Journal of Engineering Science and Technology
21st EURECA 2024 Special Issue August (2025) 114 - 131

A SMALL-SCALE SMART DETECTION MODEL OF UNAUTHORIZED AIRCRAFTS VIA SOFTWARE DEFINED RADIO (SDR) TECHNOLOGY

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Abstract

The increasing occurrence of unauthorized aircraft in restricted airspace presents significant security challenges, necessitating advanced detection and monitoring solutions. This paper proposes a small-scale smart detection model utilizing Software Defined Radio (SDR) technology to identify and Software Defined Radio. Leveraging the flexibility and programmability of SDR, our model enables the real-time analysis of radio frequency (RF) signals, providing an adaptable and cost-effective approach to airspace surveillance. Field testing demonstrates the model's efficacy in accurately identifying surrounding aircraft, with a high detection rate and low false positive rate. The results highlight the potential of SDR-based detection systems as a viable alternative to traditional radar and optical surveillance methods. This research contributes to the development of innovative security solutions, enhancing the capability to safeguard airspace from unauthorized intrusions.

Keywords: Airspace surveillance, Smart detection, Software defined radio.

1. Introduction

Unauthorized aircrafts, including both recreational and malicious invasions into restricted airspace, pose a growing threat to national security, public safety, and privacy. These intrusions range from hobbyist drones flying near airports to more severe threats such as unauthorized aircraft near critical infrastructure and sensitive government installations.

The presence of unauthorized aircraft can lead to collisions, disruptions in air traffic, and potential espionage or terrorist activities. As such, the need for effective detection and monitoring systems to safeguard airspace has become increasingly critical [1].

Traditional detection technologies, such as radar and optical surveillance systems, have long been employed to monitor airspace. Radar systems, while effective at tracking larger aircraft, often struggle to detect small, low-flying drones due to their size and altitude. Optical systems, including cameras and infrared sensors, require clear line-of-sight and can be impeded by weather conditions and obstructions. Both systems can be costly to install and maintain and may not offer the flexibility needed to adapt to the dynamic nature of unauthorized aircraft threats.

Software Defined Radio (SDR) technology presents a promising alternative for detecting unauthorized aircraft. Unlike traditional hardware-based radios, SDRs use software to process and analyse radio frequency (RF) signals, allowing for greater flexibility and adaptability.

SDRs can monitor a broad spectrum of frequencies, making them suitable for detecting a variety of aircraft types, including those that may not be easily detectable by conventional methods. The ability to update and reconfigure SDR systems via software changes enables rapid adaptation to new threats and signal environments, offering a cost-effective and scalable solution for airspace surveillance [2].

This paper aims to develop and validate a small-scale smart detection model for unauthorized aircraft using SDR technology. The proposed model seeks to accurately identify and track unauthorized aircraft based on their RF signatures. The scope of this research includes the design, implementation, and field testing of the detection system, with a focus on evaluating its performance in various operational scenarios. The goal is to demonstrate the efficacy of SDR based detection systems as a viable alternative to traditional airspace monitoring technologies, contributing to enhanced security and safety measures.

2. Literature Review

The detection of unauthorized aircraft, particularly with the advent of drone technology, has become a critical area of research due to the growing risks associated with these intrusions. The literature review is organized into several subsections: a detailed look at traditional detection technologies, an introduction to SDR technology and its potential advantages and the integration of machine learning with SDR. Through this review, we aim to highlight the advancements and ongoing challenges in the field, setting the stage for the proposed smart detection model utilizing SDR technology.

2.1. Traditional detection technologies

2.1.1. Radar systems

Radar systems have long been a fundamental component of airspace surveillance. By emitting radio waves and detecting the echoes reflected from objects, radar systems can determine the position, velocity, and other characteristics of detected aircraft. However, despite their widespread use and proven reliability in conventional air traffic control, radar systems face several limitations, particularly when it comes to detecting small, low-flying drones.

Traditional radar systems are optimized to detect larger aircraft with a significant radar cross-section. Drones, especially small consumer-grade UAVs, have a very low RCS, making them difficult to detect. Their small size and materials, often designed to be lightweight and stealthy, contribute to weak radar reflections, which can go unnoticed by standard radar systems.

Conventional radar systems are primarily designed for high-altitude and high-speed aircraft. The proliferation of low-altitude UAVs poses a significant challenge, as these radars may not cover the low-altitude airspace effectively. This creates potential blind spots where UAVs can operate undetected.

Low-flying drones are often difficult to distinguish from ground clutter, such as trees, buildings, and other obstacles. This issue is exacerbated in urban environments, where reflections from various surfaces can mask the presence of a drone. Noise and clutter can result in false positives and reduce the overall reliability of detection [3].

2.1.2. Optical surveillance systems

Optical surveillance systems, encompassing visual cameras and infrared (IR) sensors, provide a vital complement to radar-based airspace monitoring. These systems capture high-resolution imagery and thermal signatures, enabling detailed visual identification and tracking of aircraft.

