Low Cost Passive Aircraft Detection System for Remote Areas

Divide and Conquer Document

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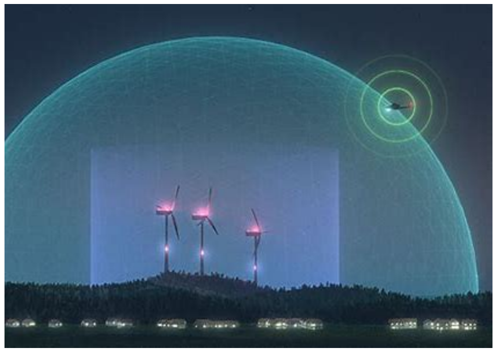

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A. Chapter 1 Executive Summary

Unauthorized border incursions by aircraft operating in remote areas without conventional air traffic control radar systems pose significant threats to the security and sovereignty of nations within the U.S. SOUTHERN COMMAND Area of Responsibility. These regions often lack radar coverage due to the high cost of implementing and maintaining such infrastructure, which is frequently beyond the financial capabilities of the affected nations. To address this challenge, the Low-Cost Passive Aircraft Detection System for Remote Areas offers an innovative solution that utilizes a passive RF detection approach with Commercial Off-The-Shelf (COTS) components. Unlike traditional active radar systems, this passive system "listens" for aircraft signals through open RF receivers arranged in an array along border areas. The detected information is then transmitted in real-time via Starlink SATCOM to a secure live-streaming website, enabling global access for users to monitor activity and take timely action as needed. By relying on passive RF detection rather than emitting radar waves, the system significantly reduces costs, energy consumption, and detectability, making it an ideal solution for remote and resource-constrained environments.

The system is designed with advanced Digital Signal Processing (DSP) and machine learning algorithms, which ensure a high detection accuracy rate of over 95% while maintaining false positive rates below 5%. Its weatherproof and solar-powered design enables continuous operation for over a decade, even in harsh environmental conditions, while its plug-and-play setup simplifies deployment and maintenance. With a prototype budget of approximately $8,000, this cost-effective solution provides a viable alternative to expensive existing systems, such as Raytheon's Silent Sentry and FlightAware Global. Unlike these systems, the proposed design emphasizes scalability, affordability, and flexibility, offering enhanced real-time data access, improved anomaly detection, and the ability to expand coverage as needed.

The initial prototype will include a single working unit comprising a remote sensor with a PC and battery power supply, enabling a field test to validate its performance in detecting aircraft using passive RF methods. The system's phased development includes research, design, testing, and a transition to a fully solar-powered configuration in its second phase. Beyond technical development, the project will conduct a comprehensive business analysis to explore the potential for producing and deploying arrays of these passive sensors on a global scale. This analysis will consider the scalability of the solution, its integration into existing monitoring infrastructures, and its potential to address similar challenges in other regions. By offering an affordable and sustainable alternative to conventional radar systems, the Low-Cost Passive Aircraft Detection System represents a transformative approach to securing remote border areas and enhancing global monitoring capabilities.

B. Chapter 2 Project Description
1. Motivation and Background

In many remote areas, keeping track of aircraft is a big challenge because traditional radar systems are not always available. Setting up radar requires a lot of money, infrastructure, and maintenance, which makes it hard for many regions to afford. Without proper monitoring, unauthorized aircraft can fly undetected, which could be a serious security risk. Some of these aircraft may be used for illegal activities like smuggling, while others might be operating without proper clearance. Governments and security agencies need a reliable way to detect these planes, but existing radar systems are often too expensive or impractical to install in remote locations.

Our project is designed to solve this problem in a more affordable and efficient way. Instead of using active radar, which sends out signals to detect aircraft, our system passively listens for signals that planes naturally emit. This method makes it harder for unauthorized aircraft to hide or interfere with the detection process. By using commercial off-the-shelf components, we can keep costs low while still creating a system that works well. The system will also be connected to Starlink SATCOM, allowing real-time transmission of detected aircraft data to a secure online platform where authorities can access it from anywhere in the world. This means that security teams don't have to be near the detection units to see the data—they can monitor everything remotely.

