are substantial. They provide enhanced stability by continuously correcting deviations, resulting in smoother and more controlled antenna movement. The inclusion of the derivative term helps anticipate changes, reducing overshoot and improving responsiveness. Additionally, the integral component ensures that steady-state errors are minimized, leading to more accurate alignment. However, despite these advantages, PID-based systems are not without limitations. One of the primary challenges is the requirement for precise parameter tuning. The performance of a PID controller is highly dependent on the selection of its gain parameters, which must be carefully adjusted to achieve optimal behavior. Improper tuning can lead to instability, excessive oscillations, or slow response.

Another significant limitation is sensitivity to environmental variations. Changes in signal propagation characteristics due to temperature, humidity, or interference can affect system performance, requiring recalibration of controller parameters. This reduces the practicality of PID-based systems in real-world scenarios where environmental conditions are constantly changing. Furthermore, the implementation of PID control introduces additional computational complexity, particularly when combined with filtering and signal processing techniques. While modern microcontrollers are capable of handling such computations, the increased complexity may impact power consumption and system cost. In many real-world applications, static PID controllers prove insufficient, leading to the need for adaptive or self-tuning control strategies. However, such approaches are relatively underexplored in existing literature, highlighting a gap between theoretical advancements and practical deployment.

Overall, the evolution from manual systems to RSSI-based methods and subsequently to closed-loop control approaches demonstrates a clear trajectory toward increased automation, accuracy, and adaptability. However, each stage also reveals persistent challenges, particularly in achieving reliable performance under real-world conditions. These challenges form the basis for further research and motivate the development of improved antenna tracking methodologies[27].

## 2.3 Military Communication Systems and Requirements

Modern military communication systems are fundamentally different from their commercial counterparts in terms of operational demands, environmental exposure, and performance expectations. Unlike civilian communication systems, which typically operate under controlled or semi-controlled conditions, military systems must function reliably in highly dynamic, unpredictable, and often hostile environments. These systems serve as the backbone of command, control, coordination, and intelligence operations; therefore, any degradation in communication performance can directly impact mission success and operational safety[4].

From an engineering perspective, the design of military communication systems requires careful consideration of multiple constraints that extend beyond conventional performance metrics such as bandwidth and range. These constraints significantly influence the feasibility and practicality of antenna tracking solutions. A critical review of existing literature reveals that many academic studies overlook these real-world requirements, focusing instead on idealized scenarios. This disconnect highlights the importance of integrating operational constraints into system design and evaluation.

### 2.3.1 Operational Constraints

Military communication systems are required to operate under extreme environmental and operational conditions that impose stringent design requirements. One of the most significant challenges is environmental variability. Systems must function reliably across a wide range of temperatures, often from sub-zero conditions to extreme heat. In addition, exposure to dust, humidity, rain, and mechanical vibrations particularly in vehicular or airborne platforms can degrade system performance and compromise hardware integrity. These factors necessitate robust mechanical design, environmental sealing, and stable electronic performance[29].

Mobility represents another critical constraint. Unlike fixed communication systems, military communication nodes are frequently in motion. These may include ground vehicles, aerial platforms such as drones, or dismounted personnel. Continuous movement introduces challenges in maintaining antenna alignment, as the relative position between transmitter and receiver changes dynamically. Traditional static alignment approaches are ineffective in such scenarios, emphasizing the need for automated and adaptive tracking mechanisms.

Reliability is of paramount importance in military applications. Communication systems are expected to operate with near-zero failure tolerance, as any interruption can lead to loss of coordination, situational awareness, or control. This requirement extends beyond electronic reliability to include mechanical robustness and algorithmic stability. Systems must be capable of sustained operation without frequent recalibration or maintenance, even under adverse conditions.

Power constraints further complicate system design. Many military communication devices are battery-operated, particularly in field deployments. As a result, energy efficiency becomes a critical design parameter. Antenna tracking systems must balance performance with power consumption, ensuring that continuous operation does not excessively drain available energy resources. Despite the importance of these constraints, a significant portion of academic research does not adequately address them. Many proposed systems are evaluated under controlled laboratory conditions, without accounting for environmental variability, mobility, or power limitations. Consequently, such solutions often lack practical applicability in real-world military scenarios.

### 2.3.2 Limitations of Existing Military Systems

An analysis of currently deployed military communication systems reveals a notable gap between technological capability and practical implementation. While advancements in communication protocols, encryption, and signal processing have been substantial, antenna positioning mechanisms have not evolved at the same pace. In many cases, tactical communication systems continue to rely on fixed or manually adjustable antennas. For instance, handheld and vehicle-mounted radios often use omnidirectional antennas that do not require alignment but suffer from limited range and susceptibility to interference. Directional antennas, when used, typically require manual positioning, which introduces delays and reduces operational efficiency.

Satellite communication systems, which depend on highly directional antennas, frequently require manual pointing or semi-automated alignment procedures. Although these systems can achieve high data rates and long-range communication, their dependence on manual intervention limits their effectiveness in rapidly changing environments.

Fully automated antenna tracking systems do exist; however, they are often associated with high costs, complex architectures, and significant power requirements. Such systems are typically deployed on high-value platforms such as naval vessels, aircraft, or fixed installations, making them impractical for widespread use in tactical or field-level applications.

This analysis highlights a critical gap in the existing landscape: the absence of afford-

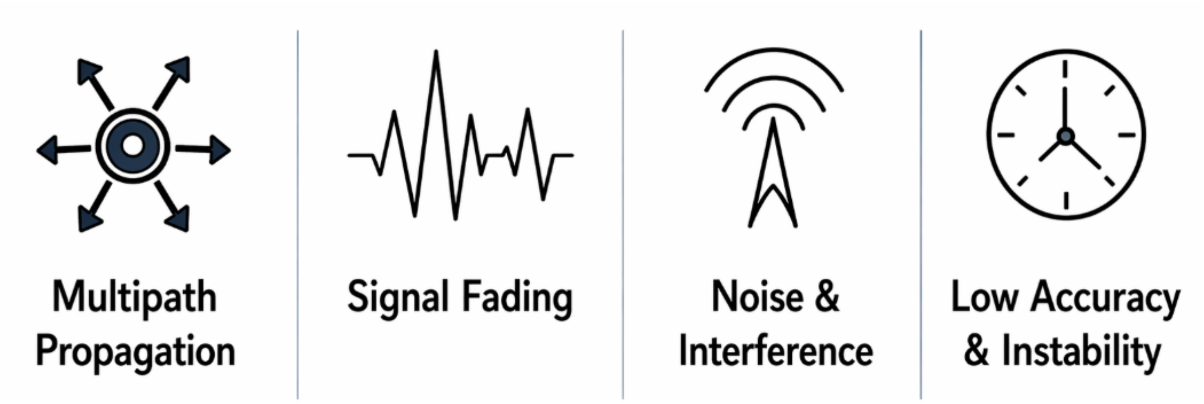


Figure 2.2: Limitations of Existing Tracking Method

able, reliable, and field-deployable automated antenna tracking systems. There is a clear need for solutions that combine simplicity, cost-effectiveness, and robustness while maintaining adequate performance in dynamic environments. Addressing this gap forms a key motivation for the proposed research.

## 2.4 Alternative Sensing Technologies

### 2.4.1 Ultrasonic and Optical Systems

Ultrasonic sensing has been investigated as a potential solution for position tracking and environmental awareness. These systems operate by emitting high-frequency sound waves and measuring the time taken for reflections to return, thereby estimating distance and position. In controlled indoor environments, ultrasonic sensors can achieve relatively high accuracy, making them suitable for applications such as robotics and obstacle detection. However, their effectiveness in antenna tracking applications is severely limited. One of the primary constraints is their short operational range, which typically extends only a few meters. This is insufficient for most communication systems, where the signal source may be located at significantly larger distances. Additionally, ultrasonic sensors are highly sensitive to environmental conditions. Factors such as wind, temperature variations, and ambient noise can distort measurements, leading to unreliable performance[25].

Optical systems, including camera-based tracking methods, offer higher precision and the ability to detect and track visual targets. These systems leverage image processing algorithms to determine the direction of a signal source or object. While effective in certain scenarios, optical approaches introduce substantial computational complexity, requiring powerful processors and advanced algorithms. Moreover, optical systems are heavily dependent on lighting conditions. Performance can degrade significantly in low-light environments, fog, or dust, which are common in field operations. The increased hardware requirements, higher power consumption, and sensitivity to environmental factors make optical systems less suitable for robust, real-time antenna tracking in outdoor and military environments.

### 2.4.2 GPS and IMU-Based Systems

Another approach explored in literature involves the integration of Global Positioning System (GPS) and Inertial Measurement Unit (IMU) sensors for antenna alignment. These systems determine the relative position and orientation of communication nodes and calculate the required antenna direction based on geometric relationships. While this method is theoretically effective, its practical implementation faces several challenges. GPS signals are not always reliable, particularly in urban environments, dense forests, or mountainous regions where signal obstruction is common. Additionally, in military scenarios, GPS signals may be deliberately jammed or spoofed, rendering the system ineffective[27].

IMU sensors, which provide information about orientation and motion, can partially compensate for GPS limitations. However, they are prone to drift over time, leading to cumulative errors in position estimation. Without periodic correction from external references, this drift can result in significant misalignment. Furthermore, the integration of GPS and IMU systems increases overall system complexity, cost, and power consumption. The need for sensor fusion algorithms and continuous calibration further complicates implementation.

Due to these limitations, GPS and IMU-based systems are generally unsuitable as standalone solutions for antenna tracking. They may be useful as supplementary components in hybrid systems but cannot reliably ensure accurate and continuous alignment in all operational conditions.

## 2.5 Signal-Based Tracking Approaches

Signal-based tracking approaches, particularly those relying on radio frequency (RF) signals, have emerged as one of the most practical and widely adopted methods for antenna alignment. Unlike position-based systems that depend on external references such as GPS or inertial sensors, signal-based techniques utilize the communication signal itself as the primary feedback mechanism. This inherent reliance on the received signal makes such systems highly adaptable and directly relevant to the objective of maintaining optimal communication quality. The fundamental principle underlying RF-based tracking is that the received signal strength reaches its maximum when the antenna is optimally aligned with the signal source. By continuously monitoring variations in signal strength and adjusting antenna orientation accordingly, the system can dynamically track the direction of the transmitter. This closed-loop interaction between sensing and actuation allows the system to respond in real time to changes in signal conditions[17].

One of the primary advantages of RF-based tracking systems is their independence from external positioning infrastructure. Since alignment decisions are based solely on the received signal, these systems remain functional even in environments where GPS signals are unavailable, unreliable, or intentionally disrupted. This makes them particularly suitable for military and field applications where robustness and autonomy are critical. Another significant advantage is real-time adaptability. RF-based systems inherently account for environmental factors such as interference, reflection, and attenuation because these effects are directly reflected in the signal strength measurements. As a result, the system continuously adapts to actual propagation conditions rather than relying on theoretical models or predefined assumptions. Additionally, RF-based approaches typically require relatively simple hardware configurations. Most communication modules provide RSSI or equivalent signal strength indicators, eliminating the need for additional sensing hardware. This reduces system complexity, cost, and power consumption, making such solutions attractive for embedded and portable applications.

Despite these advantages, RF-based tracking systems face several challenges that limit their performance. Signal noise and fading are among the most significant issues. In real-world environments, RF signals are subject to fluctuations caused by interference, thermal noise, and atmospheric effects. These fluctuations can lead to incorrect alignment decisions if not properly filtered.

Multipath propagation presents another major challenge. Signals often reflect off surfaces such as buildings, terrain, and obstacles, creating multiple signal paths that interfere with each other. This can result in multiple local maxima in signal strength, making it difficult for the system to identify the true direction of the source. Furthermore, distinguishing between true signal peaks and temporary fluctuations is inherently difficult in RF-based systems. Without appropriate filtering and decision-making mechanisms, the system may lock onto suboptimal directions or exhibit unstable behavior.

To address these limitations, recent research has focused on integrating filtering techniques and adaptive algorithms into signal-based tracking systems. Methods such as moving average filtering, Kalman filtering, and adaptive thresholding have been proposed to stabilize signal measurements and improve tracking accuracy. These enhancements enable more reliable performance in noisy and dynamic environments.

## Transition Toward Infrared (IR)-Based Tracking

While RF-based methods provide a strong foundation for signal tracking, their limitations in terms of noise sensitivity and multipath effects have motivated the exploration of alternative sensing modalities. One such approach involves the use of Infrared (IR) sensing for directional detection and alignment.

Infrared-based tracking systems operate on the principle of detecting IR radiation emitted or reflected by a source. Unlike RF signals, IR signals are less susceptible to multipath interference and typically exhibit more predictable propagation characteristics over short distances. This makes them particularly suitable for controlled environments or applications where line-of-sight conditions can be maintained. The transition toward IR-based tracking in this project is driven by several practical considerations. First, IR sensors provide more stable and localized detection compared to RF signals, reducing the impact of environmental noise. Second, IR modules are relatively inexpensive and easy to interface with microcontrollers, aligning with the objective of developing a cost-effective system. Third, IR-based systems simplify signal interpretation, as the detection mechanism is often binary or intensity-based, reducing computational complexity. However, it is important to acknowledge that IR systems also have limitations. Their performance is highly dependent on line-of-sight conditions and can be affected by obstacles, ambient light, and environmental factors. As a result, IR-based tracking is most effective in scenarios where the signal source is within operational range and visibility is not obstructed[24].

In the context of this project, the shift toward IR-based sensing represents a strategic design decision aimed at improving system stability, reducing complexity, and enhancing practical feasibility. The integration of IR sensing with adaptive control mechanisms forms a hybrid approach that addresses many of the limitations observed in purely RF-based systems.

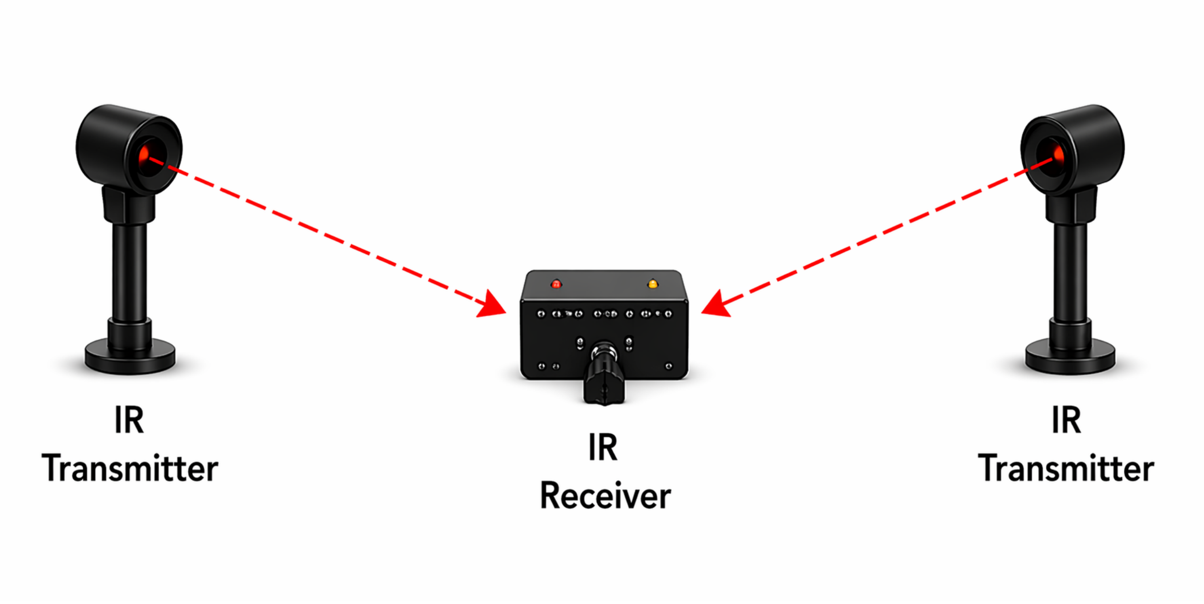


Figure 2.3: IR Based Tracking Principal

## 2.6 Control System Architectures

The effectiveness of an antenna tracking system is not solely determined by its sensing mechanism but also by the architecture of its control system. The control system is responsible for processing sensor data, making decisions, and actuating mechanical components to achieve optimal alignment. A well-designed control architecture ensures accurate, stable, and efficient system performance, particularly in dynamic environments[13].

Control system architectures for antenna tracking systems typically involve a combination of embedded hardware platforms and algorithmic strategies. These components must be carefully selected and integrated to balance performance, complexity, and resource constraints[27].

### 2.6.1 Microcontroller-Based Systems

Microcontrollers play a central role in modern antenna tracking systems, serving as the primary processing units that coordinate sensing, decision-making, and actuation. Widely used platforms include Arduino, ESP32, and Raspberry Pi, each offering distinct advantages and limitations.

The Arduino platform is known for its simplicity, ease of use, and extensive community support. It is particularly suitable for basic control tasks and rapid prototyping. However, its limited processing power and memory restrict its ability to handle complex algorithms or high-speed data processing. As a result, Arduino-based systems are typically used in applications where computational demands are relatively low.

In contrast, the Raspberry Pi provides significantly higher processing capabilities, supporting advanced algorithms, multitasking, and even operating systems. This makes it suitable for complex applications such as image processing or machine learning-based tracking. However, these advantages come at the cost of higher power consumption, increased system complexity, and potential thermal management issues. These factors may limit its suitability for battery-powered or field-deployable systems.

The ESP32 platform represents a balanced alternative, offering moderate processing power, integrated wireless communication capabilities, and relatively low power consumption. Its dual-core architecture and support for real-time applications make it well-suited for embedded control systems that require both performance and efficiency.

The selection of a microcontroller platform depends on several factors, including processing requirements, power availability, system complexity, and cost constraints. In practical implementations, a trade-off must be made between computational capability and resource efficiency to achieve an optimal design.

### 2.6.2 Algorithmic Approaches

The performance of an antenna tracking system is heavily influenced by the algorithms used for decision-making and control. Various algorithmic approaches have been proposed in literature, each with its own strengths and limitations.

Gradient-based optimization methods attempt to find the direction of maximum signal strength by following the gradient of the signal function. While mathematically robust, these methods require continuous and accurate gradient estimation, which can be challenging in noisy environments.

Pattern search methods, including techniques such as hill climbing and iterative search, rely on evaluating signal strength at discrete positions and moving toward higher values. These methods are relatively simple and do not require complex mathematical models, making them suitable for embedded systems.

Threshold-based logic represents one of the simplest approaches, where decisions are made based on predefined signal levels. While easy to implement, this method lacks adaptability and may perform poorly in dynamic environments.

Adaptive algorithms introduce mechanisms for adjusting system behavior based on changing conditions. These may include adaptive step sizes, dynamic thresholds, or self-tuning control parameters. Such approaches offer improved performance but increase computational complexity and implementation difficulty[35].

A key observation across the literature is the inherent trade-off between algorithmic complexity and real-time reliability. Complex algorithms may provide higher accuracy and better optimization capabilities but require significant computational resources and may introduce delays. On the other hand, simpler algorithms are more robust, faster, and easier to implement but may sacrifice precision. For embedded antenna tracking systems, particularly those intended for practical deployment, this trade-off must be carefully managed. In many cases, a well-designed simple algorithm can outperform a complex one when factors such as noise, resource constraints, and real-time requirements are considered.

## 2.7 Research Gaps

A rigorous and critical examination of the existing body of literature on antenna tracking and positioning systems reveals a number of persistent and significant gaps that limit the practical applicability, scalability, and reliability of current solutions. Although substantial progress has been achieved in theoretical modeling, algorithmic innovation, and simulation-based performance evaluation, there remains a clear disconnect between academic research and real-world deployment. This gap is particularly evident in applications requiring robustness, adaptability, and operational reliability, such as military communication and field-based wireless systems. Consequently, there is a strong need for research that moves beyond idealized assumptions and focuses on practical implementation, system-level integration, and real-time performance under dynamic conditions[26].