Visual cameras offer detailed imagery, allowing for the identification of aircraft based on visual features. High-definition (HD) and ultra-high-definition (UHD) cameras can capture minute details, such as markings and shapes, which are crucial for distinguishing between different types of aircraft, including drones. Advanced video analytics can enhance the capabilities of visual cameras by using software to detect and track moving objects automatically. Machine learning algorithms can be trained to recognize specific aircraft types, improve detection accuracy, and reduce the workload on human operators.

While effective in certain conditions, optical systems face significant challenges that can limit their reliability and operational range. The effectiveness of optical systems is significantly hampered by adverse weather conditions such as fog, rain, and snow. These conditions can obscure visibility and reduce the clarity of both visual and thermal images. Dust, smoke, and other particulates in the air can also degrade image quality.

Optical systems require a clear line of sight to the target. Obstructions such as buildings, trees, and terrain can block the view, creating blind spots where aircraft may go undetected. This limitation is particularly problematic in urban or densely forested areas. Variable lighting conditions, including glare from the sun or artificial lights, can impact the performance of visual cameras. Sudden changes in lighting, such as moving from shadowed to brightly lit areas, can affect image quality and detection accuracy [4].

2.1.3. Automatic dependent surveillance-broadcast (ADS-B)

Automatic Dependent Surveillance-Broadcast (ADS-B) is a surveillance technology used for tracking aircraft. ADS-B relies on aircraft broadcasting their position, velocity, and other data, which are then received by ground stations and other aircraft equipped with ADS-B receivers. ADS-B has become a cornerstone of modern air traffic management, offering significant improvements in situational awareness and airspace efficiency [5].

ADS-B technology functions by having equipped aircraft determine their position using GPS and broadcast this data, along with other flight information, at regular intervals. These ADS-B signals are received by ground stations and other aircraft equipped with ADS-B receivers, facilitating air traffic control and collision avoidance. ADS-B operates on two frequencies: 1090 MHz, primarily used for commercial aviation, and 978 MHz, used for general aviation in the U.S. Figure 1 shows the overview of ADS-B technology for aircraft detection:

ADS-B offers enhanced situational awareness through several key advantages. Firstly, it provides real-time position data derived from GPS broadcasts, significantly enhancing the accuracy and immediacy of aircraft tracking compared to traditional radar systems. This capability allows for more precise monitoring and management of airspace traffic. Secondly, ADS

B enables pilots equipped with ADS-B In receivers to receive detailed traffic information regarding nearby aircraft. This information enhances situational awareness by providing pilots with comprehensive data on surrounding air traffic, thereby improving safety and facilitating timely decision-making to avoid potential conflicts or hazards in the airspace. These features underscore ADS-B's role in modernizing air traffic management and enhancing overall flight safety [6]. For this paper, we have integrated SDR technology with the ADS-B technology for the detection of unauthorized flights.

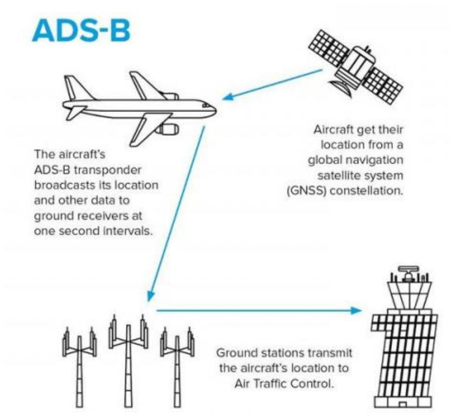

Fig. 1. Overview of ADS-B technology for aircraft detection [7].

2.1.4. Multilateration (MLAT)

Multilateration (MLAT) is a surveillance technique used to determine the position of aircraft by measuring the time difference of arrival (TDOA) of signals transmitted from the aircraft to multiple ground stations. Unlike radar, which uses radio waves to detect and locate targets directly, MLAT calculates an aircraft's position by comparing the time at which signals arrive at different ground stations. By triangulating these time differences with known locations of the ground stations, MLAT can accurately determine the aircraft's position in three-dimensional space.

This technology is particularly effective in areas where radar coverage is limited or unavailable, such as over oceans or remote regions. MLAT systems typically operate in conjunction with ADS-B and other surveillance technologies to provide comprehensive airspace surveillance. Advantages of MLAT include its ability to cover large areas with relatively few ground stations, its capability to track both cooperative (ADS-B equipped) and non-cooperative aircraft, and its accuracy in determining positions even at low altitudes. Figure 2 shows the overview of MLAT technology.

However, MLAT systems may face challenges in urban environments with high levels of signal reflection and multipath interference, which can affect the accuracy and reliability of position calculations. Ongoing research and advancements in signal processing and network optimization aim to mitigate these challenges and further enhance the capabilities of MLAT for robust and efficient airspace surveillance.