The project is being developed in two main phases, each with different responsibilities. In the first phase, another group is building and testing the aircraft detection hardware. This includes setting up RF receivers and antennas that will listen for aircraft signals and developing a program that can recognize and classify those signals. Their job is to make sure the detection system works and can reliably identify aircraft. Our team is focused on what happens after the detection process—making sure multiple detection units can work together.

In the second phase, our team takes the working detection units from the first phase and expands them into a larger system. Instead of just one unit detecting aircraft, we will deploy multiple units over a wide area and ensure they all communicate with each other. This is important because a single detection unit can only confirm that an aircraft is nearby, but multiple units working together can determine the exact location of the aircraft. Our job is to develop the networking and coordination system that allows these units to share data in real time. We will also create software that processes this information, using multiple signals to calculate the aircraft's position. Another key part of our work is testing and optimizing the system to ensure it works well in different environments.

Additionally, we will develop a centralized monitoring platform that will allow security teams to track detected aircraft, view alerts, and analyze movement patterns. This platform will act as a user-friendly interface where all detection data is displayed in one place. To make sure the system is reliable, we will also create failover mechanisms, meaning that if one unit stops working, the other units will still function without disruption.

By the end of the second phase, our system will be able to detect aircraft, determine their exact location, and send this information in real time to security teams. Compared to traditional radar, our solution is cheaper, harder to detect, and requires less maintenance, making it ideal for use in remote areas. Because it can be easily expanded by adding more detection units, it provides a flexible and scalable way to monitor large regions.

Looking ahead, this system could be expanded to monitor entire borders or other high-security areas where radar is not practical. If successful, it could provide an affordable alternative to expensive radar-based systems while still offering highly accurate aircraft tracking. By combining passive RF detection, multi-unit coordination, and real-time satellite communication, our project aims to improve aircraft monitoring in areas that currently lack proper surveillance.

2. Goals and Objectives

Basic Goals:

-Develop a working prototype capable of detecting aircraft RF signals.
-Ensure real-time reporting of detection data using Starlink SATCOM.
-Achieve cost efficiency by maintaining a unit cost below $8,000.
-Integrate multiple detection units into a network system.
-Ensure real-time communication between all deployed units.
-Develop software to process and combine data from multiple units.
-Implement an aircraft location estimation algorithm based on the signals received from the different units.
-Confirm that the system can distinguish between aircraft and non-aircraft signals.
-Establish a centralized interface to monitor all units in real time.

Advanced Goals:

-Enhance detection accuracy to exceed 95%.
-Implement robust machine learning algorithms for signal classification.
-Ensure easy deployment with a plug-and-play setup process.
-Optimize the network of detection units for accurate positioning of detected aircraft.
-Develop and refine multi-unit coordination protocols to ensure seamless communication.
-Improve signal processing algorithms to reduce false positives and negatives.
-Ensure scalability, allowing the system to expand to cover larger areas efficiently.
-Implement a failover mechanism so if one unit fails, others can still function properly.
-Integrate machine learning techniques to enhance aircraft identification accuracy.

Stretch Goals:

-Enable scalability by designing the system for deployment in arrays along border regions.
-Integrate additional features, such as anomaly detection, to identify unauthorized aircraft behavior patterns.
-Extend system durability to operate effectively in harsh environments for over 10 years.
-Enable automated deployment and self-calibration of new detection units.
-Develop predictive tracking algorithms, allowing the system to estimate an aircraft’s future location.
-Implement a secondary verification system (e.g., optical or infrared cameras) to visually confirm detected aircraft.

-Explore alternative communication methods (e.g., radio relay, 5G) in addition to Starlink SATCOM.
-Design an easy-to-use web-based dashboard for remote monitoring and management.

Objectives:
-Seamless Unit Deployment – Design a standardized process for placing multiple detection units in the field and ensuring they work together effectively.
-Multi-Unit Data Fusion – Develop software that can take input from several detection units and combine their data to improve aircraft identification and tracking
-Aircraft Positioning System – Implement algorithms that can accurately triangulate the location of a detected aircraft using signal data from multiple units.
-Reliable Communication Network – Ensure all units are synchronized and can share detection data in real time without interference or significant delay.
-Robust Performance Testing – Conduct thorough testing to ensure accuracy, reliability, and fault tolerance in real-world conditions.
-Integration with External Systems – Enable the system to connect with existing security infrastructure for wider use beyond just your group's research.
-User-Friendly Interface – Develop a dashboard that displays detected aircraft, system status, and alerts in an intuitive way.
-Scalability for Future Expansion – Ensure the system is designed in a way that allows for easy expansion with minimal additional setup.