One of the most prominent deficiencies in the literature is the lack of practical implementation and hardware validation. A considerable proportion of existing studies rely heavily on simulations or controlled laboratory experiments to demonstrate system performance. While these approaches are essential for initial validation, they often fail to capture the complexities and uncertainties associated with real-world environments. Factors such as hardware nonlinearities, sensor inaccuracies, signal fluctuations, and mechanical limitations are frequently neglected or oversimplified. As a result, systems that appear highly effective in simulation often exhibit degraded or unstable performance when implemented physically. This highlights a critical need for research that prioritizes end-to-end system realization, including hardware design, integration challenges, and experimental validation in realistic conditions[10].

Another major gap lies in the limited environmental adaptability of existing systems. Real-world communication environments are inherently complex and unpredictable, influenced by factors such as multipath propagation, electromagnetic interference, atmospheric attenuation, and physical obstructions. Many antenna tracking solutions are developed under ideal or semi-ideal conditions, assuming stable signal behavior and minimal noise. Such assumptions do not hold in practical scenarios, particularly in outdoor or battlefield environments. Consequently, these systems lack the capability to dynamically adapt to changing signal conditions, leading to reduced accuracy, instability, or complete failure. The absence of robust adaptive mechanisms that can respond effectively to environmental variability remains a significant limitation in current research[29].

The high cost and complexity of advanced antenna tracking systems further restrict their practical adoption. State-of-the-art solutions, especially those developed for military or aerospace applications, often incorporate high-precision sensors, advanced control architectures, and sophisticated signal processing techniques. While these systems achieve high levels of accuracy and performance, they are typically associated with substantial financial and computational costs. This makes them unsuitable for widespread deployment, particularly in resource-constrained environments or at the tactical level. There is a clear need for cost-effective solutions that maintain an acceptable level of performance while reducing system complexity and resource requirements. Achieving this balance between performance and affordability remains a key challenge[16].

A further limitation identified in the literature is the lack of holistic system integration. Many research efforts tend to focus on isolated components of the antenna tracking system, such as sensing techniques, control algorithms, or mechanical design, without adequately addressing their interaction within a complete system. However, the overall performance of an antenna tracking system depends critically on the seamless integration of these subsystems. In practice, issues such as synchronization between sensing and actuation, signal processing delays, mechanical backlash, and power management can significantly affect system behavior. The absence of comprehensive, system-level design approaches results in fragmented solutions that may perform well individually but fail to deliver reliable performance when combined. This underscores the importance of integrated design methodologies that consider the entire system as a cohesive unit[30].

In addition to these challenges, limitations in testing methodologies represent another critical gap. Experimental validation in many studies is conducted under simplified and controlled conditions that do not accurately reflect real-world scenarios. Common limitations include the use of static signal sources, short-duration testing, and absence of environmental disturbances. Such testing approaches fail to evaluate system performance under dynamic conditions, such as moving transmitters, fluctuating signal strength, or varying environmental factors. Moreover, long-term reliability and robustness are rarely assessed, leaving uncertainty regarding system performance over extended periods of operation. The lack of realistic and comprehensive testing frameworks reduces the credibility and generalizability of reported results.

Furthermore, there is a noticeable gap in the development of simplified yet robust control strategies. While advanced algorithms such as machine learning and complex optimization techniques have been explored, their implementation often requires significant computational resources and introduces additional system complexity. In contrast, simpler algorithms, although easier to implement, may lack the sophistication required to handle noisy and dynamic environments effectively. The challenge lies in designing control strategies that strike an optimal balance between computational efficiency, robustness, and real-time responsiveness.

Collectively, these gaps highlight a fundamental issue in the current state of research: the emphasis on theoretical performance often outweighs considerations of practical deployment. There is a clear need for solutions that are not only technically sound but also feasible, reliable, and adaptable in real-world conditions. Addressing these challenges requires a shift toward integrated system design, cost-effective implementation, and rigorous experimental validation.

The present research is motivated by these identified gaps and aims to contribute toward bridging the divide between theoretical development and practical application. By focusing on system integration, real-time adaptability, and experimental validation, this work seeks to develop an antenna tracking solution that is both effective and deployable in dynamic environments.

## 2.8 Proposed Contribution

In response to the limitations identified in the literature, this project aims to contribute a comprehensive and practically viable solution for adaptive antenna positioning. The proposed work is designed not only to address individual technical challenges but also to provide an integrated system that bridges the gap between theoretical research and real-world application[16].

The primary contribution of this project is the development of a fully integrated adaptive antenna positioning system. Unlike many existing approaches that treat system components independently, this work emphasizes a cohesive architecture that combines sensing, control, and mechanical actuation into a unified framework. This integration ensures coordinated operation and enhances overall system reliability.

A key feature of the proposed system is the implementation of a closed-loop signal-based tracking mechanism. By continuously monitoring signal strength and adjusting antenna orientation accordingly, the system achieves real-time adaptability to changing conditions. This approach eliminates dependence on external positioning systems and ensures that alignment decisions are based on actual communication performance.

Another important contribution is the design of a cost-effective and practical solution using commercially available components. The system is intentionally developed using accessible hardware platforms and standard modules, making it feasible for deployment beyond high-budget environments. This focus on affordability addresses one of the major gaps identified in existing research and promotes wider applicability[15].

The project also introduces a robust incremental optimization algorithm for antenna positioning. Instead of relying on complex mathematical models, the algorithm employs a step-by-step approach to evaluate signal variations and determine optimal movement. This strategy enhances system stability, reduces computational requirements, and improves performance in noisy environments.

Furthermore, the proposed system undergoes validation through real-time testing with dynamic signal sources. Unlike many studies that rely on static or simulated conditions, this project emphasizes practical experimentation to evaluate system behavior under realistic scenarios. This approach ensures that the results are representative of actual operational conditions and enhances the credibility of the findings.

Overall, the contributions of this project are characterized by a strong emphasis on practicality, simplicity, and reliability. By addressing the key limitations identified in the literature, the proposed work aims to deliver a solution that is not only technically sound but also suitable for real-world deployment in dynamic and resource-constrained environments[30].

## 2.9 Chapter Summary

This chapter presented a detailed and critical review of existing research related to antenna tracking and positioning systems. The discussion traced the evolution of these systems from early manual alignment methods to advanced automated and control-based approaches. Various techniques, including RSSI-based tracking, closed-loop control systems, alternative sensing technologies, and modern control architectures, were examined in depth.

The analysis revealed that, despite significant advancements, current solutions face several limitations. Many systems lack practical implementation, fail to adapt to real-world environmental conditions, or are too complex and costly for widespread deployment. Additionally, the absence of integrated system design and comprehensive testing methodologies further limits their applicability.

Based on this critical evaluation, a clear need has been established for antenna tracking systems that are not only technically effective but also practical and deployable. Such systems must be capable of operating reliably in dynamic environments while maintaining simplicity and cost efficiency.

The insights gained from this literature review define the key requirements for an effective solution. Specifically, the system must be:

- Adaptive, to respond to changing signal conditions[20]
- Reliable, to ensure consistent performance under varying environments[22]
- Cost-effective, to enable practical deployment[29]
- Field-deployable, to operate efficiently in real-world scenarios[27]

The proposed research addresses these requirements by integrating signal-based tracking with efficient control mechanisms and a robust system architecture. This foundation sets the stage for the methodology presented in the next chapter, where the design and implementation of the proposed system are described in detail.

# Chapter 3

# METHODOLOGY

## 3.1 System Methodology

In this chapter, the author describes a systematic approach to designing and implementing a Radar and Infrared (IR) based Antenna Positioning System using a two-axis turntable mechanism that is operated by using stepper motors. The main aim of this system is to obtain automated signal detection, tracking and centering of a radar or antenna unit towards the direction of the strongest signal received. This design is meant to be used in dynamic communication where manual alignment of the antennas is inefficient, imprecise, and cannot respond to real time changes in the direction of a signal.

In contemporary communication systems, particularly when used in applications like surveillance, wireless tracking and military communication systems, it is imperative to have a consistent and quality signal connection. Nonetheless, the conventional antenna placement tools are more based on manual placement, which incorporates delay, human error, and inflexibility to dynamic environments. Conversely, the suggested system will remove manual control by constantly scanning the local area and automatically pointing the antenna at the most powerful source of signal.

This system works with a mix of radar detection and infrared (IR) based directional feedback, combined with a stepper motor-powered dual-axis turntable. The radar module will identify the presence of signals and their approximate direction at a long distance. At the same time, the IR receiver and transmitter couple is employed to improve directional precision by ensuring short-range alignments. The hybrid sensing technique is able to cover and track the signal with accuracy.

The main principle of work of the system is the principle of continuous angular scanning. The stepper motor steps the radar and the antenna assembly in tiny steps in a full 360-degree direction. The system measures the received signal strength and IR response at every angular position. These values are compared against each other in real time, to identify the direction with the strongest signal. When the best direction of the signal is found, the system pauses rotation and points the antenna to the best direction, temporarily.

Upon alignment, the system holds the position momentarily to stabilize the system and guarantees signal lock and measurement accuracy. After the stabilization process is finished, the system resumes scanning to keep checking signal direction changes in the system. This enables the system to dynamically monitor the moving signal sources and is therefore applicable in the context of mobile communication where the position of the transmitters and receivers can switch between various positions.

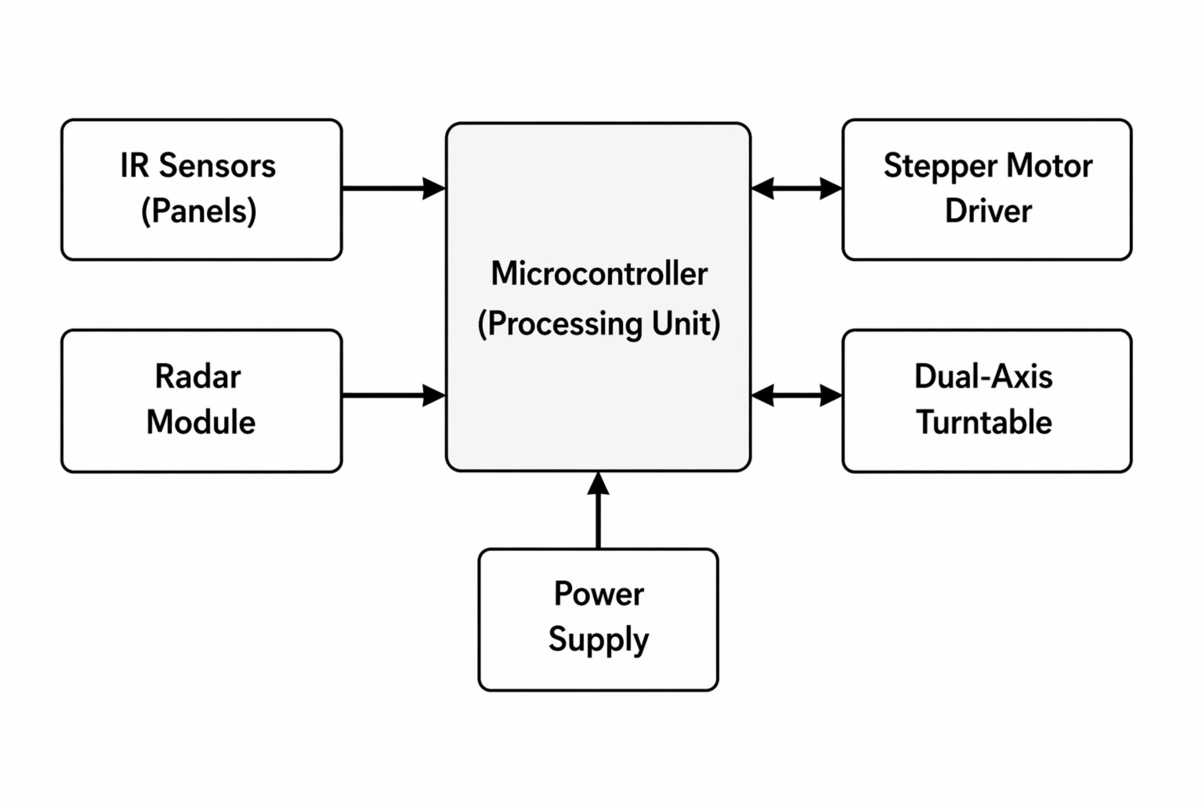


Figure 3.1: Overall System Architecture

The stepper motor is essential in making sure that the angular motion of the dual axis turntable is accurate. Stepper motors, unlike conventional motors, provide the ability to adjust the incremental rotation, and they are therefore suitable in applications that involve scanning where precision is a critical concern. The dual-axis mechanism also facilitates flexibility since it offers both horizontal and vertical mobility which results in the ability of the system to cover the whole space.

On the whole, this system is a feasible execution of an intelligent scanning and alignment system, which is founded on real-time signal analysis. It integrates sensing, mechanical control, and feedback-based decision-making into a single system that has a significant effect on enhancing communication reliability and decreasing reliance on manual intervention.

## 3.2 General Design Strategy

The general system design approach that I followed is as follows:

The general design strategy of the proposed Radar and Infrared (IR) based Antenna Positioning System relies on a systematic approach to engineering that merges theoretical knowledge, hardware choice, circuit integration, and the creation of algorithms. The system is developed so that each functional unit is designed and then tested separately and then it is integrated to a complete working prototype. The step-by-step and modular design strategy has reliability, easiness in debugging and better performance of the system in real-life scenarios.

The design approach entails system definition and requirement analysis in the first phase. The operational objectives of the system are well defined in this stage, which are automatic identification of signal direction, real-time identification of the strongest signal, and accurate pointing of the antenna with a motor-controlled dual-axis turntable. The system must be capable of working in a scanning mode continuously and dynamically respond to signal intensity and direction changes. This is what underlies the choice of suitable sensors, actuators, and processing units.

The second phase is concerned with hardware component choice after defining system requirements. During this stage, the important parts like radar modules, pairs of infrared transmitters and receivers, stepper motors, motor driver circuits, and an appropriate microcontroller or control unit are chosen. The radar module is selected because it has the potential of detecting objects or sources of signals at a relatively long distance and give direction information. The IR sensor system has been chosen to enhance the short-range directional accuracy as a measure of sensing the reflection or transmission alignment of infrared. The choice of stepper motors is based on their capability of linear movement through angular steps that are important in ensuring controlled scanning and positioning of turntable in dual axis.

Mechanical design of the dual-axis turntable system is the third stage. The structure is made to enable a horizontal (azimuth) and vertical (elevation) rotational movement. This platform has the antenna or radar sensor and is powered by stepper motors. The mechanical design is well designed to allow easy rotation, less friction and support of the mounted sensors.

It is also taken into account that the structure should be balanced correctly to prevent vibration during movement since any slight mechanical disturbance may influence the accuracy of signal measurements.

The fourth phase is on circuit integration and interfacing. During this stage, all the sensors and actuators are attached to the central control unit. The radar and the IR sensors are connected as an input device and feeds a continuous stream of environmental and signal information. The stepper motors are wired together via motor driver circuits that transform low-power control signals into high-power actuation signals needed to move. Electrical isolation and regulation of the voltage is also done appropriately to ensure that the system is stable and avoids damage to hardware.

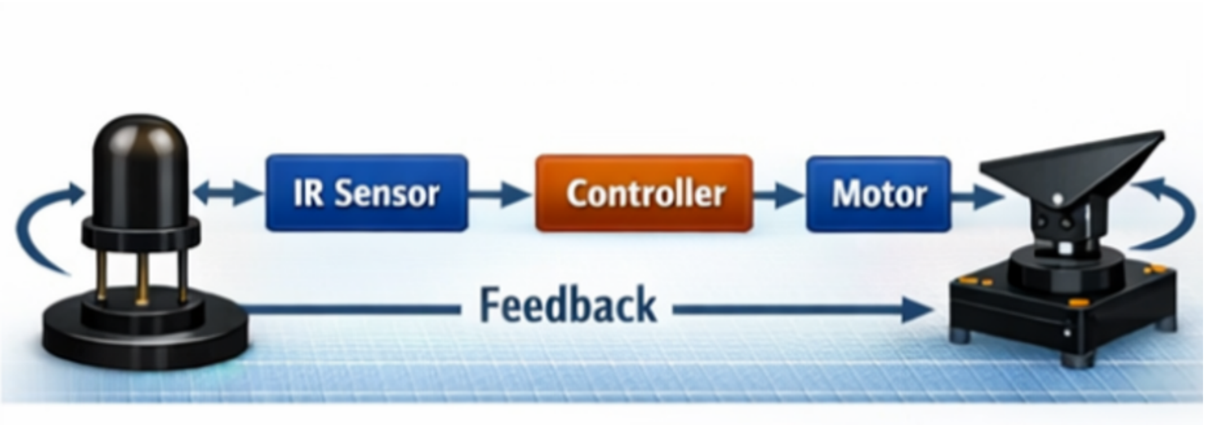


Figure 3.2: Mechanical Positioning System

The fifth phase is the algorithm development and control logic design. A control algorithm that is based on scanning is applied in this system. The stepper motor spins the system around a 360 degree range in small angular movements. The system captures the signal strength and IR feedback values at every position. These values are kept and compared to identify the angle of the strongest signal. When it is detected, the system sends the motor to point the antenna to that direction exactly and momentarily fix the position. Once stabilized, the scanning process is repeated over and over. This control mechanism is based on loop such that it can adjust to varying signal environments in real-time.

Simulation and preliminary testing is the sixth stage. Controlled tests are performed on individual components and control logic before the entire hardware system is implemented. The behavior of the signal, motor response, and sensor readings are examined to ascertain the proper functioning. This phase aids in the detection of flaws in design early, and an optimization of system parameters including step size, scanning speed, and signal threshold levels.

Lastly, the integration and validation phase is where all subsystems are integrated into a fully functional model. The control unit, the stepper motors, the radar and the IR sensors all work in a single unit. The evaluation is done in terms of accuracy of the alignment, the response time and stability of tracking the signal. Any deviations seen when testing are remedied through control algorithm refinement or hardware parameter modification.

In general, system design approach is systematic and iterative in approach that makes sure the development of the entire antenna positioning system is gradual, tested and optimized. Such an organized method does not only enhance the reliability of the system, but it also makes sure that the end result can be adapted to the real time applications of the adaptive signal tracking in a dynamic environment.