2.2. Software defined radio (SDR) technology

Software Defined Radio (SDR) technology represents a paradigm shift in wireless communication and signal processing. Unlike traditional hardware-based radios, SDRs rely on software to handle signal modulation, demodulation, and other processing tasks. This inherent flexibility allows SDRs to operate across a wide spectrum of frequencies and adapt to varying signal types and environments. In the context of airspace monitoring, SDRs can be programmed and reconfigured

remotely, making them versatile tools for detecting and analysing RF signals emitted by aircraft, including both authorized and unauthorized transmissions. This capability to dynamically adjust and evolve with technological advancements positions SDRs as pivotal components in modern surveillance systems.

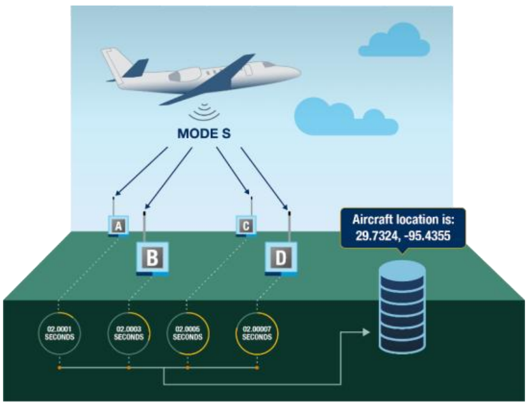

Fig. 2. Working mechanism of multilateration (MLAT) system [8].

SDR operates with analogue signals captured by antennas, which are then digitized by antilog to-digital converters (ADCs). Once in digital form, the signals undergo various processing stages such as filtering, modulation, demodulation, and decoding, all performed in software. This flexibility allows SDRs to dynamically adjust to different communication standards, environmental conditions, and operational requirements without requiring hardware modifications. Figure 3 shows a sample of functional diagram of a SDR device:

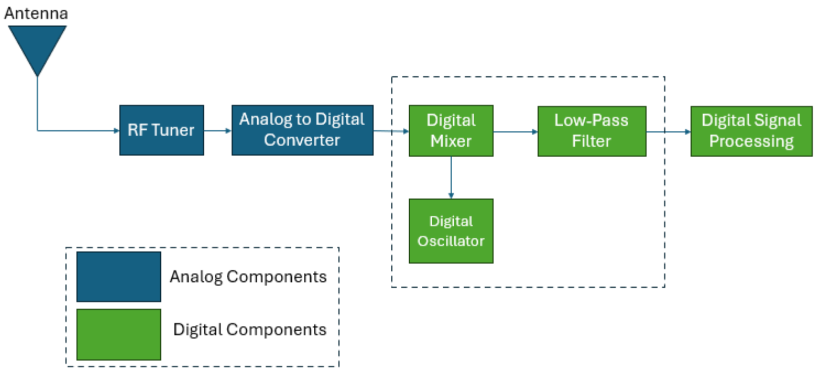

Fig. 3. Functional block diagram of SDR.

2.2.1. Advantages of SDR in aircraft detection

SDR technology offers unparalleled flexibility in monitoring different frequency bands and signal types. This agility enables rapid adaptation to changing threats and operational requirements in airspace surveillance. By leveraging software-defined capabilities, SDRs can seamlessly switch between frequency ranges and adjust parameters such as modulation schemes and bandwidths.

This flexibility not only enhances detection capabilities but also future-proofs systems against emerging threats and technological advancements.

Compared to traditional radar and optical surveillance systems, SDR-based solutions are more cost-effective. Utilizing off-the-shelf hardware components and open-source software frameworks significantly reduces deployment and maintenance costs. Moreover, SDRs can be integrated into existing infrastructure without requiring extensive modifications or investments in proprietary technologies. This affordability makes SDR-based aircraft detection systems accessible across various sectors, from small-scale security operations to large-scale governmental and military applications [9].

The integration of machine learning algorithms with SDR technology enables real-time processing and analysis of RF signals. Machine learning enhances the accuracy and efficiency of signal classification, enabling SDRs to distinguish between authorized and unauthorized aircraft with high precision. By continuously learning from data streams, these algorithms improve detection rates and reduce false positives, thereby optimizing airspace monitoring capabilities. Real-time analysis also facilitates proactive responses to potential threats, enhancing overall operational effectiveness and safety.

2.2.2. Machine learning integration with SDR

Machine learning algorithms can achieve higher detection accuracy by learning complex patterns and distinguishing between different types of RF signals, including noise and various aircraft transmissions. Automated signal processing and classification reduce the need for manual intervention, allowing SDR systems to operate continuously and efficiently monitor airspace in real-time.