3. Features and Functionalities

The Low-Cost Passive Aircraft Detection System is designed to achieve the following:

Passive Detection: The system passively "listens" for RF emissions from aircraft, eliminating the need for active radar signals. This reduces costs and energy consumption compared to traditional radar systems.

Starlink SATCOM Integration: Detected data is transmitted via the Starlink satellite communication network to a live-streaming website, enabling global monitoring and analysis.

Digital Signal Processing (DSP) and Machine Learning: Advanced DSP techniques and machine learning algorithms are employed to analyze RF signals, ensuring high accuracy (>95%) and a low false-positive rate (<5%).

Scalable Deployment: The system design supports scalability, allowing for arrays of sensors to cover vast remote areas effectively.

Ease of Setup: A plug-and-play setup process ensures quick and seamless deployment in under one hour.

Durability:Weatherproof enclosures and solar-powered operations enhance reliability, enabling a lifespan of over 10 years in remote and harsh conditions.

3.1 Customer Input:

Affordability: Customers in remote areas, particularly governments or agencies with limited budgets, emphasized the importance of keeping costs low while maintaining functionality. This directly influenced the decision to use Commercial Off-The-Shelf (COTS) components, ensuring ease of access and a unit cost under $8,000.

Ease of Use: End users requested a system that does not require extensive training or specialized skills for setup and operation. This led to the implementation of an entirely self-sufficient design to minimize maintenance.

Reliability in Harsh Environments: Stakeholders working in remote and extreme conditions needed a system that could withstand tough weather. This prompted the integration of **weatherproof enclosures** and **solar-powered functionality** to enhance durability.

3.2 Comparable Products/Projects:

Active Radar Systems: Traditional active radar systems are easily detectable through many different. While they provide excellent detection, their detectability will hinder the usefulness of the device for detecting enemy aircraft. This system eliminates the need for active radar by adopting a **passive RF detection approach**, which is simpler and undetectable.

Commercial RF Monitoring Devices: Existing RF monitoring tools inspired the use of **Digital Signal Processing (DSP)** and **machine learning algorithms** for accurate signal classification and a low false-positive rate. However, these commercial tools are not designed for scalable border monitoring, which is a unique aspect of this project.

Satellite Communication Solutions: Current surveillance systems often lack real-time global access. By incorporating **Starlink SATCOM**, this project ensures that detection data is instantly accessible from anywhere, making it more versatile and scalable than many existing solutions.

4. Existing Products

Raytheon - Silent Sentry:

- Raytheon's Silent Sentry is a passive radar system similar to the one we are trying to design.
- It uses the same application of passive RF analysis to detect aircrafts and flights, with a proprietary focus on surveillance and monitoring.
- The biggest downfall of Silent Sentry is that it is not commercially available, and it requires a "headquarters" or central operation point.
- Additionally, it is not expandable, with no access to Starlink for widespread use.

FlightAware Global:

- This system is less similar than the Raytheon Silent Sentry, as it is not passive. However, the communications side of this system is more in-line with our design.
- FlightAware Global uses ADS-B, which is compulsory of the aircrafts to give. This means that dangerous or uncooperative flights are not detected by this system.

- The big plus for this system is its UI and modularity, allowing many users to access the info once the aircrafts are detected.

Our design differs and excels compared to these two products, because of low-cost, flexible access due to Starlink communication, modular design for expansion, and the ability to physically see the aircrafts due to the Optics Component. This new design will create an in-between for companies that want flexible systems, but also passive systems that are harder to detect.