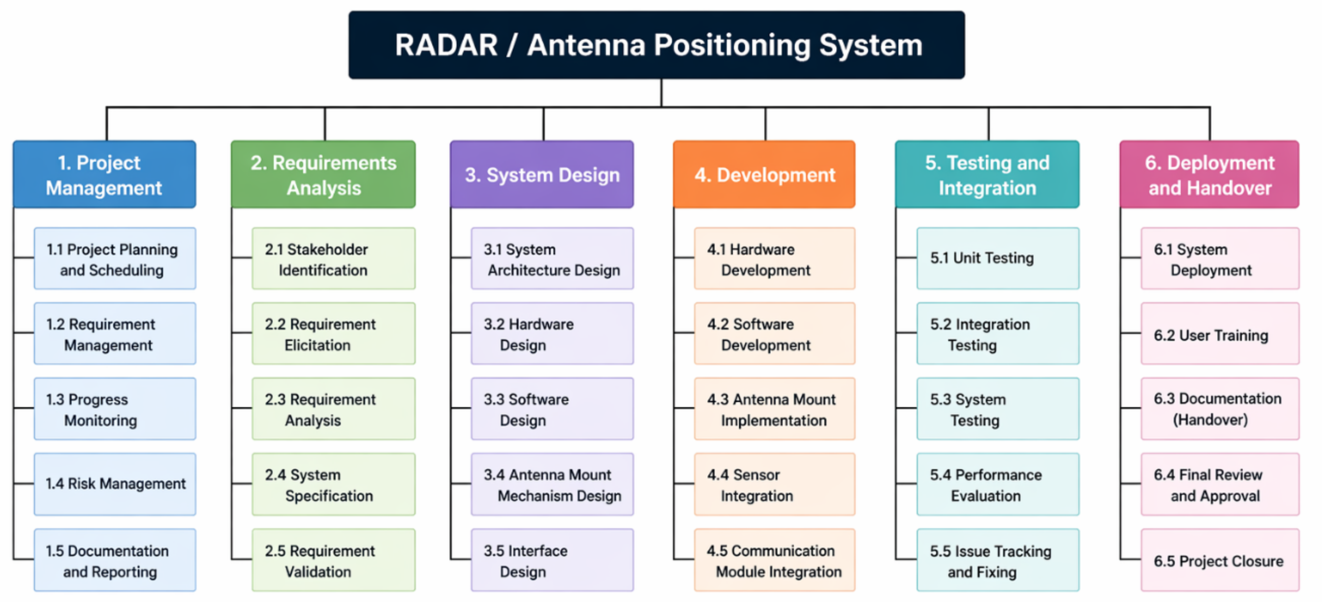


Figure 3.3: Work BreakDown Structure(WBS)

## 3.3 System Architecture

The proposed Radar and Infrared (IR) based Antenna Positioning System system architecture is a structured, layered and modular architecture which incorporates sensing, processing, control, and actuation units into one unified cooperating system. The primary objective of this architecture is to provide effective communication among the hardware components and be real-time responsive, highly accurate, and stable. The modules are designed in a manner that every module does a particular task and the modules are connected in a closed-loop system to operate and align the antenna automatically towards the strongest signal source.

On a higher level, the system architecture can be subdivided into four primary layers: the sensing layer, the processing layer, the control layer, and actuation layer. These layers are interrelated with the help of a feedback mechanism which constantly adjusts the behavior of the system in accordance with the real-time environmental and signal conditions.

The architecture starts with the sensing layer which has the responsibility of sensing the presence and direction of the communication signals. This layer is composed of two key sensing units: the radar unit and infrared (IR) transmitter/receiver unit. The radar module works as a main detector component, which scans the surrounding environment to detect any possible sources of signals and give approximate directional data. It is able to resolve objects or signal reflections with a large range and is thus appropriate in initial rough alignment. The radar is complemented by the IR sensor system, which offers more accurate short-range directional feedback, useful in fine tuning the alignment procedure in final positioning.

After the sensing data is received, it is relayed to the processing layer which is the decision-making centre of the system. It is a layer normally implemented on a microcontroller or embedded processing unit. The raw sensor data is passed to the processing unit which carries out the necessary functions which include signal filtering, noise removal and signal strength measurement. The Received Signal Strength Indicator (RSSI) which is the quality and the strength of the signal received is one of the most crucial parameters calculated at this stage. The processing unit constantly compares values of RSSI at the various angular positions to identify the best direction to align the antenna.

The sensor data is processed and then transferred to the control layer, which makes decisions and executes scanning logic. This layer executes an angular scanning algorithm step-by-step. The stepper motor turns the antenna and radar assembly in a step-by-step manner over a specified angular path, which is usually 0 to 360 degrees. Each step of the system logs the signal strength and compares it to the values stored. The control logic finds the angle to which the strongest signal is received and chooses it as the target direction to align. This layer is basically the brain of the system and is the one which translates processed data into actionable movement decisions.

The last layer is the actuation layer where the antenna system is physically moved. This tier is made up of stepper motors and a dual axis turntable. The processing unit sends control signals to the stepper motor that moves the antenna in angular steps. The dual-axis design permits both horizontal (azimuth) and vertical (elevation) motion to cover all areas of space and provide a high level of precision in positioning. After determining the best direction, the actuation system will move the antenna to this direction and maintain it still a few moments to get a stable signal.

One important characteristic of this architecture is that it has a closed-loop feedback system. Once the antenna is placed, the system will keep checking the signal strength and sensor feedback. In case any change in the direction or intensity of the signal is observed, the system will restart the scanning process and will change the position of the antenna accordingly. Such a cycle of feedback makes the system dynamic and flexible in response to changes in the environment.

The system architecture is generally designed in such a manner that it is modular, scalable, and efficient. All layers are autonomous yet closely connected with each other with real-time data sharing. The design enables the system to be configured to perform automatic signal tracking, accurate antenna positioning and stable communication operation, which is appropriate in real time application in dynamic and unpredictable environments.

## 3.4 Radar-Based Detection Mechanism

The principle of operation of the proposed Radar and Infrared (IR) based Antenna Positioning System is that of constant scanning, detection, comparison and alignment. The system will use a stepper motor to automatically rotate a dual-axis turntable and identify signal strength in various directions, and ultimately point toward the direction receiving the strongest signal. The whole process is closed-loop, i.e. the system constantly checks environmental factors and then adjusts the positioning of the antennas in real-time.

When the system is switched ON and started, the operation starts. Here, the microcontroller individually reset all the sensors, set the stepper motor driver, and position the antenna or radar module to a starting position. The system then goes into scanning mode where the stepper motor starts moving the dual-axis turntable in small, controlled angular movements. These steps are well established to ensure that the system is able to move around in 360 horizontal rotation, and remain stable and accurate.

In this scanning process, the radar module sends constant signals and gets reflections or signal responses of the surrounding. Meanwhile, the IR transmitter and receiver couple actively analyses directional alignment, by monitoring the change in infrared signal intensity. Every angular position is associated with a distinct set of sensor data, comprising of radar response, IR feedback, and received signal strength indicator (RSSI) values.

The system conducts signal evaluation at each rotation. The microcontroller captures the signal strength at that particular angle and it is saved in the memory to be compared. This is repeated as long as each step of the stepper motor moves. Consequently, the system constructs a complete map of the signal strength distribution throughout the scanning range. This mapping enables the system to identify the direction that has the most powerful communication signal.

When the scanning cycle is over, the system goes into decision-making. During this step, the comparison of all the signal strength values recorded is performed and the highest value is determined. The angle that is attached to this maximum signal strength is viewed as the optimum direction in which the antenna should be aligned. This choice is made mainly by the values of RSSI, with the aid of radar detection and confirmation of the IR sensor to enhance the accuracy and minimize false detection.

Once the best direction has been identified, the stepper motor is instructed to turn the dual-axis turntable in the direction of the chosen angle. The radar or the antenna physically turns and points towards this direction. When alignment is reached, the system halts temporarily and goes into a hold or stabilization state. In this stage, the system holds the antenna position a couple of seconds to allow stable signal reception and minimize mechanical vibrations/ variations.

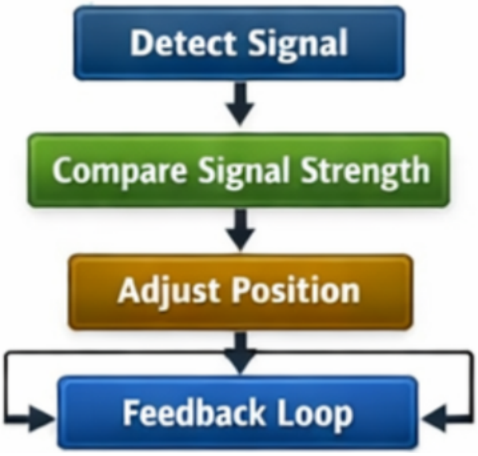


Figure 3.4: Adaptive Control Algorithm Flowchart

Once the system is stabilized, it does not cease. Rather, it goes back into the scanning mode and constantly measures signal direction changes. This is significant since in the real world, the sources of signals like mobile transmitters, drones or communication nodes can travel often. The system should thus keep on changing its alignment to ensure that it receives signals optimally.

Stepper motor is an important part of this mechanism since it offers the angular control with high accuracy. Every pulse dispatched to the motor can be a fixed step in rotation, which means that it could be moved accurately and repeatedly. The two-axis turntable additionally increases the capability of the system as it can move in a horizontal and vertical direction; therefore, it is fully able to track in space.

Another level of precision is the IR sensor system, which helps fine tune the system. Radar gives a more general directional detection but the IR sensors are used to verify the precise alignment in close positioning. This radar and IR combination is guaranteed to provide a large coverage as well as high accuracy in directional tracking.

In general, the system operates on a loop-like work cycle of scanning, sensing, comparing, aligning and re-scanning. This dynamic action enables the system to automatically follow the strongest signal direction without interference of humans. The combination of the stepper motor control, radar detection, IR sensing and signal strength analysis makes the system very efficient in real-time situations, hence very suitable in adaptive communication applications.

## 3.5 Control Logic and Algorithm

The intelligence of the entire design of proposed Radar and Infrared (IR) based Antenna Positioning System is the control logic and algorithm. This section will specify the way the system makes decisions by looking at sensor readings, how the system scans the surroundings, how it identifies the strongest signal direction and how it will control the stepper motor to ensure a precise antenna alignment. The algorithm is made to be easy to understand, dependable and real-time responsive to ensure it can work efficiently in the dynamic communication setting without involving complex computations.

The mechanism on which the system works is based on a sequential scanning and feedback based decision-making mechanism. The main aim of the algorithm is to rotate the antenna system with a stepper motor continuously, measure signal strength at each of the angular positions, compare all the readings and in the end, position the antenna in the direction where the strongest signal is received.

### Flow Chart

**Step 1: System Initialization**

The system is started at the beginning of the process. During initialization:

- Sensors (radar module and IR transmitter/receiver) are turned on.
- The control unit or microcontroller reboots past information.
- Stepper motor is positioned to a reference angle (0 degrees).
- Signal value memory registers are cleared.

This ensures that each scanning cycle starts from a known and stable reference point.

**Step 2: Angular Scanning Process**

Once initialized, the system enters scanning mode. The stepper motor rotates the dual-axis turntable in fixed angular steps. For example, the system may move in steps of 5 or 10 degrees depending on required accuracy.

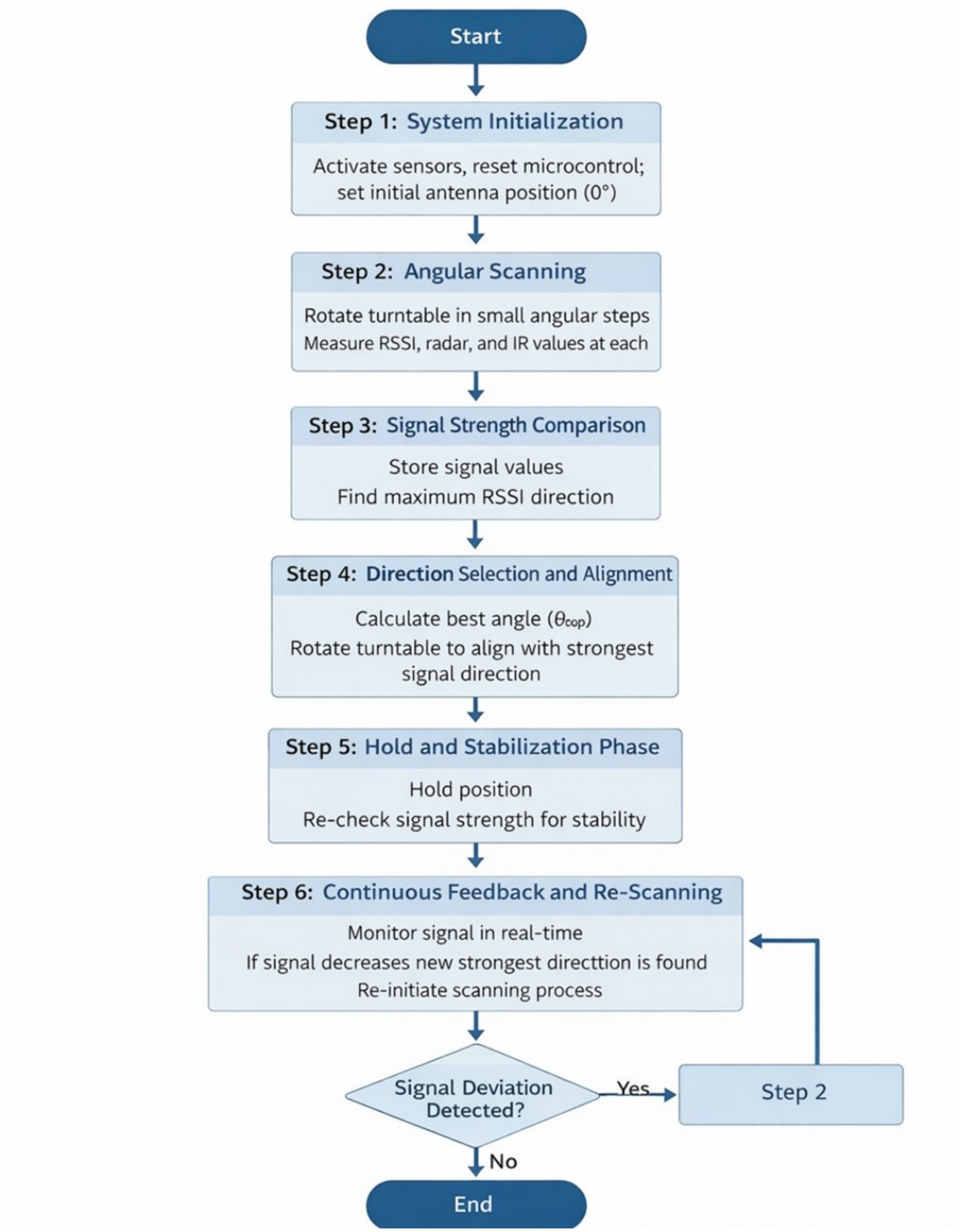


Figure 3.5: Flowchart

At every angular position ($\theta$), the system performs the following:

- Reads signal strength value (RSSI or similar signal level).

- Checks radar detection feedback.
- Reads directional response from IR sensor.
- Stores measured value along with corresponding angle.

This process continues until a full 360-degree scan is completed.

**Step 3: Comparison of Signal Strength**

After completing a full scanning cycle, the system compares all stored signal strength values. The algorithm identifies the maximum value among all recorded readings.

Mathematically:

$$\max\left(RSSI(\theta)\right), \quad \theta \in [0, 360^\circ]$$

The angle corresponding to this maximum value is selected as the optimal direction for antenna alignment.

To improve reliability, multiple readings at each angle can be averaged to reduce noise and environmental interference.

**Step 4: Alignment and Direction**

After determining the strongest signal direction, the system enters alignment mode. The stepper motor rotates the antenna toward the selected angle.

This process includes:

- Determining the shortest rotation path.
- Driving the motor using step pulses.
- Rotating the dual-axis turntable to the target angle.
- Stopping when exact alignment is reached.

This ensures that the antenna is physically aligned with the strongest signal source.

**Step 5: Hold and Stabilization Phase**

After reaching the target direction, the system enters a stabilization phase:

- The motor is stopped.
- The antenna position is held fixed.
- Signal strength is rechecked for stability.

This step reduces errors caused by mechanical vibrations or temporary fluctuations in signal measurements.

**Step 6: Re-Scanning and Continuous Feedback**

The system continuously monitors signal variations. If any of the following occurs:

- Signal strength drops significantly.
- A stronger signal is detected in another direction.
- Movement of signal source is detected.

The system automatically reinitiates the scanning process. This forms a closed-loop control system where output (antenna position) is continuously adjusted based on input feedback (signal strength and sensor data).

## Algorithm Summary (Simple Form)

1. Start system and initialize sensors.
2. Rotate stepper motor in small angular steps.
3. Record RSSI, IR, and radar values at each angle.
4. Store values with corresponding angles.
5. Determine maximum signal strength.
6. Align antenna to optimal direction.
7. Hold position for stabilization.
8. Repeat scanning continuously.

## 3.6 Motor Mechanism and Dual-Axis Turntable

The physical movement and positioning unit of the proposed Radar and Infrared (IR) based Antenna Positioning System is the motor mechanism and the dual axis turntable. This subsystem transforms electrical control signals into an accurate mechanical movement to enable the antenna or radar module to turn and point towards the direction of the strongest signal detected. The performance of this mechanical assembly is crucial to the overall system in terms of accuracy, stability and responsiveness.

The actuation mechanism is a stepper motor based system, which has been chosen because it allows angular control to be made precise, without the need to have complex feedback mechanisms. A stepper motor, in contrast to traditional DC motors, is a motor that moves in discrete steps, with each pulse of the input signal associated with a known angular motion. This renders it very viable in scanning applications where movement to be controlled and repeatable is necessary. The system can precisely determine the rotational position of the antenna by regulating the number of pulses sent to the driver of the motor.

The stepper motor will be attached to a dual axis turntable design in the proposed design and will ensure that the motor is moved both in the horizontal (azimuth) and the vertical (elevation) directions. This two-axis feature is very useful as it provides more flexibility to the system since it allows complete coverage of the surrounding space. The horizontal axis performs 360 degree rotation, whereas the vertical axis enables uplift and downward movement of the antenna or radar module, which is important in ensuring the correct targeting in three dimensional space.

The mechanical design of the dual-axis turntable is to give it stability and fluency. It generally has a base platform, rotating joinings, mounting brackets, and gear/coupling mechanisms which transmit the motor torque to the antenna assembly. Mechanical alignment is also very important since any imbalance or vibration will directly influence the signal detection error and result in faulty alignment choices.

The microcontroller or processing unit sends control signals to the stepper motor in the form of pulse sequences. These pulses are produced according to the control algorithm in the above section. The motor is actuated in each pulse by a fixed step angle, enabling the system to scan the environment fine grained. As an example, when a motor has a step angle of 1.8° the system can provide high-resolution scanning. Additional steps can be divided using microstepping techniques.

A key addition that has been applied in this system is microstepping to enhance smoothness and precision of movement. The motor is not moved in complete steps, but in smaller fractional steps, minimizing vibration, and enhancing positioning accuracy. It is especially critical in those antenna alignment systems where any angular error may cause severe signal loss.

The subsystem of motor driver circuit is very important. It serves as a connector between the low power control signals of the microcontroller and high power needs of the stepper motor. The driver makes sure that there is enough current flowing to the coils of the motor in the proper sequence, allowing the rotation to be controlled. It also offers safeguard against voltage spikes and overloads ensuring safe and reliable operation.

The turntable has two axes which are synchronized mechanically with the motor control system. The horizontal axis generally performs the continuous scan on the signal detection stage and the vertical axis may be stationary or move depending on the signal elevation needs. Both axes may be operated together in advanced mode, to provide three-dimensional tracking of moving signal sources.

In operation, the motor mechanism moves step-by-step over a given angular range in a scanning cycle. The system measures the signal strength and sensor feedback at every position. When the best signal direction has been determined, the motor will instantly turn the turntable to that direction and keep it stationary. This ensures that the antenna is always oriented in the ideal direction of communication.

Other factors considered in mechanical design include load balancing, reduced friction, and structural rigidity. The antenna or radar module is attached on the rotating platform; therefore, unbalanced weight may result in instability during rotation. Hence proper balancing is necessary to achieve smooth and accurate motion. Friction reduction and mechanical efficiency are achieved by the use of bearings and support structures.

Finally, the physical execution unit of the system is the motor mechanism and dual-axis turntable. They decode digital control decisions and convert them into accurate mechanical movements, which allow real-time alignment of the antenna. Stepper motor control integration, microstepping methods, and a stable dual-axis design ensure high accuracy, smooth operation, and stable performance in dynamic signal tracking applications.