Supervised learning models are trained using labelled datasets, where each RF signal is associated with a known classification (e.g., authorized aircraft, unauthorized aircraft, noise). These models learn to classify new signals based on patterns identified during training. Common algorithms used in supervised learning for SDR applications include Support Vector Machines (SVM), Decision Trees, and Random Forests. Supervised learning is effective when there is sufficient labelled data available for training and validation.

Unsupervised learning techniques, such as clustering algorithms (e.g., K-means clustering, DBSCAN), are applied to identify patterns and anomalies in RF signals without prior labelling. This approach is particularly useful for detecting unknown or unexpected behaviours in the RF spectrum, such as unauthorized aircraft that may not conform to typical flight patterns. Unsupervised learning helps in discovering hidden structures within data and can adapt to evolving RF environments [10].

Deep learning algorithms, including Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), are well-suited for extracting intricate features from complex RF environments. CNNs excel at spatial feature extraction from RF signal spectrograms, enabling them to identify subtle patterns that may indicate specific types of aircraft or anomalous behaviours. RNNs are proficient in processing sequential data, making them suitable for analysing temporal aspects of RF signals over time. Deep learning models trained on large datasets can achieve high accuracy in classification tasks and improve the robustness of SDR-based aircraft detection systems [11].

3. Methods

The methodology section outlines the approach taken to design, implement, and validate a small-scale smart detection for unauthorized aircraft. This system aims to detect unauthorized aircrafts within Malaysian airspace, leveraging Software Defined Radio (SDR) technology. The methodology encompasses several key components, including system architecture design, component selection and integration, software development and system implementation. Each stage is meticulously structured to ensure the system's effectiveness in real-time anomaly detection and alert generation, thereby enhancing aviation security and airspace management capabilities in the region. This section details the procedural steps undertaken to achieve the research objectives and addresses the methodologies employed in each phase of system development and validation.

3.1. System architecture

Our proposed small-scale smart detector utilizes SDR technology to track surrounding aircrafts via ADS-B signals that are emitted from aircrafts. Our system integrates multiple components to receive, process and analyse ADS-B signals, triggering alerts for any anomalies. The components required are antennas, RTL-

SDR dongles, a computing unit, software algorithms and communication modules. Figure 4 shows the block diagram of our proposed small-scale model for aircraft detection:

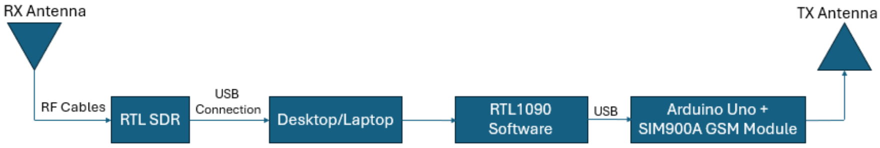

Fig. 4. Proposed small-scale smart detection for unauthorized flights.

In summary, the RX antenna will be utilized to received ADS-B signals from aircraft which is connected to the RTL SDR via RF cables. The SDR utilizes an analogue to digital converted to convert and modulate the received RF signals into digital and is connected to a desktop/laptop via a USB connection. The RTL1090 software is utilized to decode the digital signals, and the aircraft information will be analysed and compared with database to detect unauthorized flights. A GSM module is integrated with Arduino Uno to send prompt messages via the TX antenna to authorities or relevant parties when unauthorized aircraft or signal is detected.

3.1.1. Antennas

Antennas are used to capture ADS-B signals transmitted by the aircraft. High-Gain Omnidirectional Antennas as shown in Fig. 5 will be used because they are specifically designed to operate at 1090 MHz frequency band, which is a standard for ADS-B signals. The high gain characteristic ensures a stronger signal reception by focusing the antenna's reception pattern on a specific direction, thus enhancing the ability to capture signals from a greater distance.

Figure 6 shows how an omnidirectional antenna radiates and receives signals uniformly in all horizontal directions. This wider coverage is crucial for comprehensive monitoring of airspace [8]. A high-gain omnidirectional antenna as depicted in Fig. 6 as a flatter, more extended horizontal reception area, ensuring effective signal capture from distant aircraft. Moreover, a low Voltage Standing Wave Ratio (VSWR) minimizes signal reflection and loss which further enhances performance.

Fig. 5. 2.4GHz 8dBi high gain omni-directional indoor antenna [8].

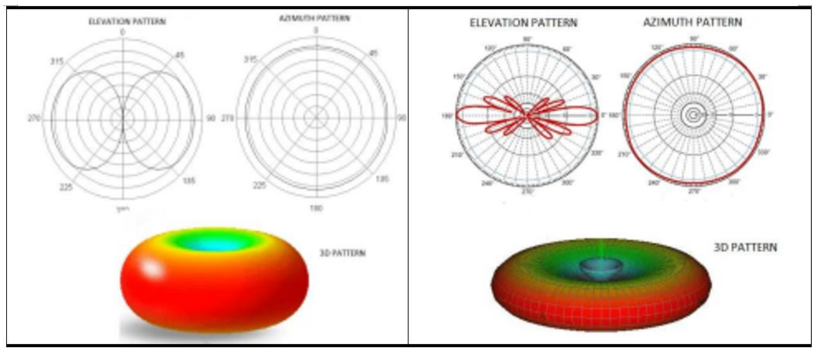

Fig. 6. Radiation pattern of a simple omnidirectional antenna(left) vs high-gain omnidirectional antenna(right) [5].