5. Specifications

Component(s)	Parameter	Specifications
Wideband Antenna	Frequency Range	300 - 3000MHz
RF Spectrum Analyzer	Frequency Range	9kHz - 6GHz
Camera Tilt Mechanism	Angle of rotation	Can rotate the camera 70° in either direction from center
Power Supply	Reliability	Can power the system for a year at a time with minimal maintenance needed
Detection Software	Processing Time	Time between startup and flagging <100ms
Detection Algorithm	Accuracy	At least 95% accurate at detecting the presence of aircraft
Camera/Lens System	Resolution	User can identify details larger the 10 ft across from a distance of 50,000 ft, and details larger than 5 ft across from a distance of 30,000 ft

Table 1: Engineering Specifications

6. Block Diagram

6.1 Hardware block diagram

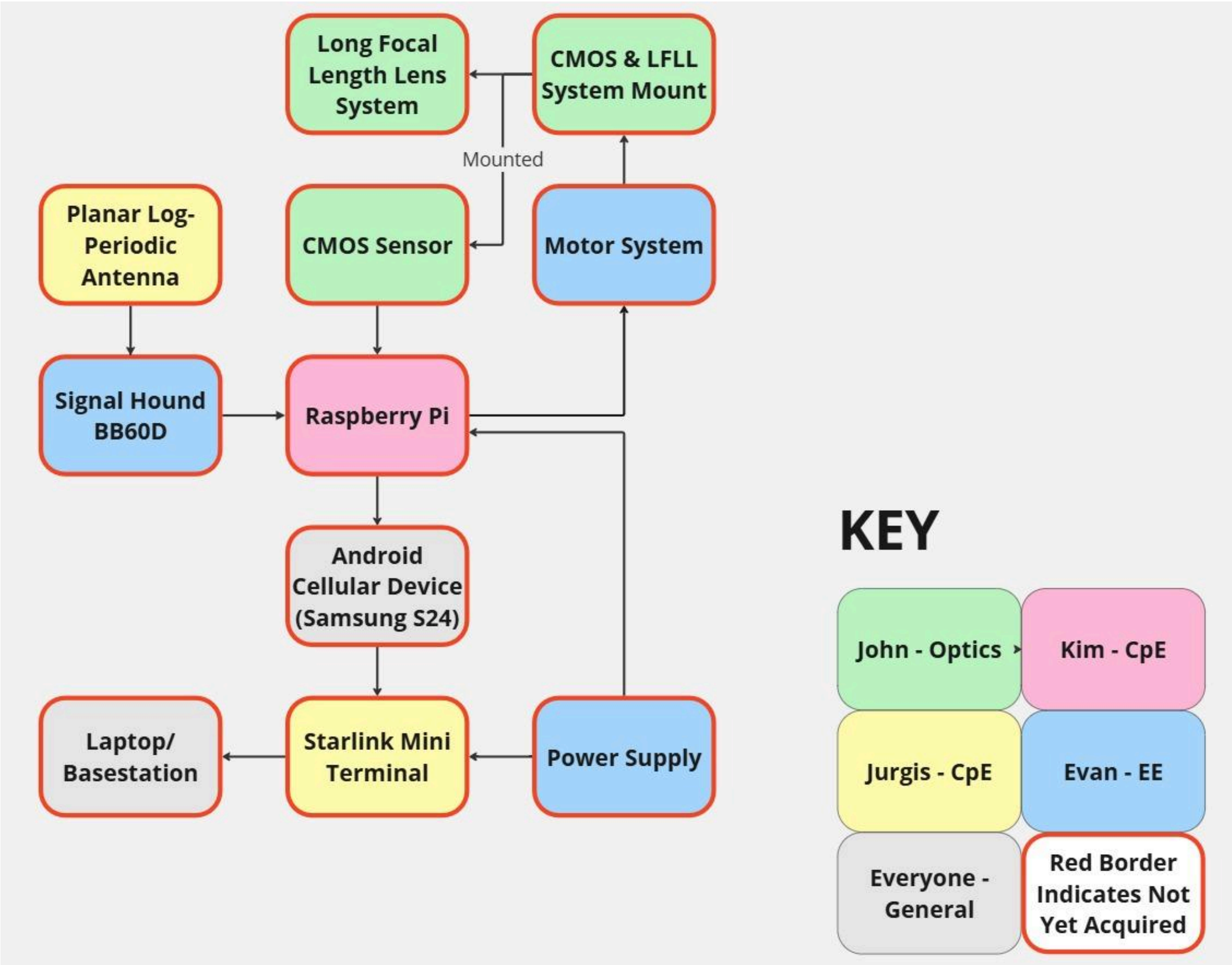

Figure 1: Hardware block diagram

6.2 Optical Schematic:

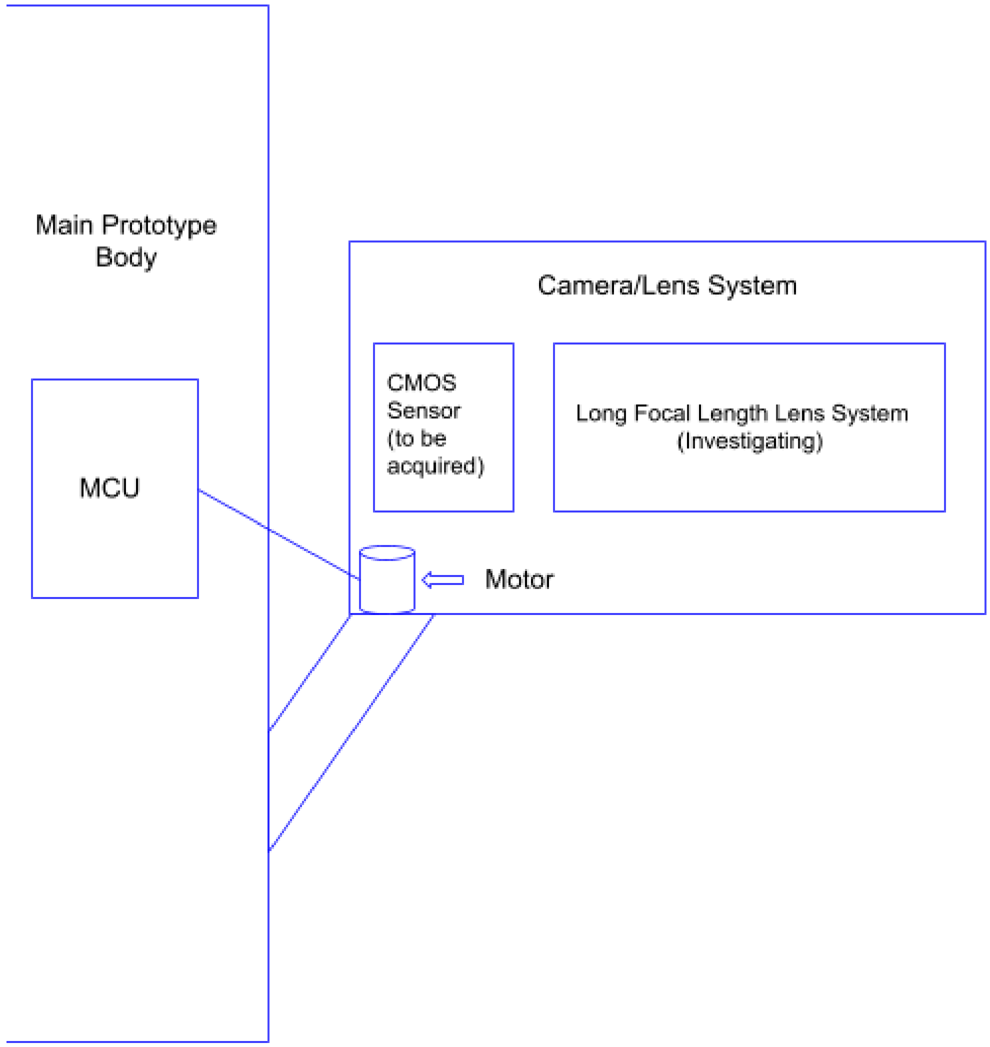

figure 2: Optical schematic

6.3 Software Block Diagram:

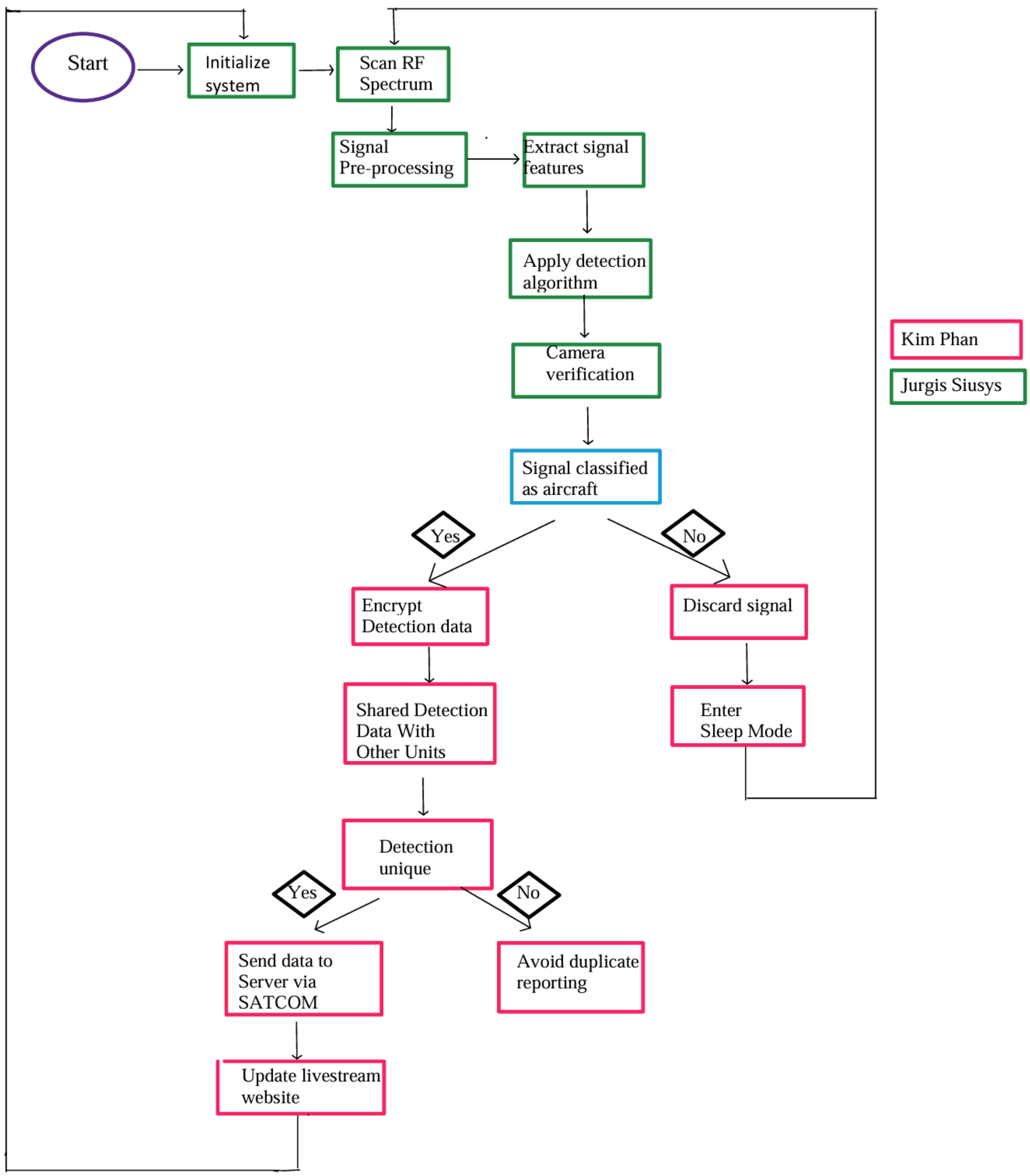

Figure 3: Software block diagram

Flowchart Description

Initialization

- The software environment is initialized, ensuring all necessary services are running and the system is ready to process data.
- Software modules that interface with the RF receivers are started to begin scanning the RF spectrum.
- A stable connection to Starlink's SATCOM service is established through the software interface to enable reliable data transmission.
- Configuration files containing detection algorithm parameters (e.g., RF signal thresholds, noise filters, aircraft signal profiles) are loaded from a database.