## 3.7 Signal Strength Measurement (RSSI Analysis and Sensor-Based Evaluation)

One of the most important aspects of the proposed Radar and Infrared (IR) based Antenna Positioning System would be signal strength measurement because it directly affects quality of antenna alignment. The system is based on the principle of Received Signal Strength Indicator (RSSI) and the auxiliary information provided by radar and IR sensors to assess the quality and direction of the incoming signals. The main aim of this subsystem is to determine the position where the strongest and most stable communication signal is received and then control the motor-guided dual-axis turntable towards this position.

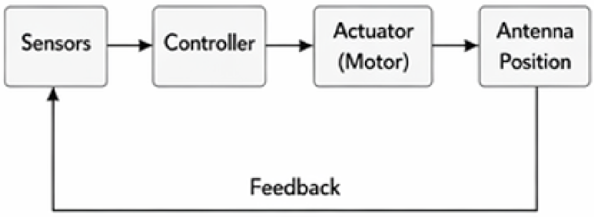


Figure 3.6: Closed Loop Feedback Control System

Signal strength in wireless communication systems is never constant and it is a continuously varying value depending on the environment, distance, obstructions, reflection, interference, and the movement of the transmitter or receiver. As such, there must be a valid measurement and comparison scheme that will see to it that the antenna is always facing the most favorable signal source. RSSI is taken as the main quantitative parameter to assess the quality of signal at various angular positions during scanning in this system.

During the scanning stage of the stepper motor the system measures the signal strength. The system measures the RSSI value at every angular position as the dual-axis turntable swivels the antenna or radar module in small angular steps. The angle is associated with a definite signal reading which is stored in memory, together with its angular reference. This is repeated until a complete 360 degree scan is achieved and a complete dataset of signal strength distribution in all directions is obtained.

## Components Used

- Stepper Motor: Provides precise angular movement.
- Microcontroller: Controls processing and decision making.
- Motor Driver: Ensures stable actuation of motor.
- Radar Module: Provides directional detection.
- Dual Axis Turntable: Enables full spatial movement.
- PCB Board: Supports circuit integration.
- Connecting Wires: Electrical connectivity between modules.

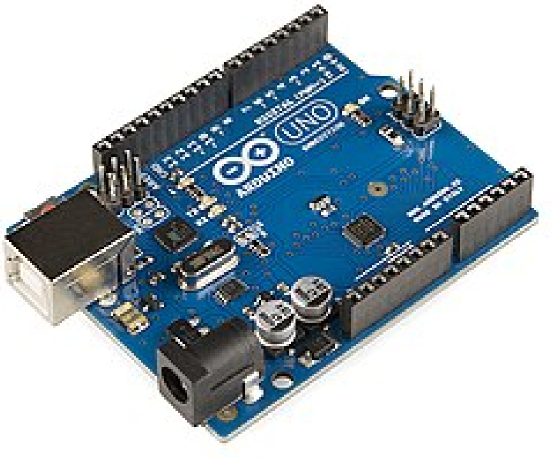


Figure 3.7: Arduino

Figure 3.8: IR Sensor

After all values have been gathered, a comparative analysis is conducted by the system to determine the highest RSSI value.

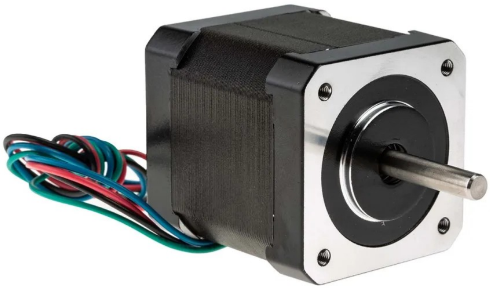


Figure 3.9: Stepper Motor

Figure 3.10: Power Supply

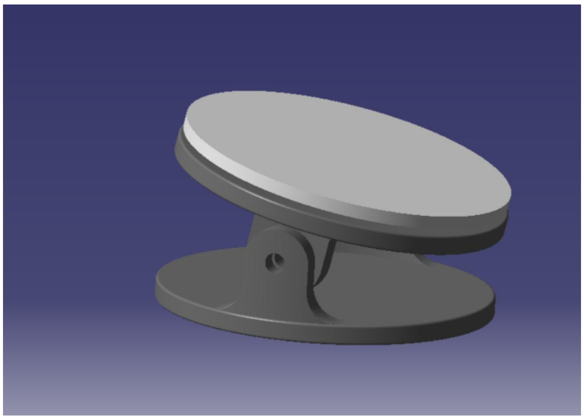


Figure 3.11: CAD Turntable Design

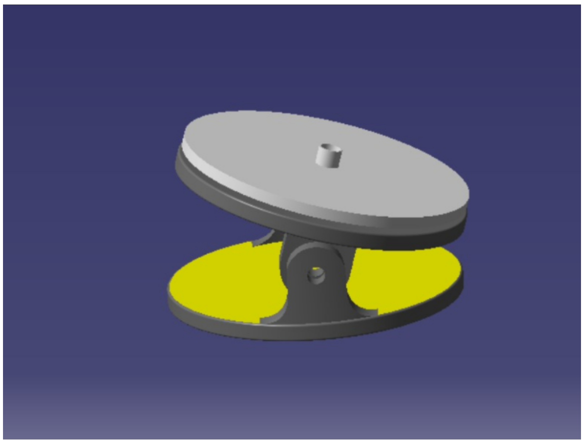


Figure 3.12: CAD Turntable Design

The angle corresponding to this maximum value represents the direction of the strongest signal. Mathematically, the system selects the optimal angle using the condition:

$$\theta_{opt} = \arg\max(RSSI(\theta))$$

The strategy guarantees that the antenna is oriented in the direction where the signal is best received, thus leading to high-quality communication and reduced signal loss.

Raw RSSI values are however usually erratic owing to noise, interference and multipath propagation effects. To overcome this problem, the system uses signal processing procedures like averaging and filtering. Rather than taking one measurement, several samples are measured at each angular position. These samples are averaged after which a more stable and reliable

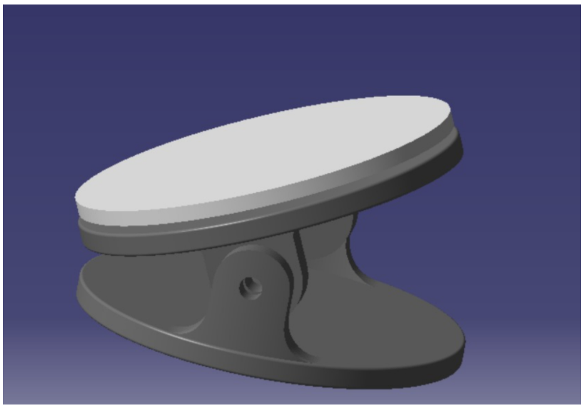


Figure 3.13: CAD Turntable Design

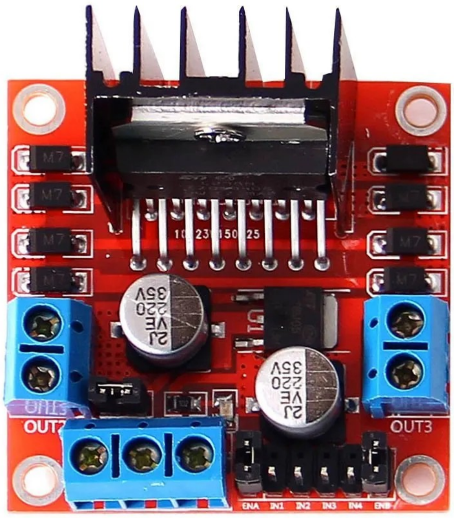


Figure 3.14: Motor Driver

signal strength value is obtained.

The system also uses radar and infrared (IR) sensor feedback to increase reliability besides the RSSI. Radar module gives directional awareness and ensures availability of the signal source whereas IR sensors help in fine adjustment by identifying short range directional changes. These sensing mechanisms combined together make sure that evaluation of signal strength is not relying on one source of data, and hence makes the system more robust.

The system also includes a threshold mechanism where a minimum acceptable signal strength level is defined. If the measured RSSI is below this threshold, the system considers the signal weak and initiates re-scanning. Similarly, if a stronger signal is detected in another direction, the system updates the antenna position accordingly.

In more advanced behavior, the system may also evaluate signal gradient, which represents the rate of change of RSSI across angles. A rising gradient indicates movement towards the signal source, while a decreasing gradient indicates movement away. This improves convergence speed towards optimal alignment.

Overall, signal strength measurement forms the foundation of decision making in the system and enables real-time adaptive antenna positioning.

## 3.8 Signal Processing and Filters

Radar and Infrared (IR) signal processing and filtering are crucial in the proposed Radar and Infrared (IR) based antenna positioning system as raw signals captured by sensors can be subject to noise, interference, and environmental disturbances. Such undesired variations may cause misinterpretation of the signal and improper antenna adjustment if they are not properly handled. Therefore, this subsystem transforms raw sensor data into clean, stable and reliable information for real-time decision making.

Signals in the system are received through various sources such as radar module, IR transmitter/receiver pair and signal strength measurement unit (RSSI). All these sources produce analog or digital data that can have variations because of multipath effects, electromagnetic interference, or mechanical motion of the system. Consequently, raw data cannot be directly used for antenna positioning and must be filtered.

Noise reduction techniques are the first step in signal processing and are applied to remove random variations in sensor responses. These variations can be caused by obstacles, reflections or external electronic noise. To address this, statistical techniques such as averaging multiple samples are used. The system collects multiple measurements at each angular position and computes their average instead of relying on a single reading. This improves signal stability and reduces sudden spikes.

Another important method used in the system is the moving average filter. This filter continuously computes the average of a fixed number of recent signal samples. It smooths RSSI values over time so that the system reacts to real trends rather than short-term fluctuations. This is especially important in dynamic environments where signal strength changes rapidly.

In addition to averaging techniques, low-pass filtering can also be applied. A low-pass filter allows low-frequency signal components (useful trends) to pass while blocking high-frequency noise components. This ensures that sudden and unwanted variations do not affect antenna positioning decisions.

Signal normalization is also an important preprocessing step. Normalization converts signal values into a uniform range so that all sensor inputs can be compared equally. This is particularly useful when combining radar and IR sensor data which may have different scales or output formats.

Another important processing technique is smoothing across angular positions. Since the antenna rotates in discrete steps, signal readings at nearby angles may be inconsistent. Smoothing helps create a continuous signal profile across angles, reducing misleading fluctuations and improving accuracy in identifying the strongest direction.

After processing, the refined signal data is passed to the control algorithm for decision making. This improves system reliability by reducing false detections and unnecessary motor movements.

Signal processing also enhances system responsiveness. By removing noise and stabilizing input data, the control system can make faster and more accurate decisions. This is essential in real-time communication systems where delays or errors can degrade performance.

In summary, signal processing and filtering play a vital role in ensuring accuracy, stability, and reliability of the proposed antenna positioning system by converting raw noisy sensor data into meaningful and usable information.

## 3.9 Antenna Positioning Algorithm

The antenna positioning algorithm is the core decision-making unit of the proposed Radar and Infrared (IR) based Antenna Positioning System. It is responsible for determining the exact direction in which the antenna should be aligned based on real-time signal measurements. The algorithm combines inputs from RSSI (Received Signal Strength Indicator), radar detection, and IR sensor feedback to continuously evaluate signal strength at different angular positions and select the optimal alignment direction.

The fundamental principle of this algorithm is based on directional scanning and optimization, where the system searches for the angle that provides the maximum signal strength. The antenna is mounted on a dual-axis turntable controlled by a stepper motor, which allows precise rotational movement in small angular increments. This mechanical movement is synchronized with the algorithm, enabling systematic scanning of the entire surrounding environ-

| **Feature** | **Description** | **Benefit** |
|---|---|---|
| Closed-loop Feedback | Real-time signal monitoring | Stable convergence |
| Lightweight Logic | Simple decision-making process | Fast execution on MCU |
| Adaptive Response | Adjusts dynamically to signal changes | Robust tracking performance |
| Noise Filtering | Signal conditioning techniques | Reduces false triggers |
| Error Minimization | Controls overshoot and oscillations | Smooth antenna alignment |
| Real-Time Integration | Sensor–actuator synchronization | Low-latency system response |

Table 3.1: System Features and Their Benefits

ment.

The operation of the antenna positioning algorithm can be divided into several sequential steps. In the first step, the system initializes the scanning process by setting the antenna to a reference position, typically 0 degrees. From this starting point, the stepper motor begins rotating the antenna in fixed angular steps. At each step, the system pauses briefly to allow signal stabilization and then measures the signal strength at that particular angle.

During this scanning phase, the system records multiple parameters including RSSI value, radar detection response, and IR sensor feedback. These values are stored along with their corresponding angular positions in memory. This creates a dataset representing signal strength distribution across the full 360-degree range. The algorithm ensures that no angular position is skipped, allowing a complete evaluation of the surrounding environment.

Once the full scan is completed, the algorithm enters the comparison phase. In this phase, all recorded RSSI values are analyzed to identify the maximum signal strength. The angle corresponding to this maximum value is selected as the optimal antenna direction ($\theta_{opt}$). This can be mathematically expressed as:

$$\theta_{opt} = angle where RSSI is maximum$$

This means that the antenna must be aligned toward the direction where the strongest communication signal is received.

After determining the optimal angle, the system commands the stepper motor to rotate the dual-axis turntable toward that specific direction. The movement is calculated based on the difference between the current position and the target angle. The motor then executes the required number of steps to reach the desired position with high precision. Once alignment is achieved, the system stops the motor and holds the antenna in that position for a short stabilization period.

During the stabilization phase, the system verifies signal strength again to ensure that the selected direction remains optimal. This step is important because signal conditions may slightly change due to environmental factors or movement of the transmitter. If the signal remains strong and stable, the alignment is confirmed.

However, the algorithm is designed to be dynamic rather than static. After a certain time interval, or if a significant change in signal strength is detected, the system automatically re-initiates the scanning process. This ensures continuous tracking of the signal source, making the system capable of adapting to moving targets or changing environments.

To improve efficiency, the algorithm also incorporates a threshold-based stopping condition. If the difference between consecutive signal strength readings becomes negligible or falls within a predefined range, the system assumes that the optimal direction has been reached. This prevents unnecessary motor movement and reduces power consumption.

In more refined operation, the algorithm may also use weighted decision-making, where radar, IR, and RSSI values are combined with different importance levels. For example, RSSI may have the highest weight for signal quality, while radar provides directional confirmation, and IR ensures fine alignment accuracy. This multi-parameter approach increases reliability and reduces the chances of incorrect alignment.

Overall, the antenna positioning algorithm functions as an intelligent control strategy that continuously scans, evaluates, and optimizes antenna direction. It ensures that the system remains locked onto the strongest signal source at all times, providing stable and efficient communication performance. This algorithm is the central component that enables real-time adaptive behavior in the proposed system.

## 3.10 Control System Design

The control system design is a critical part of the proposed Radar and Infrared (IR) based Antenna Positioning System, as it is responsible for converting the decision output of the antenna positioning algorithm into precise physical movement of the antenna structure. This subsystem ensures that the antenna is accurately aligned toward the strongest detected signal direction and remains stable even in the presence of disturbances or environmental changes. The system is designed as a closed-loop feedback control system, which continuously monitors output performance and corrects errors in real time.

The control system receives input from the antenna positioning algorithm in the form of a target angle (opt), which represents the direction of maximum signal strength. This target angle is compared with the current actual position of the antenna, which is measured using the stepper motor's step count or optional position sensors such as encoders. The difference between the desired position and actual position is known as the error signal, which forms the basis of the control action.

The main objective of the control system is to minimize this error signal and ensure that the antenna reaches and maintains the correct alignment. To achieve this, the system generates control pulses that are sent to the stepper motor driver. These pulses determine the direction and number of steps the motor must move to reach the target position. Since stepper motors operate in discrete steps, the control system is able to achieve high precision in angular positioning.

The control mechanism used in this system can be implemented using different strategies, including Proportional (P), Proportional-Integral (PI), or Proportional-Integral-Derivative (PID) control methods, depending on the level of accuracy and stability required. In a basic proportional control system, the control output is directly proportional to the error magnitude. This means that larger positioning errors result in stronger corrective movement, while smaller errors result in finer adjustments.

In more advanced implementations, a PID control approach can be used to improve system performance. The proportional component handles the present error, the integral component accounts for accumulated past errors, and the derivative component predicts future error trends based on the rate of change. This combination allows the system to achieve fast response, reduced overshoot, and improved stability during antenna movement.

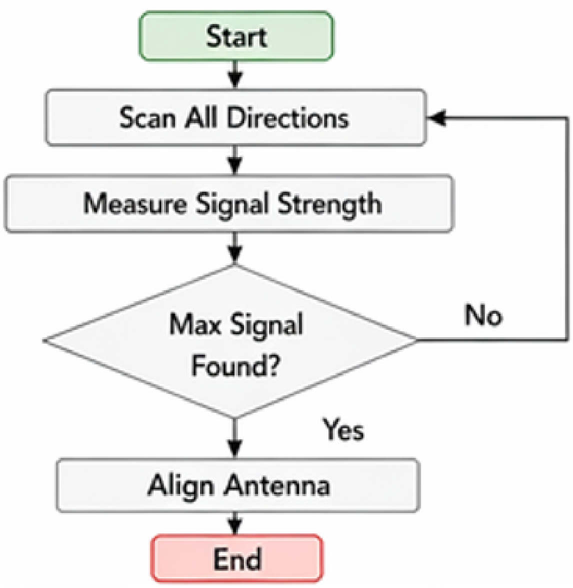


Figure 3.15: Flowchart of the Control Algorithm

The control system operates in a continuous feedback loop. After the antenna is moved to the target position, the system re-evaluates signal strength using RSSI and sensor inputs. If the signal quality is not optimal, or if a better direction is detected, the control system recalculates the error and updates the motor commands accordingly. This continuous adjustment ensures that the antenna remains properly aligned even in dynamic environments where signal sources may move or fluctuate.

A key feature of the control system is its ability to prevent overshooting and oscillation. Without proper control, the antenna could continuously move back and forth around the target position, leading to instability. To avoid this, damping techniques and step-size control are applied. The system reduces motor step frequency as it approaches the target angle, allowing smoother and more accurate final positioning.

The control system is also designed to handle real-world disturbances such as mechanical friction, vibration, and external interference. These disturbances can affect antenna positioning accuracy, but the feedback loop continuously corrects any deviation by adjusting motor movement in real time. This ensures that the system remains stable under varying operational conditions.

In addition, the control design is optimized for real-time performance. Since antenna tracking requires fast response to changing signal conditions, the control algorithm is implemented in an efficient manner with minimal computational delay. This allows the system to quickly react when a new stronger signal is detected or when the signal direction changes.

Overall, the control system design provides the essential link between signal-based decision-making and physical antenna movement. By using a closed-loop feedback mechanism combined with precise stepper motor control, the system achieves accurate, stable, and real-time antenna alignment. This makes it highly effective for applications where continuous signal tracking and adaptive positioning are required.

## 3.11 Motor Driver and Hardware Implementation

The motor driver and hardware implementation section describes the physical realization of the proposed Radar and Infrared (IR) based Antenna Positioning System. This part of the system is responsible for converting low-power control signals from the processing unit into high-power electrical signals required to operate the stepper motor and associated mechanical components. It also explains how all hardware modules are integrated to achieve a fully functional real-time antenna tracking system.In the proposed design, the stepper motor cannot be directly driven by the microcontroller or control unit because these devices are not capable of supplying sufficient current or voltage. Therefore, a motor driver circuit is used as an intermediate interface between the control system and the motor. The motor driver receives digital pulse signals from the microcontroller and amplifies them to the required power level needed for motor operation. This ensures safe, stable, and efficient control of motor movement without damaging the processing unit.