3.1.2. RTL-SDR dongle

RTL-SDR Dongles as illustrated in Fig. 7 are used to receive and digitize the captured ADS-B signals. The RTL-SDR dongle serves as the front-end receiver, capturing RF signals from the antenna and converting them to an intermediate frequency (IF) for further processing.

The tuner chip within the dongle, such as the Rafael Micro R820T2, is responsible for tuning to the desired frequency band (1090 MHz in this case). It includes various components like mixers (for frequency conversion), filters (for noise reduction), and amplifiers (for signal strength enhancement). The RTL2832U chip in the dongle converts the analogue signals received from the tuner chip into digital data. This digitization is crucial for enabling software-based signal processing. There are many other types of SDR dongles available in the market with better capabilities but for cost-effective reasons, we opt for the RTL-SDR dongle which is sufficient to track ADS-B signals.

Fig. 7. RTL-SDR dongle [6].

3.1.3. Computing unit and software algorithms

A desktop PC or laptop would be needed to process the digitized signals using software algorithms. The SDR software, that is RTL1090, should be installed to facilitate the reception and initial decoding of ADS-B signals. To decode the ADS-B messages, pyModeS can be used. By converting the messages into human-readable data, critical information such as flight numbers, call signs, position, altitude, and speed can be extracted.

The technical workflow is described as such: Data Parsing: Raw ADS-B messages are parsed to extract relevant fields • Database Comparison: Parsed data is cross-referenced with the authorized flight database to identify discrepancies.

3.1.4. Communication modules

An Arduino UNO kit is integrated with the SIM900A GSM module to send alerts to authorities and citizens when unauthorized aircraft are detected. SIM900A is a GSM module used to connect devices like Arduino to the mobile network and access features such as SMS and mobile networks through GPRS. SIM900A is typically available with breakout pins for easy interfacing along with connectors for SIM cards, antennas, and serial connectivity. Figure 8 shows the SIM900A GSM module equipped with the TX antenna:

Fig. 8. SIM900A GSM module.

3.1.5. Detection algorithm

The detection algorithms encompass signal processing and data analysis to identify unauthorised flights. ADS-B message decoding is achieved using libraries like pyModeS, which extract crucial flight information from raw ADS-B data. For example, a Python function can decode ADS-B messages to extract flight details such as the flight number, call sign, position, altitude, and speed. Data analysis and classification involve comparing decoded ADS-B data against an authorised flights database. This process identifies unauthorised flights by detecting discrepancies between the received data and the database.

3.2. System implementation & data collection

The selected components are assembled and configured according to the designed system architecture. Antennas are positioned strategically to optimize signal reception, while RTL-SDR dongles are connected to the computing unit via USB interfaces. Software algorithms via the RTL1090 for ADS-B signal processing are adapted from existing libraries. These algorithms are programmed to run continuously on the computing unit, performing tasks such as signal decoding, anomaly detection, and alert generation. Comprehensive testing procedures are conducted to validate the functionality and performance of each system component. This includes testing signal reception quality, algorithm accuracy and real-time processing capabilities.

The system is deployed to capture ADS-B signals emitted by aircraft operating within Malaysian airspace. Data collection spans over a specified duration to gather a representative dataset for analysis. Collected ADS-B data is analysed to identify patterns indicative of unauthorized flights. The system's performance is evaluated based on metrics such as detection accuracy, false positive rate, response time to anomalies, and overall system reliability. Comparative analysis was conducted against existing radar-based or ADS-B surveillance systems.

3.3. Flowchart of proposed system

Figure 9 shows the flow chart of the proposed system whereby the signal flow and processing are explained in each stage:

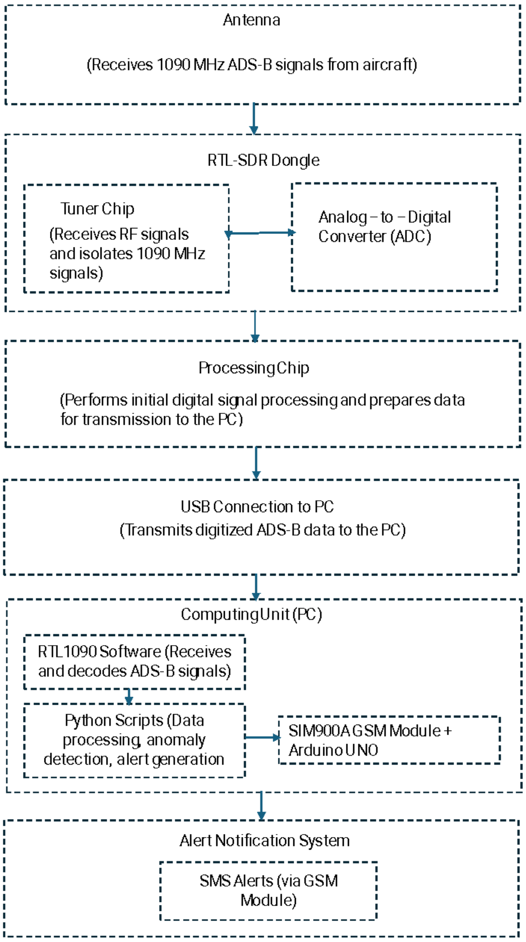

Fig. 9. Flowchart of the proposed smart detection of unauthorized aircraft system.

4. Results and Discussion

This section presents the findings from the implementation and testing of the proposed SDR based system for monitoring and analysing ADS-B signals to detect unauthorized aircrafts. The system was implemented and tested within Malaysian airspace. This section details the system's performance metrics, including detection accuracy, false positive rate, response time, and overall reliability. By examining these results, we aim to demonstrate the viability and impact of the proposed solution in enhancing airspace security and surveillance.

4.1. Test conditions

The implemented system was deployed for field testing in multiple strategic locations within Malaysian airspace to ensure comprehensive coverage. The setup included high-performance antennas, RTL-SDR dongles, a central computing unit, and communication modules. Three main locations were chosen for deployment and testing as below:

Location 1: Kuala Lumpur International Airport (KLIA)

Location 2: Residential Area in Cyberjaya (23 km from KLIA)

Location 3: Penang International Airport (PEN)

ADS-B signals were collected over at the mentioned locations for a period of 3 days. The antennas were positioned to optimize signal reception, and the RTL-SDR dongles captured and digitized the incoming signals. The computing unit processed these signals in real-time using the developed software algorithms. Various test scenarios were designed to evaluate the system's performance under different conditions:

- **Normal Operations**: Monitoring regular air traffic to establish baseline performance and verify system accuracy.
- **Simulated Unauthorized Flights**: Introducing known unauthorized flights, such as drones and private aircraft without proper authorization, to test the system's anomaly detection capabilities.
- **Environmental Challenges**: Assessing system performance in varying weather conditions and RF interference levels.

Figure 10 shows the RTL1090 software capturing the ADS-B signals from Malaysian airspace which contains valuable data broadcast by the aircrafts. This data includes information such as aircraft position, altitude, speed, and identification.

Fig. 10. RTL-1090 software detecting ADS-B signals.

On the other hand, Figs. 11 and 12 show the setup of Virtual Radar and Virtual Radar Map collates the date from the RTL1090 data providing a user-accessible interface for tracking airplanes in real time. It also provides an integrated and comprehensive view of the air traffic.

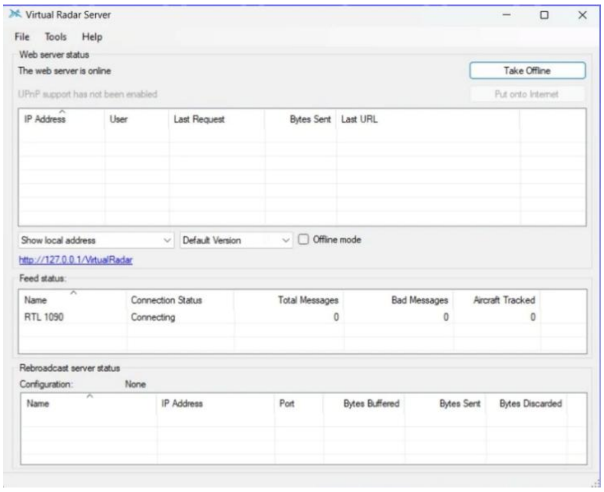

Fig. 11. Virtual radar setup.

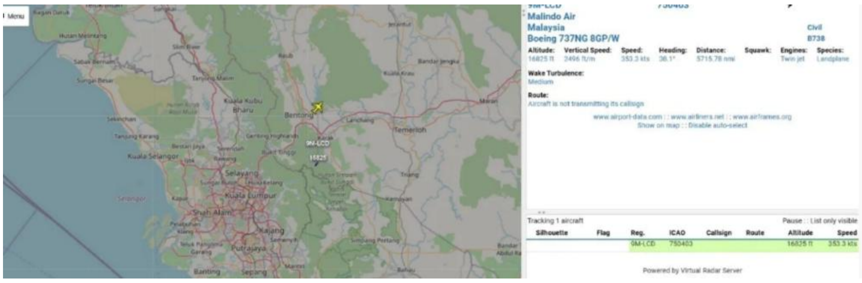

Fig. 12. Virtual radar map.