RF Signal Reception

- The software continuously scans the RF spectrum by controlling the RF receivers for real-time data collection.
- Incoming analog RF signals are digitized using Analog-to-Digital Conversion (ADC) techniques for processing.
- The digitized signals are stored in memory buffers to ensure uninterrupted data processing during continuous scanning.

Signal Pre-Processing

- Digital Signal Processing (DSP) algorithms (e.g., Fast Fourier Transform (FFT) or wavelet transform) are applied to filter out noise and enhance signal quality.
- Candidate signals are identified, focusing on known aircraft-related RF signatures such as ADS-B, Mode S, or other specific transmission protocols.
- Signals with insufficient strength are discarded based on predefined noise thresholds to optimize detection accuracy.

Feature Extraction

- The software extracts critical signal features such as frequency, amplitude, and modulation type and organizes them into structured data formats (e.g., arrays, data frames).
- Extracted features are compared against a locally stored database of known aircraft RF profiles, which is continuously updated with new and evolving signal patterns.

Detection Algorithm

- The software applies machine learning models (e.g., Random Forest, Support Vector Machine (SVM)) or rule-based heuristics to classify signals as aircraft-related or noise.
- Detected signals are cross-referenced with time, location, and trajectory data from a GPS or onboard sensors to confirm aircraft identity and improve detection accuracy.

Camera Verification

- If an aircraft is detected, the software activates the camera to capture real-time images or video of the detected area.
- The captured footage is processed using image recognition algorithms (e.g., OpenCV, deep learning models) to visually confirm the presence of an aircraft, improving detection reliability.

Data Transmission

- Detection data, including RF signal details and camera footage, is encrypted to ensure security and privacy.
- The encrypted data is transmitted via the Starlink SATCOM link using a secure communication protocol to a centralized server or a livestream platform.

Live Data Display and Alerts

- The software updates the livestream website with real-time detection data, including location, altitude, and trajectory, along with any relevant images or videos.
- The software triggers automated alerts to users when unauthorized aircraft are detected. Alerts can be sent via email, SMS, or system notifications.

Continuous Monitoring

- The system repeats the RF scanning and data processing cycle continuously to ensure 24/7 aircraft detection.
- All detection events, system logs, and performance metrics (e.g., detection accuracy, latency) are logged for later analysis and optimization.

Sleep Mode

- If no significant signals are detected, the software temporarily shuts down non-essential services (e.g., signal reception, data transmission, and camera operation) to conserve power.
- Detection results, system logs, and status updates are saved to persistent storage for future analysis and troubleshooting.
- The software enters a low-power standby state while periodically scanning the RF spectrum, ensuring quick wake-up when new signals appear.

7. Budget:

Our budget for the project is funded by the team and a sponsor. The sponsor will not be sending funds but rather has already picked out parts that we must use and bought them. Through conversation with the sponsor it is unlikely that they will fund anything other than the components they are already buying and thus the team will be handling those costs. As the optical design is the most expensive of the non-sponsored part of the project and it is still in the works, we cannot know for sure what it will cost but we would like to stay under $200.

Component	Name	Price	Quantity
Spectrum Analyzer	Signal Hound BB60D Real-Time Spectrum Analyzer	$4835.00	5
Wideband Antenna	Planar Log-Periodic Antenna AX-37A	$459.95	10
Starlink Terminal	Starlink Mini Terminal	$599.00	5

Starlink Connection	Roam Unlimited (2 months)	$330.00	1
Phone	Samsung Galaxy S24	$799.99	5
Cell Service	T-Mobile Essential Saver Plan (2 months, 5 lines)	$300.00	1
Laptop PC	HP Laptop 17	$549.99	1
MCU	Raspberry Pi 5	$120	5
CMOS Sensor	Undecided	$10-40	1
Lenses	A variety of lenses	~ $200	1
Motor	Greartisan DC 5V 0.5RPM Turbo Worm Geared Motor	$14.99	1
Total		$37,804.43	