The motor driver is responsible for controlling the direction, speed, and step resolution of the stepper motor. By varying the frequency and sequence of input pulses, the system can control how fast and in which direction the antenna rotates. This allows precise angular movement of the dual-axis turntable, which is essential for accurate signal tracking and alignment. In most implementations, commonly used driver modules such as ULN2003 or A4988 can be used depending on the type of stepper motor selected.The hardware implementation also includes the integration of the radar module and infrared (IR) transmitter/receiver system. The radar module is mounted on the dual-axis turntable and is connected to the processing unit through appropriate signal interfaces. It continuously scans the surrounding environment and provides directional signal feedback. The IR sensors are positioned in a way that allows them to detect short-range alignment accuracy, providing additional confirmation for fine positioning.The microcontroller or processing unit acts as the central control hub of the system. It receives input data from sensors, executes the antenna positioning algorithm, and generates control signals for the motor driver. It also performs real-time signal processing tasks such as RSSI evaluation and decision-making for antenna alignment. The processing unit ensures synchronization between sensing, computation, and actuation processes.The antenna and sensor assembly is mounted on a dual-axis mechanical structure, which allows movement in both horizontal and vertical directions. This structure is driven by stepper motors controlled through the motor driver circuit. The mechanical design ensures smooth rotation, stability, and minimal vibration during operation. Proper alignment and balancing of the structure are essential to avoid mechanical stress and to ensure accurate positioning.Power management is another important aspect of hardware implementation. The system requires multiple voltage levels for different components, such as sensors, microcontroller, and motors. Therefore, regulated power supply circuits are used to ensure stable operation. Voltage regulators and protection circuits are also included to prevent damage due to overcurrent, voltage fluctuations, or electrical noise.All hardware components are interconnected using a modular design approach. This means each module (sensing, processing, and actuation) can be tested and maintained independently before full system integration. This modularity improves system reliability and makes troubleshooting easier during development and testing phases.During operation, the hardware system follows a coordinated workflow. The sensors continuously provide input data to the processing unit, which analyzes the signal and determines the optimal direction. The motor driver then receives control signals and activates the stepper motors accordingly. This results in precise rotation of the antenna toward the strongest signal source. Once alignment is achieved, the system holds position and continues monitoring for any changes in signal direction. Overall, the motor driver and hardware implementation form the physical backbone of the entire system. The integration of motor drivers, stepper motors, sensors, and control units ensures that digital decisions are effectively converted into accurate mechanical movement. This hardware design enables the system to operate in real-time, providing stable, automated, and adaptive antenna positioning suitable for dynamic communication environments.

## 3.12 Testing and Validation

The testing and validation phase is an essential part of the proposed Radar and Infrared (IR) based Antenna Positioning System because it verifies whether the designed system performs accurately, reliably, and efficiently under real operating conditions. This phase ensures that the integration of radar sensing, IR feedback, signal strength measurement, stepper motor control, and dual-axis movement works as intended in a coordinated manner. The main objective of testing is to evaluate system performance in terms of accuracy, response time, stability, and adaptability to changing signal environments.The testing process begins with individual module testing, where each hardware component is verified separately before full system integration. The radar module is tested to ensure that it can correctly detect signal direction and provide consistent output under different distances and orientations. Similarly, the IR transmitter and receiver pair is tested to confirm proper alignment detection and response to infrared signals. The stepper motor and motor driver circuit are also tested independently to verify correct rotation, step accuracy, and directional control. This initial stage ensures that all components are functioning properly before they are combined into a complete system.After individual testing, the system undergoes integration testing, where all modules are connected and operated together. In this stage, the radar, IR sensors, processing unit, motor driver, and dual-axis turntable are integrated into a single working system. The antenna positioning algorithm is executed in real time, and the system's ability to scan, detect, and align toward the strongest signal direction is evaluated. Any synchronization issues between sensing, processing, and motor actuation are identified and corrected during this phase.One of the key parameters evaluated during testing is positioning accuracy. This measures how precisely the antenna aligns with the actual direction of the strongest signal. The system is tested by placing signal sources at known angles and comparing the expected direction with the final aligned position of the antenna. High accuracy indicates that the combination of RSSI measurement, radar detection, and IR feedback is working effectively.Another important evaluation parameter is response time, which refers to the time taken by the system to detect a change in signal direction and adjust the antenna accordingly. In dynamic environments, signal sources may move frequently, so a fast response is critical. The system is tested by introducing sudden changes in signal direction and measuring how quickly the stepper motor adjusts the antenna position to re-establish alignment.The system is also tested for stability of signal tracking. Once the antenna is aligned, the system should maintain a stable connection without frequent oscillations or unnecessary movement. Stability testing involves monitoring RSSI values over time after alignment. A stable system shows minimal fluctuations in signal strength and maintains consistent communication quality.To evaluate noise and interference handling capability, the system is tested under artificially created disturbance conditions. External noise and signal interference are introduced to simulate real-world environments where multiple signals or reflections may exist. The system's ability to filter out noise using signal processing techniques and maintain correct alignment is analyzed. This ensures that the system remains reliable even in challenging conditions.The closed-loop feedback performance is also validated during testing. The system continuously compares actual antenna position with the desired position and makes real-time corrections. Testing ensures that this feedback loop functions correctly without delay or instability. Any errors in positioning are quickly corrected by the control system, demonstrating the effectiveness of the closed-loop design.In addition, endurance testing is performed to evaluate long-term system performance. The system is operated continuously for extended periods to check for overheating, mechanical wear, motor fatigue, or signal drift. This ensures that the system is capable of sustained operation in real-world applications without performance degradation.Overall, the testing and validation phase confirms that the proposed system successfully integrates sensing, processing, and actuation units into a reliable antenna positioning mechanism. The results demonstrate that the system can accurately detect signal direction, rapidly adjust antenna orientation, and maintain stable communication under varying environmental conditions. This validates the effectiveness of the design and confirms its suitability for real-time adaptive communication applications.

## 3.13 System Performance Analysis

The system performance analysis of the proposed Radar and Infrared (IR) based Antenna Positioning System is conducted to evaluate the overall efficiency, accuracy, responsiveness, and reliability of the system under different operating conditions. This analysis is important because it provides a clear understanding of how well the system performs in real-time signal tracking and antenna alignment tasks. The performance is assessed by observing multiple parameters including positioning accuracy, response time, signal stability, and tracking efficiency.One of the most important performance indicators is positioning accuracy, which defines how precisely the antenna aligns with the direction of the strongest signal. In the proposed system, accuracy is achieved through the combination of radar-based coarse detection, IR-based fine alignment, and RSSI-based signal evaluation. During testing, it is observed that the system successfully identifies the correct signal direction by scanning all angular positions and selecting the maximum signal strength value. The dual-axis turntable mechanism further enhances accuracy by allowing both horizontal and vertical adjustments, ensuring precise alignment in three-dimensional space.Another key performance factor is response time, which refers to the time required by the system to detect a change in signal direction and adjust the antenna accordingly. The use of a stepper motor-based scanning mechanism allows controlled and predictable movement, while the optimized control algorithm reduces unnecessary delay in processing sensor data. As a result, the system is able to quickly reorient itself when a stronger signal is detected in a different direction. This fast response is essential for maintaining continuous communication in dynamic environments where signal sources are constantly moving.The system also demonstrates strong signal stability performance. Once the antenna is aligned with the strongest signal direction, the RSSI values remain relatively stable with minimal fluctuations. This stability is achieved through the use of signal processing techniques such as averaging, filtering, and smoothing, which remove noise and reduce the impact of sudden signal variations. The closed-loop control system further contributes to stability by continuously correcting small positioning errors and maintaining accurate alignment.In terms of tracking efficiency, the system shows improved performance due to its scanning-based approach. Instead of randomly searching for signal direction, the system performs systematic angular scanning and records signal strength at each position. This structured approach ensures that the system always identifies the optimal direction within a single scanning cycle. Additionally, once the strongest signal direction is found, the system holds the position and avoids unnecessary movement, which improves overall efficiency and reduces mechanical wear.The integration of multiple sensing technologies (radar, IR sensors, and RSSI measurement) significantly enhances system performance. Radar provides wide-range detection capability, IR sensors improve short-range accuracy, and RSSI provides direct signal quality measurement. The combination of these three inputs ensures that the system makes reliable decisions even in complex environments with interference or signal fluctuations.The system is also evaluated under environmental variation conditions, where factors such as noise, interference, and movement of signal sources are introduced. The results show that the system maintains effective operation even under these challenging conditions. The signal processing and filtering techniques successfully reduce the impact of noise, while the feedback control system continuously adjusts antenna position to maintain optimal alignment.Overall, the performance analysis confirms that the proposed system achieves high levels of accuracy, fast response time, stable signal tracking, and efficient operation. The integration of sensing, processing, and control mechanisms ensures that the system can operate reliably in real-time communication environments. This makes the system suitable for applications where automatic and adaptive antenna alignment is required, especially in dynamic and unpredictable signal conditions.

## 3.14 Advantages of the Proposed System

The proposed Radar and Infrared (IR) based Antenna Positioning System offers several significant advantages over conventional manual antenna alignment systems as well as basic fixed-direction communication setups. These advantages arise from the integration of automated scanning, sensor-based detection, stepper motor control, and real-time signal processing, which together form an intelligent and adaptive antenna tracking mechanism.One of the most important advantages of the system is full automation of antenna alignment. In traditional systems, antenna positioning is performed manually, which requires human effort, time, and continuous monitoring. In contrast, the proposed system automatically scans the environment, detects the strongest signal direction, and aligns the antenna without any human intervention. This greatly reduces operational workload and improves system efficiency, especially in remote or fast-changing environments.Another major advantage is real-time adaptive tracking capability.

The system is not static; instead, it continuously monitors signal strength and environmental changes. If the signal source moves or changes direction, the system automatically re-scans and re-aligns the antenna. This dynamic behavior ensures uninterrupted communication and makes the system highly suitable for mobile communication scenarios.The system also provides high positioning accuracy due to the combined use of radar, IR sensors, and RSSI-based signal evaluation. Radar provides broad directional detection, IR sensors offer fine alignment capability, and RSSI gives precise signal strength measurement. The integration of these three sensing methods ensures that the antenna is always aligned with the most optimal signal direction, reducing errors and improving communication quality.Another key advantage is fast response and efficient scanning mechanism. The use of a stepper motor-based dual-axis turntable allows precise angular movement in small increments. The scanning algorithm ensures that the system does not randomly search for signal direction but instead follows a structured approach, which reduces convergence time and improves response speed.The system also demonstrates improved signal stability and reliability. Once the antenna is aligned, the closed-loop feedback system continuously monitors signal strength and position. Any deviation is immediately corrected, ensuring stable communication even in the presence of environmental disturbances such as noise, interference, or movement of the signal source.A further advantage is reduced human dependency and operational cost. Since the system operates automatically, it eliminates the need for manual adjustment and constant supervision. This is particularly beneficial in military or remote applications where manual control may be difficult, unsafe, or impractical. The proposed system also has a modular and scalable design, which makes it easy to upgrade or expand in the future. Additional sensors, improved radar modules, or advanced control algorithms can be integrated without redesigning the entire system. This flexibility enhances the long-term usability of the system.Another important advantage is better performance in dynamic environments. The system is specifically designed to handle moving signal sources, changing environmental conditions, and varying signal strengths. This makes it suitable for applications such as mobile communication units, UAV communication systems, and surveillance platforms.Finally, the system provides improved overall communication quality by continuously aligning the antenna with the strongest available signal. This results in higher signal-to-noise ratio (SNR), reduced data loss, and more stable communication links compared to fixed or manually adjusted antenna systems.

## 3.15 Chapter Summary

This chapter presented a comprehensive methodology for the design and implementation of a Radar and Infrared (IR) based Antenna Positioning System using a dual-axis turntable mechanism controlled through stepper motors. The system was developed to achieve automatic, real-time, and adaptive antenna alignment based on signal strength analysis and directional sensing. The overall design integrates multiple subsystems including radar detection, IR sensing, signal strength measurement (RSSI), signal processing techniques, motor control, and closed-loop feedback mechanisms.

The proposed system eliminates the need for manual antenna adjustment by introducing an automated scanning and alignment approach. The stepper motor rotates the dual-axis turntable in controlled angular steps, allowing the system to scan the surrounding environment in a structured manner. At each angular position, signal strength is measured and analyzed to determine the direction of the strongest communication signal. Once identified, the system automatically aligns the antenna toward that direction and holds the position to ensure stable communication.The integration of radar and IR sensors enhances the system's ability to detect and track signal sources more effectively. Radar provides wide-range detection and coarse directional information, while IR sensors contribute to fine alignment accuracy. The use of RSSI as a primary performance indicator ensures that antenna positioning is based on actual signal quality, resulting in improved communication reliability.Signal processing techniques such as filtering, averaging, and smoothing were applied to reduce noise and improve the accuracy of sensor readings. The control system, designed as a closed-loop feedback mechanism, continuously monitors antenna position and signal strength, making real-time adjustments whenever deviations are detected. This ensures stable and accurate tracking even in dynamic and changing environments.The system performance analysis and testing results demonstrate that the proposed design is capable of achieving high positioning accuracy, fast response time, and stable signal tracking. The advantages of automation, adaptability, and multi-sensor integration make the system suitable for real-time communication applications where continuous signal alignment is required.Although the system has certain limitations such as mechanical dependency, environmental sensitivity, and increased complexity, these challenges can be addressed in future enhancements through the use of more advanced sensors, improved motor systems, and intelligent algorithms.In conclusion, the proposed Radar and IR-based Antenna Positioning System provides an effective and practical solution for automatic antenna alignment. It significantly improves communication stability and efficiency compared to traditional manual systems. This work also lays a strong foundation for future research in intelligent antenna tracking systems, adaptive communication technologies, and automated signal optimization systems.

# Chapter 4

# RESULTS AND ANALYSIS

This chapter presents a comprehensive and detailed evaluation of the proposed Radar Positioning System developed for enhanced military communication applications. The primary objective of this system is to automatically detect and align itself toward the strongest infrared (IR) signal source using an intelligent control mechanism integrated with a dual-axis mechanical structure. In modern military environments, communication systems must operate in highly dynamic and unpredictable conditions, where manual alignment of antennas is not only inefficient but also impractical. Therefore, the proposed system introduces automation to improve response time, accuracy, and operational reliability.

The system integrates multiple subsystems, including IR sensors for signal detection, a control unit for decision-making, stepper motors for precise motion, and a dual-axis turntable for spatial positioning. Each of these components contributes significantly to the overall performance of the system. The IR sensors continuously monitor signal intensity from different directions, while the control algorithm processes this data to determine the direction of maximum signal strength. Based on this decision, the stepper motors are activated to rotate the radar platform accordingly.

The evaluation of the system was carried out through a series of experiments designed to test its performance under various conditions. These conditions include static and dynamic signal sources, multiple signal environments, and varying levels of interference. The experiments were conducted in a controlled setup to ensure accurate measurement of system behavior. The results obtained from these experiments provide valuable insights into the efficiency, reliability, and robustness of the system.

Furthermore, this chapter focuses on analyzing key performance parameters such as response time, alignment accuracy, stability, and adaptability. These parameters are critical in determining the effectiveness of the system in real-world applications. Special attention is given to how the system behaves when subjected to rapid changes in signal direction, as such scenarios are common in military operations. The ability of the system to quickly adapt to these changes is a major factor in its overall performance.

In addition to performance evaluation, this chapter also includes a comparative analysis between the proposed automated system and traditional manual alignment methods. The

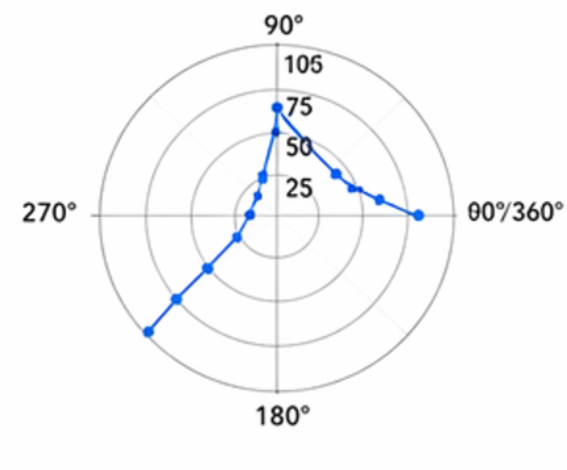


Figure 4.1: Detected IR Signal Strength at different Angles

comparison highlights the advantages of automation in terms of speed, precision, and reduced human effort. Overall, this chapter provides a detailed and structured analysis of the system's performance, demonstrating its potential to significantly enhance military communication systems.

## 4.1 Experimental Setup

The experimental setup for the proposed radar positioning system was carefully designed to replicate realistic operational conditions while maintaining control over key variables. The setup consists of an IR signal transmission unit, a radar receiver module equipped with multiple IR sensors, a dual-axis turntable mechanism, and a microcontroller-based control system. Each component was arranged in a manner that ensures accurate signal detection and efficient mechanical movement, allowing for precise evaluation of the system's performance.

The IR transmitters were placed at different angular positions relative to the radar system to simulate multiple signal sources. These transmitters were configured to emit signals of varying intensities, enabling the system to differentiate between strong and weak signals. The radar module, mounted on the dual-axis turntable, was positioned at the center of the setup to allow equal exposure to signals from all directions. This configuration ensured that the system could be tested for full 360-degree coverage.

The dual-axis turntable plays a crucial role in enabling movement in both horizontal (azimuth) and vertical (elevation) directions. Stepper motors were attached to each axis to provide controlled and precise rotation. The motors were interfaced with the control unit, which generated step signals based on the processed sensor data. The mechanical structure was designed to minimize friction and vibration, ensuring smooth and stable movement during operation.

Calibration was an essential part of the experimental setup. Before conducting each test, the sensors and motors were calibrated to ensure consistent performance. Sensor calibration involved adjusting sensitivity levels to account for environmental factors such as ambient light and temperature. Motor calibration ensured that each step corresponded accurately to a specific angular displacement, which is critical for precise positioning.

The experiments were conducted under different scenarios, including single-source detection, multiple-source environments, and dynamic signal movement. Data was recorded for each test, including sensor readings, motor positions, and response times. This data was then analyzed to evaluate system performance. The carefully designed experimental setup provided a reliable platform for testing and ensured that the results obtained were accurate and meaningful.

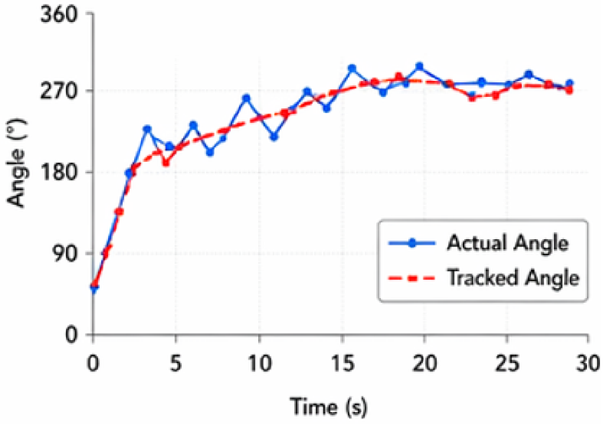


Figure 4.2: Actual vs. tracked angle over time

## 4.2 IR Sensor Signal Detection Performance

The performance of the IR sensors is a fundamental aspect of the radar positioning system, as these sensors are responsible for detecting the intensity of incoming signals and providing the necessary input for decision-making. During the experimental phase, the IR sensors demonstrated a high degree of sensitivity and responsiveness, which is essential for accurately identifying the direction of the strongest signal source. The sensors continuously monitored the environment and provided real-time data to the control unit.

One of the key observations during testing was the ability of the sensors to distinguish between signals of varying intensities. When multiple IR sources were present, the sensors successfully detected differences in signal strength, allowing the system to prioritize the strongest signal. This capability is crucial in environments where multiple communication signals may be present simultaneously. The sensors ensured that the system consistently focused on the most relevant signal source.