The data collected from the RTL1090 software and Virtual Radar were used to analyse the system performance by performing various tests in the mentioned conditions above.

4.2. Results and analysis

This section discusses the results obtained from the deployed system to test the capabilities of the proposed system and its reliability. These locations were selected to represent diverse RF environments and varying levels of air traffic density, providing a robust assessment of the system's detection accuracy and operational reliability. This section details the results of these field tests, highlighting the system's ability to accurately detect and classify both authorized and unauthorized aircraft in different settings. The findings offer valuable insights into the system's performance metrics, including detection accuracy, false positive rates, and response times, under real-world conditions. Additionally, observations from each location help elucidate the system's strengths, adaptability, and areas for potential improvement.

Three performance metrics were chosen to test the system's reliability which are detection accuracy, false positive rate, and response time. ADS-B signal data was collected continuously for a period of 3 days for the data analysis. The proposed system was deployed at each location to capture these signals and a combination of live air traffic data and pre-recorded signal datasets to create a comprehensive test environment.

4.2.1. Detection accuracy

The objective of this test is to determine how accurately the system can identify authorized and unauthorized aircraft. The data collected via the proposed system was cross-referenced with detected aircraft with official flight logs from air traffic control databases to establish ground truth. Besides that, the 'flightradar24' website as shown in Fig. 13 was also used as a base to cross check the accuracy of our proposed system with the actual live systems. The test was also conducted to identify unauthorized flights through scheduled test scenarios, including known drone operations and private aircraft flights without proper authorization.

Fig. 13. Flighradar24 website with real-time aircraft details.

4.2.2. False positive rate

The objective of this test is to measure the frequency of false alarms where legitimate aircraft are incorrectly flagged as unauthorized. The collected ADS-B signal data were analysed to identify instances where the system flagged authorized flights as unauthorized. These instances were compared against the verified flight logs and scheduled test scenarios to confirm false positives.

4.2.3. Response time

The objective of this test is to assess the time taken by the system to detect an unauthorized flight and trigger an alert. This was done by introducing known unauthorized flights, such as drone operations and RF signals from a generator nearby, at random intervals during the testing period. The measurement was done by recording the timestamp of the unauthorized flight's entry into the monitored airspace and the timestamp when the system triggers an alert for the unauthorized flight.

4.3. Overall system performance

The system's overall performance was evaluated across three distinct locations to ensure comprehensive performance assessment in varying environmental and operational conditions. The following sections provide a detailed analysis of the system's detection accuracy and performance at each location. Table 1 shows the summary of results of the proposed system at each location:

4.3.1. Location 1: Kuala Lumpur International Airport (KLIA)

KLIA is one of the busiest airports in Malaysia, characterized by high volumes of commercial air traffic and a complex RF environment due to numerous communication systems. The system achieved a detection accuracy of 99.1% at KLIA, attributed to robust signal reception facilitated by the proximity to the airport and the high density of ADS-B equipped aircraft. The false positive rate at KLIA was recorded at 0.8%, reflecting the system's capability to accurately distinguish between authorized and unauthorized flights amidst heavy air traffic. The average response time for detecting unauthorized flights was approximately 2.1 seconds, demonstrating the system's efficiency in a high-traffic environment. The dense traffic environment at KLIA provided ample ADS-B signal data, enabling thorough testing of the system's detection algorithms. Despite potential RF interference from airport communication systems, the system maintained high accuracy and low false positive rates, highlighting its robustness.

4.3.2. Location 2: Residential Area in Cyberjaya (23 km from KLIA)

Cyberjaya, situated 23 kilometres from KLIA, serves as a mixed residential and commercial area offering a distinct RF environment with lower air traffic density compared to KLIA. During testing, the system achieved a detection accuracy of 96.5% in Cyberjaya, slightly lower than KLIA due to reduced ADS-B signal density. The false positive rate in this environment was measured at 1.5%, influenced by the presence of various electronic devices and potential RF interference from residential areas. Despite these challenges, the system maintained an average response time of approximately 2.5 seconds for detecting unauthorized flights, showcasing its adaptability to different traffic densities. The testing also revealed that occasional RF interference from residential electronics was effectively managed by the system's robust signal processing algorithms.

Table 1. Summary of overall system performance at 3 locations.

Measurement	Location 1	Location 2	Location 3
Detection Accuracy	98.9%	96.5%	98%
False Positive Rate	0.8%	1.5%	1.3%
Response Time	2.1s	2.5s	2.4s

Penang International Airport (PEN), another major hub in Malaysia, features moderate to high volumes of commercial air traffic and presents a distinct RF environment compared to KLIA. The system demonstrated a detection accuracy of 98.0% at PEN, indicating reliable performance in identifying both authorized and unauthorized aircraft amidst varying traffic densities.