Table 2: Budget list

8. Milestones and Schedule

8.1 Senior Design 1

Senior Design 1	
Week	**Description and Dates**
1-2	Formulate Ideas and Construct Groups
3	Research/Write Divide and Conquer Document and Form Committee(1/24/25)
4	D&C Meeting with SD Coordinators(1/29/25), Revise D&C(2/7/25), Start 60 Page Report (3/24/25)
5-6	Research/Order Components and Research Software, 15 Page Check-in
7-8	Build/Test Designs, Midterm Optics Showcase(2/25/25), 30 Page Check-In
9-10	More Testing and Optimizing Designs, 45 Page Check-In
11-12	Finish 60 Page Draft(3/24/23), Feedback Meeting, Begin 120 Page Report(4/22/25)

13	Begin Constructing Prototype, 75 Page Check-In
14	Finish Construction of Prototype and Begin Testing, 90 Page Check-In
15	Complete Testing of Prototype, 105 Page Check-In, Final Optics Showcase(4/15/25)
16	Produce Complete Prototype, Finish 120 Page Report(4/22/25)

Table 3: Milestones

8.2 Senior Design 2

Senior Design 2	
Week	**Description and Dates**
1	Edit 120 Page Report as Needed
2-3	Start Converting Device to be Self-Sustained on a Raspberry Pi and Solar Power
4-5	Research Interconnecting Devices, Continue Making Original Prototype Self-Sustained
6	Finish Converting Prototype to be Self Sufficient
7-8	Test Self Sufficient System, Build Additional Prototypes for Final Report
9-10	Assess and Fix Potential Errors, Finish up Interconnection Software
11-12	Begin Full System Testing, Assess Problems and Begin on Solutions
13-15	Just Keep Testing, Just Keep Testing, Just Keep Testing Testing Testing
16	Final Presentation for the Committee

Note: The sponsor has been very unclear about what exactly he wants us to do in SD2 seeing as we will have a fully built prototype by the end of SD1 so this table may be inaccurate.

Table 4: Schedules

9. House of Quality:

Group:	D
Project leader:	John Billecci
Date:	2/7/2025

Correlation:

+	.	-
Positive	0 correlation	Negative

Relationships:

9	3	1	
Strong	Moderate	Weak	None

1: low, 5: high

	Customer importance rating	Customer Requirements ↓ / Design Specifications) →	Detection Algorithm	Antenna	Camera Mount System	Cost of Production	Power Supply	Weighted Score
		Desired direction of improvement (↑,0,↓)	↑	↑	↑	↓	↑	
1	5	High Battery Life	3	0	1	9	9	110
2	4	Ease of Use	3	0	0	0	0	12
3	4	Reliability	0	3	9	9	9	120
4	5	Detection Accuracy	9	9	9	3	1	155
5	5	Cheap	0	3	9	9	9	150
6	3	Adaptibility to Region	3	9	9	3	9	99
7	3	Size of Planes Detected	9	9	3	0	0	63
8	4	Weather Durability	0	9	9	9	3	120
9	3	High Quality Camera	0	0	9	9	0	54
		Technical importance score	108	162	230	213	170	883
		Importance %	12%	18%	26%	24%	19%	100%
		Priorities rank	**5**	**4**	**1**	**2**	**3**	

The house of quality for the Low-Cost Passive Aircraft Detection System emphasizes key features and their importance. The system ensures cost-efficient detection by using Commercial Off-The-Shelf (COTS) components, achieving a target cost of less than $8,000 per unit, making it affordable for deployment in remote areas. Reliable detection is prioritized through advanced Digital Signal Processing (DSP) and machine learning algorithms, aiming for an accuracy rate exceeding 95%, ensuring effective identification of aircraft signals. To support scalability, the system integrates with Starlink SATCOM, allowing worldwide access to detection data and enabling seamless global deployment. The system design focuses on ease of setup and operation, targeting a plug-and-play setup that can be completed in less than one hour, with a user-friendly web interface for real-time monitoring. Durability in harsh environments is addressed through a weatherproof enclosure and solar-powered operations, ensuring a lifespan of over 10 years. Additionally, the system minimizes disruptions by achieving a low false-positive rate of less than 5%, utilizing robust classification algorithms to filter out irrelevant signals. Collectively, these attributes align to deliver a high-quality, efficient, and reliable solution for passive aircraft detection in remote locations.

APPENDIX A |REFERENCES

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