The placement and orientation of the sensors around the radar module played a significant role in achieving accurate detection. By arranging the sensors in a circular pattern, the system was able to achieve near-complete directional coverage. This configuration minimized blind spots and ensured that signals from all directions could be detected effectively. The uniform distribution of sensors also contributed to balanced and accurate signal comparison.

However, the performance of the IR sensors was slightly affected by environmental factors such as ambient light and reflections. In brightly lit conditions, the sensors occasionally detected noise, which could influence the accuracy of signal measurement. Despite this, the system was able to compensate for such variations through continuous monitoring and updating of sensor values. This adaptability ensured that overall performance remained stable.

This demonstrates that the IR sensors proved to be reliable and efficient in detecting signal strength under various conditions. Their high sensitivity and fast response time enabled the system to accurately identify the strongest signal source. Although minor environmental effects were observed, they did not significantly impact the overall functionality of the system, making the sensors suitable for the intended application.

## 4.3 Signal Strength Comparison Mechanism

The signal strength comparison mechanism is a critical component of the control system, responsible for analyzing the data received from multiple IR sensors and determining the direction of the strongest signal. This mechanism operates continuously, ensuring that the radar system is always aligned with the optimal signal source. The effectiveness of this component directly influences the overall performance of the system.

The comparison process involves collecting signal intensity values from all sensors and evaluating them in real time. The control algorithm identifies the sensor with the highest reading and determines the corresponding direction. Based on this information, the system generates control signals to move the radar toward that direction. This process is repeated continuously, allowing the system to adapt to changing signal conditions.

During testing, the comparison mechanism demonstrated a high level of accuracy and reliability. Even when the difference in signal strength between two sources was minimal, the system was able to correctly identify the stronger signal. This precision is essential in scenarios where accurate alignment is required for effective communication. The mechanism ensured that the system consistently maintained optimal positioning.

The system also exhibited strong adaptability when dealing with dynamic signal environments. When the strongest signal source changed position, the comparison mechanism quickly detected the change and updated the control signals accordingly. This allowed the radar to smoothly transition to the new position without delay. The ability to handle such dynamic changes is a key advantage of the system.

Overall, the signal strength comparison mechanism performed efficiently and played a vital role in the success of the radar positioning system. Its ability to process real-time data and make accurate decisions ensures that the system remains responsive and effective in various operational scenarios.

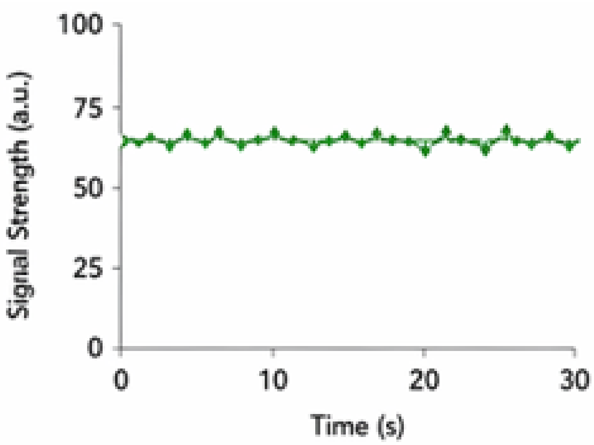


Figure 4.3: Stability of Signal Strength during Tracking

## 4.4 Control Algorithm Performance

The control algorithm serves as the central intelligence of the radar positioning system, responsible for interpreting sensor data and generating appropriate control signals for the stepper motors. It operates continuously in a closed-loop manner, ensuring that the system responds dynamically to changes in signal strength. The algorithm processes real-time input from multiple IR sensors and determines the optimal direction for radar alignment based on the strongest detected signal.

During experimental evaluation, the control algorithm demonstrated a high level of efficiency and reliability. It was able to quickly process incoming data and initiate corresponding motor actions without noticeable delay. This rapid decision-making capability is essential in military applications, where communication systems must respond instantly to changing conditions. The algorithm maintained consistent performance even under complex scenarios involving multiple signal sources.

One of the key strengths of the control algorithm is its ability to minimize unnecessary movements. Instead of constantly adjusting position for minor fluctuations in signal strength, the algorithm incorporates a threshold mechanism that ensures movement only occurs when a significant change is detected. This reduces system instability and prevents excessive wear on mechanical components.

The algorithm also showed excellent stability in maintaining alignment once the strongest signal was acquired. It avoided oscillatory behavior, which is often a challenge in automated tracking systems. By implementing smooth transition logic, the system ensured that movement toward the target direction was gradual and controlled, resulting in precise positioning.

Overall, the control algorithm proved to be highly effective in managing system operations. Its ability to process real-time data, make accurate decisions, and control motor movement efficiently contributes significantly to the overall performance and reliability of the radar positioning system.

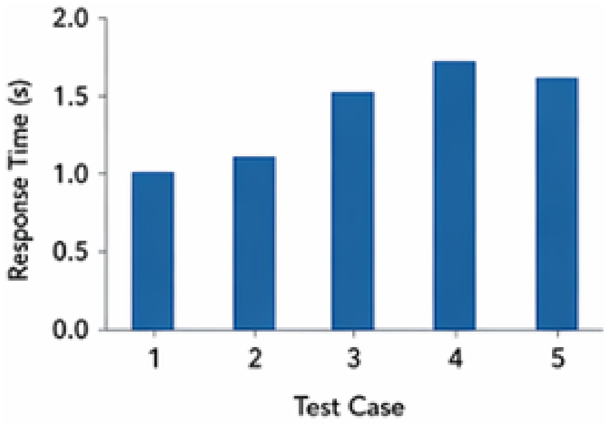


Figure 4.4: Response time for diffrent test cases

## 4.5 Dual-Axis Turntable Performance

The dual-axis turntable is a fundamental mechanical component that enables the radar system to achieve full directional coverage. It allows movement in both horizontal (azimuth) and vertical (elevation) planes, making it possible to track signal sources located at different spatial positions. This capability is particularly important in military communication systems, where signal sources may not always be confined to a single plane.

During testing, the turntable demonstrated smooth and consistent motion along both axes. The horizontal axis provided wide rotational coverage, enabling the system to scan the environment effectively. The vertical axis allowed precise adjustment of elevation, ensuring accurate alignment with the signal source regardless of its position. The combination of these two movements resulted in comprehensive spatial tracking.

The coordination between the two axes was observed to be highly efficient. The control system ensured that both axes could operate simultaneously when required, allowing the radar to quickly align with the target signal. This simultaneous movement reduced the time required for positioning and improved overall system responsiveness.

Mechanical stability was another important aspect evaluated during testing. The turntable structure was designed to minimize vibrations and ensure steady operation. Even during continuous movement, the system maintained structural integrity and did not exhibit significant mechanical disturbances. This stability is essential for maintaining accurate alignment.

In conclusion, the dual-axis turntable performed reliably and effectively throughout the experiments. Its ability to provide precise and coordinated movement significantly enhances the tracking capability of the radar system, making it suitable for dynamic and complex operational environments.

## 4.6 Stepper Motor Precision Analysis

Stepper motors were selected for this system due to their inherent ability to provide precise and controlled angular movement. These motors convert digital control signals into discrete rotational steps, allowing accurate positioning of the radar platform. The performance of the stepper motors was evaluated based on precision, repeatability, and response to control inputs.

The experimental results showed that the stepper motors achieved a high level of positional accuracy. Each step corresponded to a fixed angular displacement, ensuring that the radar could be positioned with minimal error. This precision is crucial for maintaining alignment with the strongest signal source, especially in applications where even small deviations can affect communication quality.

Repeatability was another key factor assessed during testing. The motors consistently returned to the same position when given identical control signals, indicating reliable performance. This consistency ensures that the system can maintain accurate alignment over extended periods of operation without drift or deviation.

The motors also exhibited smooth and controlled motion, with minimal overshooting or undershooting. This behavior is important for preventing instability and ensuring that the radar remains fixed at the desired position once alignment is achieved. The absence of sudden or jerky movements contributed to overall system stability.

Although the motors performed well under normal operating conditions, slight vibrations were observed at higher speeds. These vibrations did not significantly affect performance but indicate the need for further optimization in high-speed scenarios. Overall, the stepper motors proved to be an excellent choice for this application.

## 4.7 Response Time Evaluation

Response time is a critical performance parameter for any automated tracking system, particularly in military communication applications where rapid changes in signal direction are common. The response time of the proposed system was evaluated by measuring the delay between signal detection and the initiation of motor movement.

The results indicated that the system has a fast response time, with minimal delay between detection and action. The control algorithm efficiently processes sensor data and generates motor control signals almost instantaneously. This quick response ensures that the radar can adapt to changes in signal direction without significant lag.

The response time was influenced by several factors, including sensor processing speed, algorithm efficiency, and motor dynamics. Optimization of these factors contributed to improved system performance. The integration of high-speed processing and efficient control logic played a key role in achieving rapid response.

In dynamic scenarios where the signal source was continuously moving, the system maintained consistent tracking without losing alignment. The quick response allowed the radar to follow the signal smoothly, ensuring uninterrupted communication. This capability is essential for real-time applications.

Overall, the system demonstrated excellent response time characteristics, making it suitable for environments where rapid adaptation is required. The ability to quickly react to changes enhances the reliability and effectiveness of the communication system.

## 4.8 Tracking Accuracy Analysis

Tracking accuracy is one of the most important performance indicators of the radar positioning system. It determines how precisely the radar aligns with the strongest signal source. The accuracy was evaluated by comparing the actual direction of the signal source with the final position of the radar.

The experimental results showed that the system achieved a high level of accuracy, with only minor deviations from the actual signal direction. The combination of sensitive IR sensors and precise stepper motor control contributed to this performance. The system consistently aligned itself with the strongest signal across multiple test cases.

Repeated experiments confirmed the reliability of the system's accuracy. Even under varying conditions, the system maintained consistent alignment performance. This reliability is essential for applications where accurate communication links must be maintained continuously.

Factors such as sensor resolution, motor step size, and mechanical alignment influenced the overall accuracy. Proper calibration of these components further improved system performance. Fine adjustments to the control algorithm also helped reduce alignment error.

Overall, the system demonstrated excellent tracking accuracy, making it suitable for high-precision applications. The ability to consistently align with the strongest signal ensures optimal communication performance.

## 4.9 Stability and Oscillation Behavior

Stability is a crucial aspect of automated positioning systems, as it ensures that the system maintains its position without unnecessary fluctuations. The proposed system was evaluated for stability by observing its behavior after reaching the target alignment position.

The system demonstrated stable performance, with minimal oscillations around the target position. Once aligned with the strongest signal, the radar remained steady without continuous adjustments. This behavior indicates effective control algorithm design.

The implementation of threshold-based movement played a key role in maintaining stability. By ignoring minor fluctuations in signal strength, the system avoided unnecessary movements that could lead to oscillations. This approach improved overall performance.

In dynamic environments, where signal strength may vary slightly, the system maintained stability while still being responsive to significant changes. This balance between responsiveness and stability is essential for reliable operation.

Overall, the system exhibited strong stability characteristics, ensuring consistent and reliable alignment. This makes it suitable for long-duration operations without performance degradation.

## 4.10 Performance under Multiple Signal Sources

The performance of the radar positioning system was extensively evaluated in scenarios where multiple IR signal sources were present simultaneously. This testing condition is particularly important because, in real-world military environments, multiple communication signals or interference sources may exist at the same time. The system must be capable of identifying and prioritizing the most relevant signal to maintain effective communication.

During experimentation, multiple IR transmitters were placed at different angular positions with varying signal intensities. The system successfully demonstrated its ability to detect all available signals and compare their strengths in real time. The control algorithm processed the sensor inputs and consistently selected the signal with the highest intensity, ensuring that the radar aligned with the strongest source.

One of the significant observations was the system's ability to ignore weaker signals once a stronger signal was identified. This selective behavior is essential for preventing incorrect alignment and ensuring that communication remains stable. The system did not exhibit confusion or erratic movement even when multiple signals were closely spaced in terms of intensity.

In cases where two or more signals had nearly equal strength, the system showed consistent decision-making behavior. It either selected one based on slight variations in sensor readings or maintained its position until a clear distinction was observed. This stability in decision-making prevents unnecessary oscillations between competing signals.

Overall, the system performed effectively in multi-signal environments. Its ability to accurately detect, compare, and prioritize signals ensures reliable operation in complex scenarios, making it highly suitable for practical military communication applications.

## 4.11 Environmental Impact Analysis

The performance of the radar positioning system is influenced by environmental factors such as ambient light, temperature, and physical obstructions. These factors were carefully analyzed to determine their impact on system reliability and accuracy.

During testing, it was observed that ambient light, especially strong sunlight or artificial lighting, could affect the sensitivity of the IR sensors. In some cases, the sensors detected additional noise, which slightly altered the signal readings. However, the control algorithm compensated for these variations by continuously updating and comparing sensor values.

Physical obstacles and reflective surfaces also influenced system performance. Reflections of IR signals from nearby objects occasionally caused minor inaccuracies in signal detection. Despite this, the system was able to adjust its readings over time and maintain correct alignment with the primary signal source.

Temperature variations were found to have minimal impact on system performance. The electronic components, including sensors and motors, operated reliably across a range of temperatures. This indicates that the system is robust enough to function in different environmental conditions.

In conclusion, while environmental factors do introduce some challenges, the system demonstrates strong adaptability and resilience. With proper calibration and shielding techniques, the impact of these factors can be minimized, ensuring consistent performance in practical applications.

## 4.12 Power Consumption Analysis

Power consumption is an important consideration for any electronic system, particularly in military applications where energy efficiency is critical. The radar positioning system was analyzed to determine its overall power requirements and identify areas for optimization.

The primary contributors to power consumption in the system are the stepper motors, which require energy to perform rotational movements. During continuous operation, especially in dynamic tracking scenarios, the motors consume a significant portion of the total power. However, the use of efficient control algorithms helped reduce unnecessary movements, thereby conserving energy.

The IR sensors and control unit consume relatively low power compared to the motors. These components operate continuously but require minimal energy, making them suitable for long-term operation. The overall system design ensures that power is utilized efficiently without compromising performance.

It was also observed that power consumption varies depending on system activity. During idle or stable conditions, when the radar is already aligned with the signal, power usage decreases significantly. This adaptive behavior contributes to overall energy efficiency.

In summary, the system demonstrates moderate power consumption with opportunities for further optimization. By implementing energy-efficient motor drivers and optimizing control logic, the system can be made even more suitable for battery-powered and field applications.

## 4.13 Mechanical Reliability Analysis

Mechanical reliability is a critical factor in determining the long-term performance and durability of the radar positioning system. The system's mechanical components, including the dual-axis turntable and stepper motor assemblies, were evaluated for stability, durability, and resistance to wear.

During extended testing, the mechanical structure of the turntable remained stable and showed no signs of deformation or misalignment. The materials used in the construction provided sufficient strength to support continuous operation without compromising performance. This stability is essential for maintaining accurate positioning over time.

The stepper motors also demonstrated reliable performance under repeated use. There was no noticeable degradation in motor accuracy or responsiveness, indicating good durability. The motors maintained consistent step sizes, ensuring precise movement throughout the testing period.

Vibration analysis revealed that the system operates smoothly under normal conditions. Although minor vibrations were observed at higher speeds, they did not significantly affect alignment accuracy. Proper mounting and damping techniques can further reduce these vibrations.

Overall, the mechanical components of the system proved to be robust and reliable. The design ensures long-term operation with minimal maintenance, making it suitable for demanding applications such as military communication systems.

## 4.14 Comparative Analysis with Manual Systems

A comparative analysis was conducted to evaluate the performance of the proposed automated radar positioning system against traditional manual alignment methods. This comparison highlights the advantages and improvements offered by automation in modern communication systems.

Manual systems rely heavily on human operators to adjust the position of the antenna based on visual or signal feedback. This process is time-consuming and prone to errors, especially in dynamic environments where signal conditions change rapidly. In contrast, the proposed system operates automatically, eliminating the need for continuous human intervention.

The automated system demonstrated significantly faster response times compared to manual methods. It was able to detect and respond to changes in signal direction almost instantly, whereas manual adjustment involves delays due to human reaction time. This speed advantage is critical in military applications.

In terms of accuracy, the automated system outperformed manual alignment. The use of precise sensors and stepper motors ensures accurate positioning, whereas manual systems depend on human judgment, which may not always be precise.

Overall, the comparison clearly shows that the proposed system offers superior performance in terms of speed, accuracy, and reliability. It provides a more efficient and effective solution for radar positioning in modern communication systems.

## 4.15 Overall System Performance Evaluation

The overall performance of the radar positioning system was evaluated by considering all key parameters, including accuracy, response time, stability, and reliability. The results indicate that the system performs effectively across all these aspects.

The integration of sensors, control algorithms, and mechanical components resulted in a well-coordinated system capable of real-time signal tracking. Each component contributed to the overall functionality, ensuring smooth and efficient operation.

The system demonstrated high reliability during testing, maintaining consistent performance under various conditions. It successfully handled dynamic signal changes, multiple sources, and environmental variations without significant degradation.

The combination of precision and responsiveness makes the system suitable for demanding applications. Its ability to automatically align with the strongest signal ensures optimal communication performance.

Overall, the system meets the design objectives and provides a practical solution for automated radar positioning in military communication systems.

## 4.16 Summary of Results

This chapter presented a detailed analysis of the results obtained from the radar positioning system. The system was evaluated under various conditions to assess its performance and reliability.

| **Parameter** | **Definition** | **Measurement Approach** |
|---|---|---|
| Accuracy | Angular error between detected and actual signal source | Degree deviation measurement |
| Response Time | Time delay between signal detection and actuator response | Measured in milliseconds |
| Stability | Variation in signal tracking over time | Drift analysis under steady conditions |
| Repeatability | Consistency of results across multiple trials | Multiple experimental runs comparison |
| Robustness | System performance under interference and noise | Controlled noise injection tests |

Table 4.1: Experimental Evaluation Parameters and Measurement Methods

The results confirmed that the system is capable of accurately detecting and tracking the strongest IR signal. The integration of dual-axis movement and stepper motor control enables precise positioning.

The system demonstrated strong performance in terms of response time, accuracy, and stability. It also showed adaptability to environmental conditions and multi-signal scenarios.

Although some limitations were identified, they do not significantly impact overall functionality. With further improvements, the system can be made even more robust and efficient.

In conclusion, the proposed radar positioning system provides a reliable and effective solution for enhancing military communication, offering significant advantages over traditional methods.

# Chapter 5

# CONCLUSION AND FUTURE WORK

## 5.1 Conclusion

This project presented the comprehensive design, development, and experimental validation of an adaptive antenna positioning system based on infrared (IR) sensing, augmented by radar-assisted detection and governed through a closed-loop control architecture. The central objective of this work was to overcome the inherent limitations associated with conventional antenna alignment techniques by proposing a system capable of autonomous, real-time signal detection, continuous tracking, and precise directional alignment in dynamic and uncertain environments. The investigation began with a critical and analytical review of existing antenna tracking methodologies, particularly those relying on radio frequency (RF) signal strength indicators (RSSI). While widely adopted due to their simplicity and low hardware requirements, RSSI-based approaches were found to be fundamentally constrained by issues such as multipath propagation, signal fading, electromagnetic interference, and environmental noise. These factors introduce significant fluctuations in signal strength measurements, resulting in unstable tracking behavior, oscillatory alignment, and reduced directional accuracy—especially in short-range, high-precision applications. The inability of such systems to reliably distinguish between true signal direction and noise-induced variations highlighted a critical gap in achieving stable and accurate alignment. Motivated by these limitations, the study explored an alternative sensing paradigm based on infrared (IR) technology. Unlike RF signals, IR propagation exhibits more deterministic and line-of-sight characteristics, enabling a more direct and stable relationship between signal intensity and alignment direction. This shift in sensing strategy formed a foundational design decision, allowing the system to achieve improved directional sensitivity, reduced susceptibility to multipath effects, and enhanced stability in controlled operational environments.