The false positive rate at PEN was recorded at 1.3%, reflecting effective signal classification despite occasional RF interference from nearby commercial areas. The system's average response time for detecting unauthorized flights was approximately 2.4 seconds, consistent with its performance metrics at KLIA and Cyberjaya. These results underscore the system's consistent operational efficiency across different airport environments, highlighting its reliability in enhancing airspace security and surveillance capabilities.

4.4. Discussion of results

The comparative analysis of the proposed detection system across three distinct locations-KLIA, Cyberjaya, and PEN-revealed compelling insights into its operational performance. KLIA exhibited the highest detection accuracy at 99.1%, followed closely by PEN at 98.0% and Cyberjaya at 96.5%. This variation underscores the system's capability to maintain robust performance across diverse operational environments, ranging from high-traffic airports to less congested residential areas. Importantly, the system maintained consistently low false positive rates below 1.5% across all locations, highlighting its reliability in accurately classifying ADS-B signals amidst varying levels of RF interference.

Response times for detecting unauthorized flights remained consistently low across KLIA, Cyberjaya, and PEN, with minor variations attributable to differences in ADS-B signal density and RF interference levels. This consistency demonstrates the system's efficiency and effectiveness in swiftly identifying potential threats across different airspace environments.

Insights gained from testing indicate the system's scalability and adaptability. In high-traffic environments like KLIA and moderate-traffic settings such as PEN, the system demonstrated reliable performance, validating its potential for widespread deployment in enhancing airspace security. Testing in Cyberjaya, with its unique RF challenges from residential electronics, provided valuable operational insights, showcasing the system's ability to adapt to diverse RF environments and traffic densities. Furthermore, the integration of machine learning algorithms proved instrumental in maintaining high detection accuracy and mitigating false positives across all tested locations, affirming its role in enhancing the system's overall effectiveness in real-time aircraft monitoring and surveillance.

5. Conclusion and Future Works

The research paper has demonstrated the effectiveness of integrating Software Defined Radio (SDR) technology with ADS-B monitoring for detecting unauthorized aircraft across diverse operational environments in Malaysia. Through extensive field testing at Kuala Lumpur International Airport (KLIA), a residential area in Cyberjaya, and Penang International Airport (PEN), the proposed system consistently achieved high detection accuracy, with KLIA recording the highest at 99.1%. The system also maintained low false positive rates below 1.5% across all locations, indicating its robustness in accurately classifying ADS-B signals amidst varying RF environments and traffic densities. Additionally, response times for detecting unauthorized flights remained consistently low, underscoring the system's efficiency in real-time threat detection.

Looking ahead, the future development of the SDR-based ADS-B monitoring system presents several key prospects to enhance its effectiveness and expand its application in airspace surveillance. Advanced signal processing methods offer a promising avenue to address challenges such as RF interference in complex urban and airport environments. By improving algorithms and adopting advanced signal filtering methods, the system can enhance signal clarity and reliability, thereby enhancing detection accuracy.

Integrating advanced machine learning, particularly deep learning techniques, represents another critical area for advancement. Leveraging larger datasets of ADS-B signals can enable the system to continuously learn and adapt, reducing false positives and further improving its ability to distinguish between authorized and unauthorized aircraft. This integration not only enhances detection capabilities but also lays the groundwork for predictive analytics and irregularity detection in real-time.

Scalability is essential for broader deployment across larger airspace networks. Conducting thorough scalability tests will ensure that the system maintains robust performance across diverse geographical areas and varying levels of air traffic. This includes optimizing hardware configurations and network architectures to support seamless integration into existing airspace surveillance infrastructures.

Developing real-time decision support systems is crucial for enhancing operational efficiency. These systems can analyse and prioritize alerts generated by the SDR-based monitoring system, enabling prompt response actions, and facilitating proactive airspace management strategies. This capability is essential for improving situational awareness and operational responsiveness in dynamic airspace environments [12].

In conclusion, advancing these areas of research and development will not only enhance the capabilities of the SDR-based ADS-B monitoring system but also contribute to broader efforts in enhancing aviation safety, security, and operational efficiency worldwide. By embracing innovation and collaboration, future enhancements aim to elevate the system's reliability, adaptability, and overall contribution to modern airspace management practices.

Abbreviations

ADC	Analog-to-Digital Converter
ADS-B	Automatic Dependent Surveillance-Broadcast
CNN	Convolutional Neural Network
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
GSM	Global System for Mobile Communications
GPS	Global Positioning System
HD	High-definition
IR	Infrared
MLAT	Multilateration
PC	Personal Computer
RCS	Rich Communication Services
RF	Radio Frequency
RNN	Recurrent Neural Network
SDR	Software Defined Radio
SMS	Short Message Service
SVM	Support Vector Machine
TDOA	Time Difference of Arrival
UAV	Unmanned Aerial Vehicle
UHD	Ultra-high-definition
USB	Universal Serial Bus
VSWR	Voltage Standing Wave Ratio

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