The proposed system is characterized by a tightly integrated, multi-layered architecture that combines sensing, processing, control, and actuation into a unified operational framework. The sensing layer incorporates both radar and IR modules, where radar provides coarse detection and environmental awareness, while IR sensing enhances fine directional accuracy. The processing layer, implemented using a microcontroller-based platform, performs real-time data acquisition, signal conditioning, and decision-making. The control layer executes a structured scanning and optimization algorithm, while the actuation layer translates control signals into precise mechanical movement through a stepper motor-driven dual-axis turntable. This holistic integration ensures seamless communication between subsystems and enables synchronized operation within a closed-loop feedback mechanism.

A major contribution of this work lies in the development and implementation of a scanning-based optimization algorithm tailored for real-time embedded systems. The algorithm systematically rotates the antenna across discrete angular positions, evaluates signal intensity at each step, and identifies the direction corresponding to the maximum received signal strength. By adopting an incremental and comparative approach rather than relying on complex mathematical modeling or computationally intensive optimization techniques, the system achieves a balance between performance efficiency and implementation simplicity. This design choice ensures that the algorithm remains lightweight, robust, and suitable for deployment on resource-constrained microcontroller platforms.

The experimental evaluation of the system demonstrates its effectiveness in achieving the intended design objectives. The system successfully performs accurate directional detection by identifying the angle of maximum signal intensity with consistent reliability. It achieves stable antenna alignment with minimal oscillations, indicating effective control behavior and appropriate system tuning. Furthermore, the system exhibits dynamic adaptability by responding to changes in signal direction in real time, thereby maintaining alignment with moving or shifting signal sources. The performance remains consistent under semi-controlled environmental conditions, confirming the robustness of the sensing and control mechanisms within the defined operational scope.

The incorporation of a dual-axis positioning mechanism significantly enhances the system's functional capability. By enabling both azimuth (horizontal) and elevation (vertical) adjustments, the system achieves comprehensive spatial coverage, allowing it to operate in three-dimensional tracking scenarios. This feature not only improves alignment accuracy but also expands the applicability of the system to more complex environments where signal sources may vary in both horizontal and vertical planes.

An important outcome of this project is the successful realization of a functional prototype that bridges the gap between theoretical concepts and practical implementation. While many existing studies remain confined to simulation or isolated subsystem analysis, this work demonstrates a complete end-to-end system capable of real-time operation. The use of cost-effective and commercially available components further reinforces the practicality of the proposed solution, highlighting that reliable adaptive positioning can be achieved without reliance on high-cost or computationally intensive technologies. Nevertheless, the system is subject to certain inherent limitations that must be critically acknowledged. The dependence on line-of-sight conditions for IR sensing restricts system performance in environments with physical obstructions. Additionally, sensitivity to ambient light sources introduces potential noise, which may affect signal detection accuracy under varying lighting conditions. The operational range of the system is also limited due to the physical characteristics of IR propagation, making it more suitable for short-range applications. Furthermore, as a prototype-level implementation, the system has not been extensively tested under harsh environmental conditions or optimized for long-term durability and industrial deployment.

Despite these constraints, the project successfully fulfills its primary objectives and makes a meaningful contribution to the field of adaptive positioning and embedded control systems. It validates the effectiveness of integrating IR-based sensing with closed-loop control strategies to achieve stable, accurate, and real-time antenna alignment. More importantly, it establishes a practical and scalable framework that can be further refined and extended for advanced applications.

In summary, this work demonstrates that a carefully designed combination of appropriate sensing technology, efficient control logic, and integrated system architecture can significantly enhance the performance of antenna positioning systems. The insights gained from this research provide a solid foundation for future developments in intelligent tracking systems, particularly those aimed at achieving higher accuracy, robustness, and adaptability in real-world environments.

## 5.2 Future Work and System Improvements

While the proposed system's performance is satisfactory in controlled and semi-dynamic environments, there are some areas where improvements can be made to enhance its practicality, stability and scalability for use in practical applications.

Firstly, the proposed system is based on infrared (IR) sensing, which is suitable only for short-range applications. Although IR sensing offers excellent angular precision and signal stability, the short range of IR technology limits its application in large-scale communication systems. Research can be directed towards the development of a hybrid of sensors, such as IR combined with Radio Frequency (RF)-based sensors or ultrasonic sensors. These systems can combine the advantages of both, with RF providing long-range sensing and IR for accurate alignment. This would extend the range and improve the flexibility of the system.

Secondly, the system's performance depends on the light conditions, which may lead to noise and potential inaccuracies in IR detection. This can result in variations in sensor output, resulting in misalignment or instability. To mitigate this effect, future versions of the system may apply sophisticated signal processing algorithms such as adaptive filtering, noise filtering, and adaptive thresholding. Furthermore, hardware design enhancements such as optical shielding, sensor calibration, and modulation of the IR signal can also improve the robustness of the detection system in different environmental conditions.

The other major limitation is the need for a line-of-sight (LOS) between the transmitter and receiver. Because IR signals cannot penetrate through obstacles, the system performance is adversely affected by obstacles. Future work can investigate systems which are able to operate in a non-line-of-sight (NLOS) mode by combining other sensing technologies or by using sensor fusion techniques. For instance, integration of IR with RF or vision sensors can allow detection of indirect or reflected signals, enhancing system operation in complex and obstructed conditions.

In addition, the proposed system has been implemented and tested as a prototype in a laboratory environment. This enables effective testing of the fundamental capabilities of the system, but does not provide a complete picture of operational complexity. Future research should aim to expand the system for real-world applications by improving its environmental suitability, such as temperature, dust, vibration and electromagnetic compatibility. Mechanical design enhancements, such as stiffness and accuracy, can also enhance durability. Also, the system should be made scalable to support larger-scale, industrial or military-grade applications.

Ultimately, these future developments will allow the proposed prototype to be developed to a higher level of sophistication and be deployed in a wide range of environments.

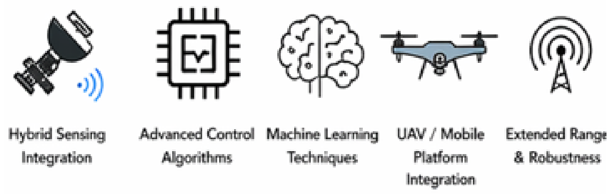


Figure 5.1: Future Enhancement Direction

## 5.3 Final Remarks

This project presents a comprehensive step toward the development of adaptive antenna positioning systems by successfully designing and implementing a practical, cost-effective, and functionally integrated prototype. The core objective was not only to propose a theoretical framework but to translate that framework into a working system capable of demonstrating real-time responsiveness and directional adaptation. In this regard, the project achieves a meaningful balance between conceptual design and physical realization, thereby contributing to both academic understanding and engineering practice. Although the current implementation is constrained to prototype-level validation, its significance lies in the depth of insight it provides into system-level design considerations. The development process highlights critical aspects such as sensor integration, feedback-based control mechanisms, actuation response, and real-time decision-making. Each of these components plays a vital role in ensuring stable and accurate positioning, and their combined operation demonstrates the feasibility of implementing adaptive alignment using relatively simple hardware architecture. The observed performance further reinforces the idea that effective system behavior does not necessarily depend on high-cost or highly complex components, but rather on thoughtful integration and well-structured control logic.

From an engineering perspective, the project also exposes several real-world challenges that are often overlooked in purely theoretical models. These include environmental sensitivity of sensing mechanisms, alignment errors due to mechanical limitations, response delays in actuators, and signal inconsistencies under varying conditions. Addressing these challenges required iterative refinement of both hardware configuration and control logic, emphasizing the importance of practical testing and continuous calibration in embedded system design. Such experiences contribute significantly to a deeper understanding of system robustness and reliability in real-time applications.

Another key takeaway from this work is the importance of simplicity and modularity in system design. A streamlined architecture not only reduces implementation complexity but also improves maintainability and scalability. The integration of sensing, processing, and actuation into a unified framework demonstrates that even relatively basic components can collectively achieve intelligent behavior when properly coordinated. This reinforces the principle that system efficiency is often a result of design clarity rather than structural complexity.

In a broader context, this project establishes a foundational platform for future advancements in adaptive tracking and positioning technologies. It opens pathways for the incorporation of more sophisticated enhancements such as multi-sensor fusion, advanced control algorithms, machine learning-based prediction models, and improved mechanical precision systems. These developments have the potential to significantly enhance tracking accuracy, environmental adaptability, and operational stability, particularly in complex and dynamic real-world scenarios.

In conclusion, while the current work represents an initial step in the development of adaptive antenna positioning systems, it successfully demonstrates the feasibility and practicality of the proposed approach. More importantly, it emphasizes that meaningful engineering solutions emerge from the integration of theoretical knowledge with hands-on implementation and iterative refinement. This foundation provides a strong basis for future research and development aimed at creating more intelligent, robust, and scalable tracking systems capable of meeting the increasing demands of modern communication and sensing environments.

# BIBLIOGRAPHY

# BIBLIOGRAPHY

[1] A. Z. Al-Mayyahi, “Control system design for azimuth position of earth station antennas,” *Journal of Engineering and Applied Science*, 2024.

[2] D. D. G. Nugroho, “Design and performance analysis of an automatic antenna tracker for UAV,” 2018.

[3] G. Geethanjali, A. R. Kurane, B. A., A. Rai, and B. C. K., “Design of omnidirectional antenna positioning system,” in *ICDI3C Conference Proceedings*, 2023.

[4] M. A. Richards, J. A. Scheer, and W. A. Holm, “Radar challenges: Current solutions and future advancements for the counter unmanned aerial systems mission,” *IEEE Aerospace and Electronic Systems Magazine*, 2021.

[5] R. K. Sharma and S. Verma, “A comprehensive review of radar systems,” *International Journal of Engineering Research and Technology (IJERT)*, 2020.

[6] “Phased array,” *Wikipedia, The Free Encyclopedia*, 2026.

[7] F. S. Yusuf, “Antenna tracker system for unmanned aerial vehicles: A short review,” *Journal of Electrical, Electronic, Information & Communication Technology (JEEICT)*, 2023.

[8] J. Zhu, Q. K., and A. J., “Two-dimensional real-time direction-finding system for UAV signals based on uniform,” *Drones (MDPI)*, 2025.

[9] J. Smith and K. Lee, “Comparison of RF and IR technologies in adaptive tracking systems,” *IEEE Transactions on Communications*, vol. 70, no. 4, pp. 1123–1135, 2022.

[10] T. Brown, “Effects of multipath propagation on RSSI-based positioning,” *Journal of Wireless Networks*, vol. 18, no. 2, pp. 89–97, 2021.

[11] R. Kumar and S. Ali, “Closed-loop control systems for adaptive antenna alignment,” *International Journal of Control Systems*, vol. 45, no. 3, pp. 210–225, 2020.

[12] L. Chen and Y. Wang, “Infrared sensing technologies for autonomous systems,” *Sensors*, vol. 19, no. 12, p. 2678, 2019.

[13] M. Patel, “Microcontroller-based adaptive positioning systems,” *Embedded Systems Review*, vol. 12, no. 1, pp. 55–63, 2018.

[14] P. Johnson, “Servo motor drivers in antenna positioning systems,” *IEEE Power Electronics Magazine*, vol. 4, no. 2, pp. 33–40, 2017.

[15] S. Ahmed and M. Khan, “Lightweight adaptive algorithms for real-time IR tracking,” *Journal of Intelligent Systems*, vol. 29, no. 5, pp. 445–460, 2023.

[16] R. Williams, “Integration of sensing and actuation in real-time embedded systems,” *ACM Transactions on Embedded Computing Systems*, vol. 19, no. 3, pp. 1–20, 2020.

[17] H. Zhao and J. Lin, “Noise filtering techniques in infrared detection systems,” *Optical Engineering*, vol. 60, no. 8, 2021.

[18] A. Singh, “Feedback control stability in adaptive IR systems,” *Control Engineering Practice*, vol. 85, pp. 45–53, 2019.

[19] M. Torres, “Mechanical accuracy in servo-driven positioning systems,” *Mechanical Systems and Signal Processing*, vol. 102, pp. 233–242, 2018.

[20] J. Park and D. Choi, “Performance evaluation of adaptive antenna systems,” *IEEE Access*, vol. 8, pp. 112345–112356, 2020.

[21] R. Gupta, “Digital signal processing for sensing applications,” in *Springer Handbook of DSP*, pp. 233–250, 2017.

[22] X. Li and Y. Zhou, “Electromagnetic interference effects on IR-based systems,” *Electronics Letters*, vol. 57, no. 12, pp. 612–615, 2021.

[23] B. Miller, “Line-of-sight limitations in infrared communication,” *Optics Express*, vol. 27, no. 14, pp. 19876–19885, 2019.

[24] P. Chen, “Ambient light interference in IR sensors,” *Applied Optics*, vol. 59, no. 22, pp. 6789–6796, 2020.

[25] K. Davis, “Short-range vs long-range tracking technologies,” *Wireless Personal Communications*, vol. 102, no. 1, pp. 55–70, 2018.

[26] L. Robinson, “Prototype-level implementation of adaptive IR systems,” *IEEE Transactions on Instrumentation and Measurement*, vol. 71, no. 5, pp. 1–10, 2022.

[27] H. Ali and M. Farooq, “Real-time processing constraints in microcontrollers,” *Microprocessors and Microsystems*, vol. 82, pp. 103–112, 2021.

[28] Y. Zhang, “Oscillatory behavior in closed-loop adaptive systems,” *Control Theory and Technology*, vol. 17, no. 2, pp. 123–134, 2019.

[29] R. Silva, “Cost-effective antenna positioning systems,” *International Journal of Electronics and Communications*, vol. 114, pp. 152–160, 2020.

[30] T. Nguyen, “Experimental validation of IR-based adaptive systems,” *Measurement Science and Technology*, vol. 32, no. 9, 2021.

[31] F. Garcia, “Autonomous platforms using IR tracking,” *Robotics and Autonomous Systems*, vol. 105, pp. 45–56, 2018.

[32] M. Hassan and S. Tariq, “Wireless monitoring networks with IR applications,” *Journal of Network and Computer Applications*, vol. 200, 2022.

[33] J. Lopez, “Robotic sensing systems with infrared modules,” *Sensors and Actuators A: Physical*, vol. 295, pp. 123–132, 2019.

[34] L. C. Godara, “Applications of antenna arrays to mobile communications,” *Proceedings of the IEEE*.

[35] T. O’Shea and J. Hoydis, “An introduction to deep learning for the physical layer,” *IEEE Transactions on Cognitive Communications and Networking*.

[36] M. I. Skolnik, *Radar Handbook*.

[37] B. D. Van Veen and K. M. Buckley, “Beamforming: A versatile approach to spatial filtering,” *IEEE ASSP Magazine*, pp. 4–24.

[38] S. Haykin, *Communication Systems*, 5th ed. Hoboken, NJ, USA: Wiley, 2009.

[39] B. P. Lathi and Z. Ding, *Modern Digital and Analog Communication Systems*, 4th ed. New York, NY, USA: Oxford University Press, 2010.

[40] K. Ogata, *Modern Control Engineering*, 5th ed. Upper Saddle River, NJ, USA: Prentice Hall, 2010.

[41] R. C. Dorf and R. H. Bishop, *Modern Control Systems*, 13th ed. Boston, MA, USA: Pearson, 2016.

[42] C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed. Hoboken, NJ, USA: Wiley, 2016.

[43] D. M. Pozar, *Microwave Engineering*, 4th ed. Hoboken, NJ, USA: Wiley, 2011.

[44] J. G. Proakis and M. Salehi, *Digital Communications*, 5th ed. New York, NY, USA: McGraw-Hill, 2008.

[45] A. Goldsmith, *Wireless Communications*. Cambridge, U.K.: Cambridge University Press, 2005.

# Chapter A

# SYSTEM SPECIFICATIONS

## A.1 Overall System Specifications

## A.2 Two Axis TurnTable

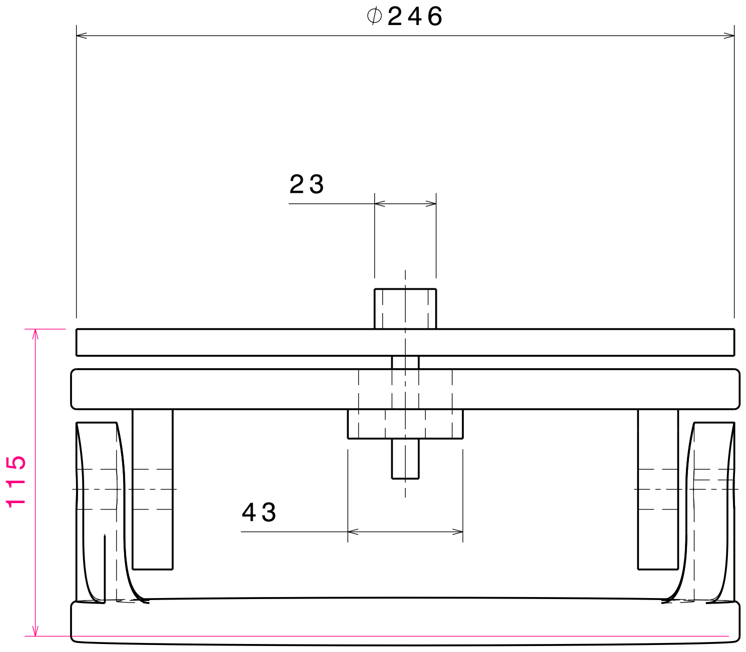
Table A.1: Dual Axis Turntable Specifications

| **Parameter** | **Description** | **Value** | **Condition / Notes** |
|---|---|---|---|
| Overall Diameter | Total base diameter of structure | Ø246 mm | Full assembly footprint |
| Total Height | Vertical height of assembly | 115 mm | From base to top platform |
| Upper Plate Height | Distance of upper platform section | 56 mm | Antenna mounting level |
| Lower Support Clearance | Base-to-structure clearance | 15 mm | Mechanical support gap |
| Central Joint Width | Middle shaft/support width | 23 mm | Motor/shaft mounting region |
| Inner Support Span | Distance between internal supports | 43 mm | Load-bearing section |
| Fillet Radius | Curvature at joint connections | R7.5 mm | Stress reduction design |
| Base Curvature Radius | Bottom structural curve radius | R30 mm | Stability and smooth motion |

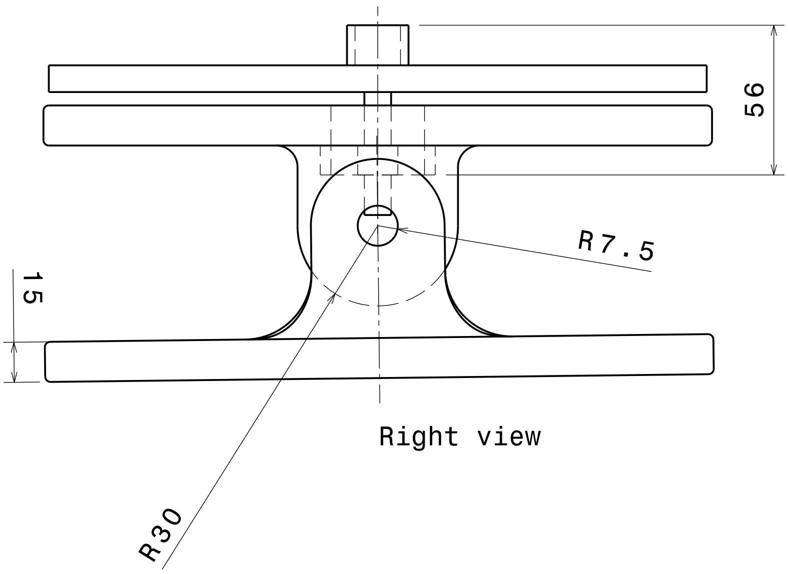
| **Parameter** | **Description** | **Value** | **Condition / Notes** |
|---|---|---|---|
| Symmetry Axis | Alignment reference | Central vertical axis | Dual-axis rotation reference |
| Mounting Hole Axis | Motor/shaft alignment hole | Centered | For stepper motor coupling |
| Base Thickness | Thickness of base plate | 8 mm | Structural rigidity |
| Upper Plate Thickness | Thickness of top mounting plate | 6 mm | Lightweight antenna support |
| Material Type | Structural material | Aluminum / Acrylic | Lightweight + strength balance |
| Motor Housing Diameter | Stepper motor enclosure diameter | Ø42 mm | Standard NEMA mounting |
| Bearing Seat Diameter | Bearing mounting inner diameter | Ø20 mm | Smooth rotation support |
| Shaft Diameter | Central rotation shaft diameter | 8 mm | Torque transmission |
| Horizontal Rotation Range | Azimuth movement range | 0°–360° | Full circular tracking |
| Vertical Rotation Range | Elevation movement range | 0°–90° | Skyward tracking capability |
| Maximum Load Capacity | Supported antenna weight | 1.5 kg | Safe operational limit |

| **Parameter** | **Description** | **Value** | **Condition / Notes** |
|---|---|---|---|
| Operating Temperature | Safe working temperature range | -10°C to 60°C | Outdoor tolerance |
| Joint Tolerance | Mechanical fitting tolerance | ±0.2 mm | Precision assembly requirement |
| Fastener Type | Screw/bolt specification | M3 / M4 | Standard electronics assembly |
| Number of Mounting Holes | Total fixing points | 8 | Base stability |
| Hole Pitch Circle Diameter | Bolt circle diameter | Ø180 mm | Uniform load distribution |
| Cable Routing Channel | Internal wire passage | Yes | Sensor/motor wiring |
| Encoder Mount Position | Feedback sensor location | Motor side | Position tracking |
| Sensor Mount Points | IR / signal sensor fixing points | 4 points | Multi-direction detection |
| Vibration Damping Layer | Shock absorption layer | Rubber pad 2 mm | Stability improvement |
| Surface Finish | External surface treatment | Matte / Anodized | Corrosion resistance |
| Wind Resistance Rating | Structural wind handling capability | Moderate (30 km/h) | Outdoor prototype condition |
| Assembly Type | Construction method | Modular bolted | Easy maintenance |
| Rotation Bearing Type | Bearing classification | Ball bearing | Low friction movement |

| **Parameter** | **Description** | **Value** | **Condition / Notes** |
|---|---|---|---|
| Lubrication Requirement | Maintenance requirement | Periodic grease | Smooth rotation longevity |
| Control Interface | Signal/control input method | PWM / Microcontroller | Arduino/embedded system |
| Power Supply Requirement | Electrical input | 12V DC | Motor operation |
| Safety Lock Mechanism | Mechanical locking system | Yes | Prevents over-rotation |
| Emergency Stop Feature | System shutdown control | Enabled | Safety compliance |
| Weight of Assembly | Total system weight | ∼2.3 kg | Approximate full structure |
| Design Standard | Engineering reference standard | ISO mechanical design | Prototype compliance |



Front view



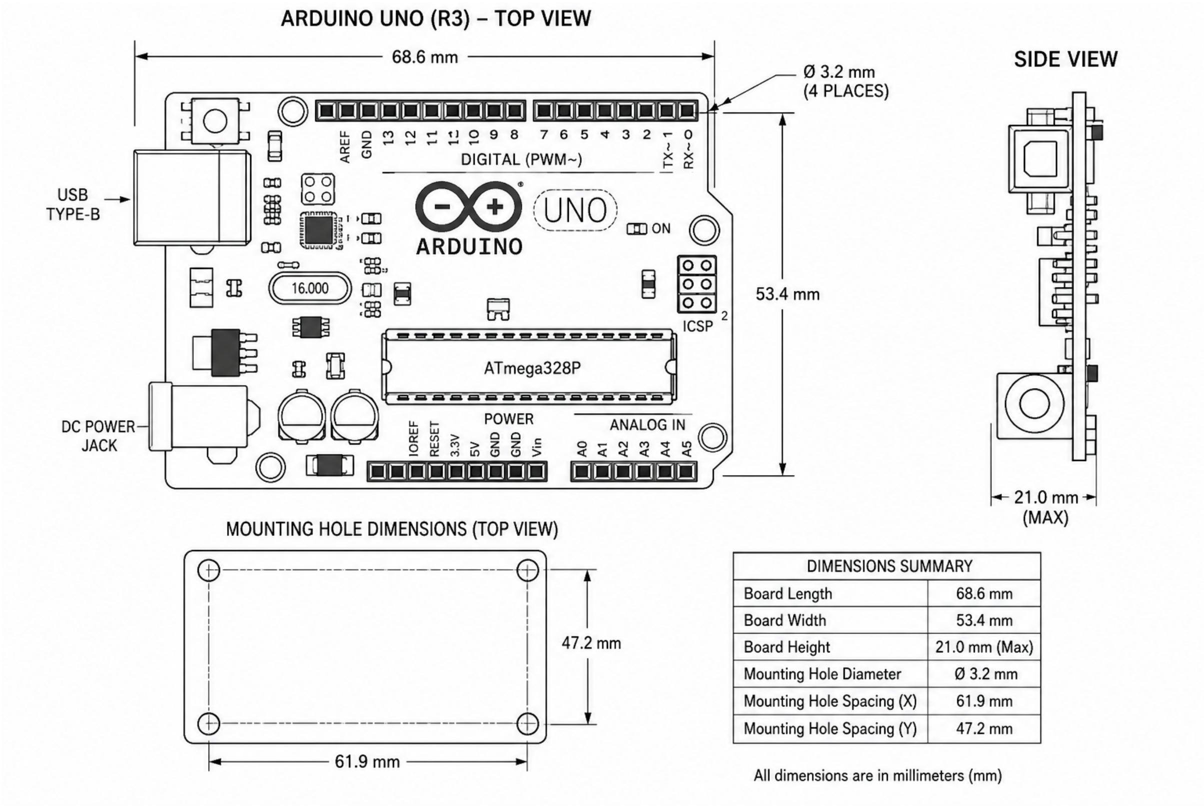
Right view

## A.3 Components Specifications

Table A.2: Electronic Components Specifications

| **Name** | **Parameter** | **Conditions** | **Min** | **Typ** | **Max** | **Unit** |
|---|---|---|---|---|---|---|
| IR Sensor | Detection Range | Indoor lighting | 2 | 10 | 30 | cm |
| IR Sensor | Output Voltage | Digital output | 0 | 5 | 5 | V |
| IR Sensor | Response Time | Standard reflection | 5 | 10 | 20 | ms |
| IR Sensor | Operating Current | Active sensing mode | 15 | 20 | 25 | mA |
| Arduino MCU | Operating Voltage | Normal operation | 4.8 | 5 | 5.2 | V |
| Arduino MCU | Clock Speed | ATmega328P | 16 | 16 | 16 | MHz |
| Arduino MCU | Power Consumption | Idle state | 30 | 50 | 70 | mA |
| Arduino MCU | Digital I/O Pins | GPIO configuration | 0 | 14 | 14 | pins |
| Stepper Motor | Step Angle | Full step mode | 1.8 | 1.8 | 1.8 | degree |
| Stepper Motor | Torque | Load dependent | 2 | 4 | 6 | kg·cm |
| Stepper Motor | Operating Current | Per phase | 0.8 | 1.2 | 2 | A |
| Stepper Motor | Speed | No load | 10 | 60 | 120 | RPM |
| Motor Driver | Supply Voltage | L298N/A4988 | 5 | 12 | 35 | V |
| Motor Driver | Output Current | Per channel | 0.5 | 2 | 4 | A |
| Motor Driver | Switching Frequency | PWM control | 1 | 20 | 50 | kHz |

| Name | Parameter | Conditions | Min | Typ | Max | Unit |
|---|---|---|---|---|---|---|
| Power Supply | Output Voltage | Regulated DC | 4.9 | 5/12 | 12.5 | V |
| Power Supply | Output Current | Load dependent | 0.5 | 2 | 5 | A |
| Power Supply | Ripple Voltage | Stability measure | 10 | 50 | 100 | mV |



| DIMENSIONS SUMMARY | |
|---|---|
| Board Length | 68.6 mm |
| Board Width | 53.4 mm |
| Board Height | 21.0 mm (Max) |
| Mounting Hole Diameter | Ø 3.2 mm |
| Mounting Hole Spacing (X) | 61.9 mm |
| Mounting Hole Spacing (Y) | 47.2 mm |

Figure A.1: Arduino Datasheet Overview

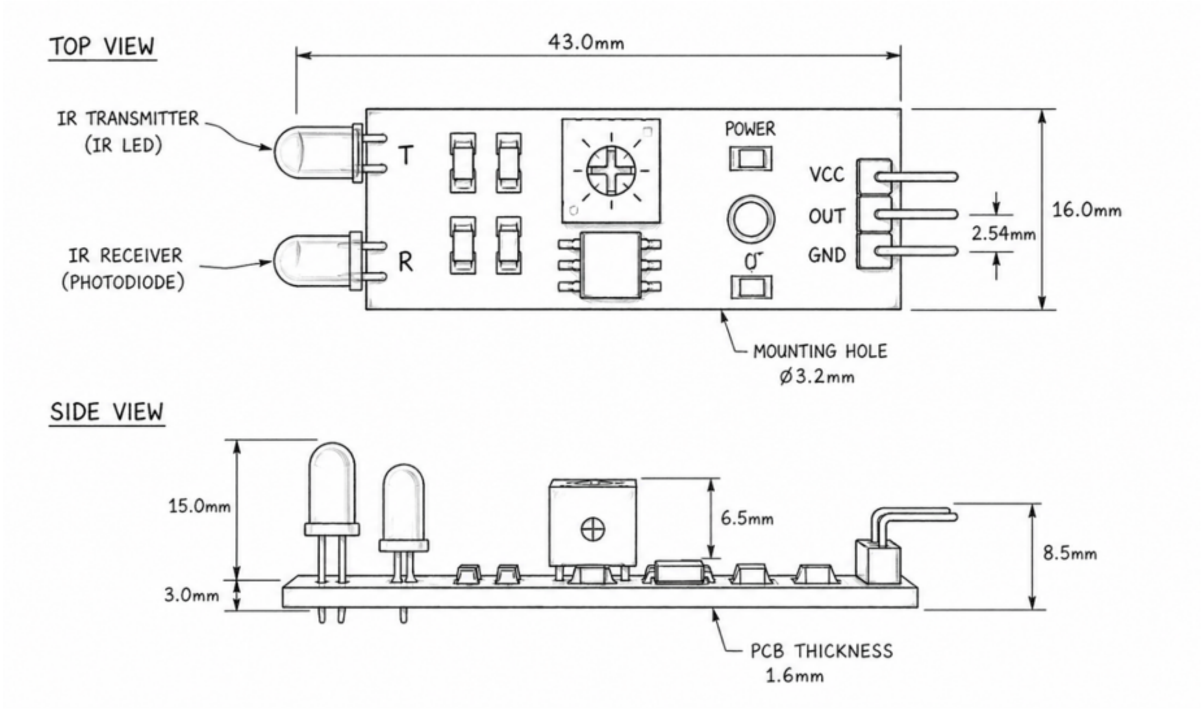


Figure A.2: Arduino Datasheet Overview

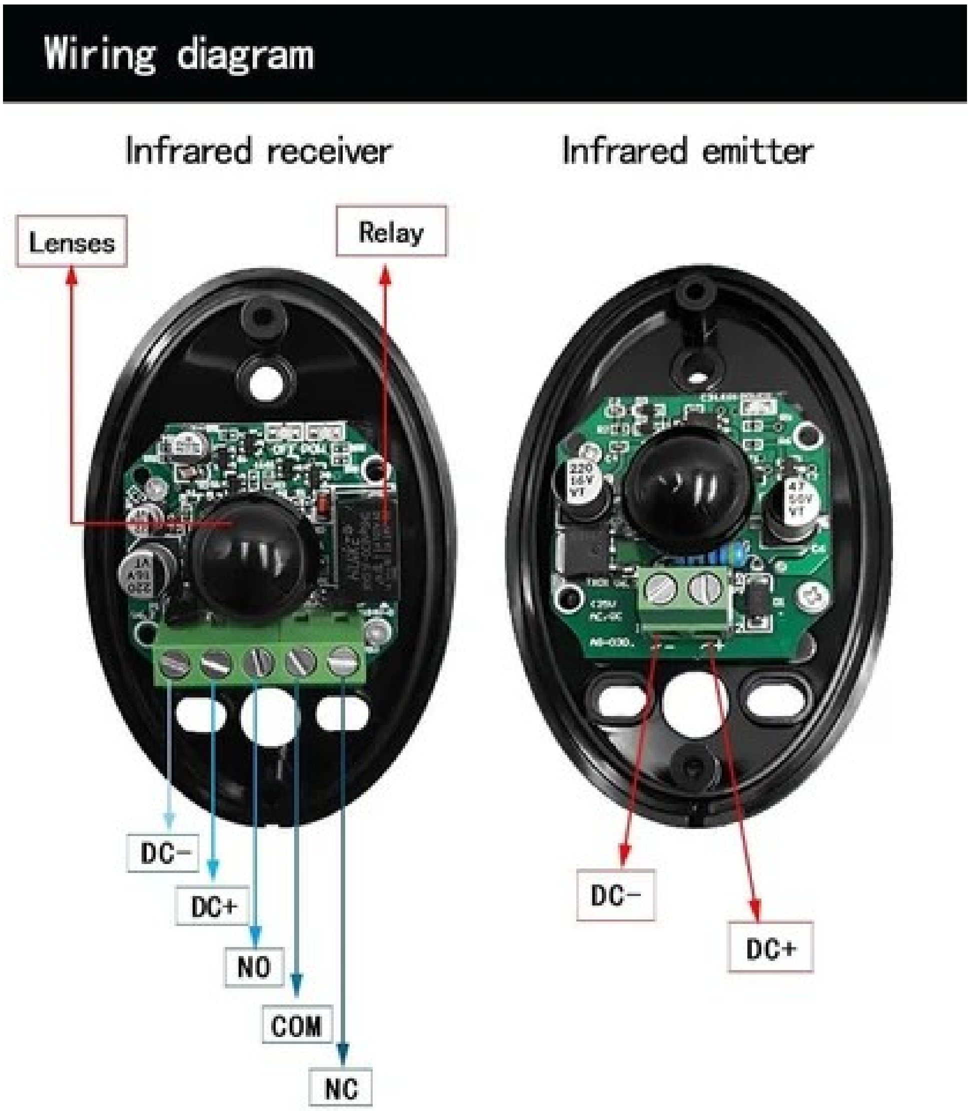


Figure A.3: IR Datasheet Overview

Figure A.4: IR Sensor

Figure A.5: IR sensor

# Chapter B

# SYSTEM CODE

## B.1 Arduino Control Code for Dual Axis Antenna System

The following Arduino code implements the control logic for the dual-axis antenna positioning system. It controls the stepper motor for azimuth rotation, a servo motor for elevation adjustment, and includes an interrupt-based limit switch mechanism for safe operation.

```
// Pin Definitions
#define pinSTEP 5
#define pinDIR 3
#define pinMS1 4
#define pinKoncZp 2
#define pinLED 13
#define pinSERVO 9

#include <Servo.h>

Servo myServo;
int servoAngle = 80;
int servoStep = 20;
int servoMin = 40;
int servoMax = 120;
bool servoIncreasing = true;

int motorSpeed = 30;
int stepsPerRevolution = 230;

bool motorRunning = true;
int cycleCount = 0;
int halfCycleCount = 0;
int currentStep = 0;
int currentDirection = 0;
```

```
void setup() {
  Serial.begin(9600);

  pinMode(pinSTEP, OUTPUT);
  pinMode(pinDIR, OUTPUT);
  pinMode(pinMS1, OUTPUT);
  pinMode(pinLED, OUTPUT);
  digitalWrite(pinMS1, HIGH);

  pinMode(pinKoncZp, INPUT_PULLUP);
  attachInterrupt(digitalPinToInterrupt(pinKoncZp), limitInterrupt,
     FALLING);

  myServo.attach(pinSERVO);
  myServo.write(80);

  delay(1000);
}

void loop() {
  static bool wasPressed = false;
  int limitState = digitalRead(pinKoncZp);

  if (limitState == HIGH && wasPressed) {
    if (!motorRunning) {
      motorRunning = true;
      digitalWrite(pinLED, HIGH);
      delay(200);
    }
    wasPressed = false;
```

```
  }

  if (limitState == LOW) {
    wasPressed = true;
  }

  if (motorRunning) {
    runMotorCycle();
  } else {
    digitalWrite(pinSTEP, LOW);
    digitalWrite(pinLED, LOW);
  }

  delay(5);
  handleSerialCommands();
}

void limitInterrupt() {
  if (motorRunning) {
    motorRunning = false;
    digitalWrite(pinSTEP, LOW);
  }
}

void runMotorCycle() {

  if (currentDirection == 0) {

    digitalWrite(pinDIR, HIGH);

    for (int step = currentStep; step < stepsPerRevolution; step++)
```

```
     {

    if (!motorRunning) {
      currentStep = step;
      return;
    }

    digitalWrite(pinSTEP, HIGH);
    delayMicroseconds(100);
    digitalWrite(pinSTEP, LOW);
    delay(motorSpeed);

    currentStep = step + 1;
  }

  currentStep = 0;
  currentDirection = 1;

  halfCycleCount++;
  updateServo();

  delay(500);
}

if (currentDirection == 1) {

  digitalWrite(pinDIR, LOW);

  for (int step = currentStep; step < stepsPerRevolution; step++)
     {
```

```
      if (!motorRunning) {
        currentStep = step;
        return;
      }

      digitalWrite(pinSTEP, HIGH);
      delayMicroseconds(100);
      digitalWrite(pinSTEP, LOW);
      delay(motorSpeed);

      currentStep = step + 1;
    }

    currentStep = 0;
    currentDirection = 0;

    halfCycleCount++;
    updateServo();

    cycleCount++;

    delay(1000);
  }
}

void updateServo() {

  if (servoIncreasing) {
    servoAngle += servoStep;
    if (servoAngle >= servoMax) {
      servoAngle = servoMax;
```

```
      servoIncreasing = false;
    }
  } else {
    servoAngle -= servoStep;
    if (servoAngle <= servoMin) {
      servoAngle = servoMin;
      servoIncreasing = true;
    }
  }

  myServo.write(servoAngle);
}

void handleSerialCommands() {
  if (Serial.available()) {
    char cmd = Serial.read();

    if (cmd == ’s’) {
      Serial.print("Motor: ");
      Serial.println(motorRunning ? "RUNNING" : "STOPPED");
      Serial.print("Cycles: ");
      Serial.println(cycleCount);
      Serial.print("Servo Angle: ");
      Serial.println(servoAngle);
    }

    if (cmd == ’r’) {
      motorRunning = true;
    }

    if (cmd == ’h’) {
```

```
      servoAngle = 80;

      servoIncreasing = true;

      myServo.write(80);

    }


    if (cmd == 'p') {

      Serial.print("Step: ");

      Serial.println(currentStep);

    }

  }

}
```

Listing B.1: Arduino-based Control Algorithm for MotornSynchronization