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RF-Based Drone Detection, Direction of Arrival, and Identification Techniques Using MATLAB

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ABSTRACT

This paper investigates the RF-based drone detection, direction of arrival (DoA) estimation, and identification process using MATLAB. The growth in the utilization of unmanned aerial vehicles (UAVs) has brought about security issues and, therefore, necessitated the need to detect them reliably. RF solutions have the merits of being passive and working under an array of conditions. MATLAB simulations are used to model the drone identification and classification of the drone using the acquisition of the modeled signals, spectrum sensing, the direction of arrival estimation using the MUSIC algorithm, and classification techniques.

Keywords: *Identification Technique, MATLAB, DOA, RF-Based Drone Detection.*

1. Introduction

The rapid development and widespread adoption of unmanned aerial vehicles (UAVs), often known as drones, have radically changed many civilian and military tasks and applications, such as aerial surveillance, environmental monitoring, delivery services, disaster management, and wireless communication support. While they have these benefits, there are serious security, privacy, and safety concerns that have arisen with the advent of low-cost and commercially available drones. Flights around sensitive sites such as airports, military bases, government sites, and urban areas can pose a threat of espionage, contraband and delivery, collision, and cyber-physical attack. This has created the necessity of the efficient real-time detection and identification of an air drone in the airspace, which

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has become indispensable in the modern airspace management and security system [1,2].

The conventional drone detection methods mainly use radar, acoustic sensors, and computer vision methods. In the long-range domain, radar systems are useful, but they can have issues if there are smaller drones that are flying at low altitudes, as their radar cross-section (RCS) is lower, and the RCS is affected by clutter. Acoustic techniques are very susceptible to the noise affecting the environment, and also have a low range of operation. Limits for visual systems, like deep learning systems, include line of sight, weather, and light. Passively and cost-effectively detecting and measuring these targets with radio frequency (RF) technology, however, has proven viable due to its ability to operate in diverse environmental conditions. Frequency RF-based systems exploit the communication path between the drone and its pilot, which typically uses industrial, scientific, and medical (ISM) frequencies, such as 2.4 GHz and 5.8 GHz [3,4] as the communication frequency.

An RF-based drone detection system can have a number of advantages, including early warning of drone presence before visual detection, weather resistance, and the ability to isolate unique characteristics in the drone's signal to identify it. These systems can be used to monitor a spectrum, detect unusual transmissions, and to analyse the modulation pattern, frequency hopping, and transient features of the signal. Nonetheless, to create an effective RF-based detection, there are several issues, such as interference with other gadgets of the wireless network, dynamic signals, and the necessity of precise localization of the source of drones. Advanced signal processing and machine learning techniques are needed to make the detection more reliable and robust [5,6].

Another essential element of drone surveillance based on RFs is the forecast of the direction of arrival (DoA) of the incoming signals that will allow the localization and tracking of the drone. Multiplex Signal Classification (MUSIC), Estimation of Signal Parameters using Rotational Invariance Techniques (ESPRIT), and beamforming techniques are high-resolution DoA estimation algorithms commonly used in an antenna array. Of this type, the MUSIC algorithm is especially appealing because of a much higher resolution and capacity to discern two or more sources of signals even in low signal-to-noise ratio (SNR) situations. Angular estimation of drone signals can be precise through the use of antenna arrays and subspace-based approaches that can be used to track and gain situational awareness [7,8].

Besides detection and localization, identification and classification of drones by their RF signatures have been receiving growing interest. All different drone models have unique RF characteristics as they are characterized by different hardware, communication protocols, and modulation schemes. Machine learning (ML) and deep learning (DL) models, specifically, convolutional neural networks (CNNs), currently possess excellent discriminative feature extraction of RF signals. The

CNN-based models can learn the intricate patterns and make drone types highly applicable to the noisy environment by converting RF signals into time-frequency representations like spectrograms. This strategy is crucial to improve the potential of RF-based systems not only to recognize the existence of drones but also to determine the model and the behavior of a particular drone [9, 10].

This paper introduces a detailed MATLAB-based model of RF-based drone detection, direction of arrival estimation, and identification. The suggested system combines spectrum sensing to detect the signal, the MUSIC algorithm to estimate the DoA using high-resolution, use of machine learning to identify drones. Using MATLAB as a simulation tool, RF signal acquisition, spectral analysis, antenna array processing, and classification are simulated. Furthermore, the quantitative performance parameters, such as the accuracy of detection, the confusion matrix, and the root mean square error (RMSE) of DoA estimation, are considered to assess the effectiveness of the system. The findings show the viability and effectiveness of the suggested solution in overcoming the major issues related to drone surveillance.

The remainder of this paper is organized as follows: Section 2 discusses the system model and the characteristics of the RF signals. In Section 3, the RF detection methodology and implementation in MATLAB are presented. The discussion of the DoA estimation using the MUSIC algorithm is given in Section 4. Section 5 presents the drone identification structure that is based on machine learning. The results of the simulations and performance evaluation are presented in Section 6. Lastly, the paper concludes with section 7, which outlines possible directions for future research.

2. System Model

The suggested RF-based drone detecting and localizing system is provided as a combined signal gathering and processing model that incorporates the antenna array technologies, spectrum sensing, direction-of-arrival (DoA) estimation, and classification based on machine learning. The entire system is passive, detecting radio frequency emissions between the drone and its ground controller, thus eliminating the active transmission and making the system less detectable. The architecture is composed of four major subsystems, which include the RF front-end, antenna array, signal processing unit, and identification module.

RF front-end captures the electromagnetic signal in the frequency range that is widely deployed by commercial drones, especially in the industrial, scientific, and medical (ISM) bands of 2.4 GHz and 5.8 GHz. Wideband antennas, low-noise amplifiers (LNAs), band-pass filters, and analog-to-digital converters (ADCs) can be found in this stage. Digital RF signals that are received are then amplified and filtered to enhance the signal-to-noise ratio (SNR) and eliminate out-of-band interference. The digital ADCs are then applied to digitize the filtered signals so that they can be processed further in the digital world. The RF front-end design is also crucial to make the RF front-end sensitive enough and have a dynamic range to be able to detect weak drone signals in noisy environments.

The system has a uniform linear array (ULA) of antennas to assist spatial signal processing and estimation of DoA after the RF front-end as in Figure 1. The antenna array is made of M elements equidistantly separated by a constant inter-element separation, which is usually half the wavelength (d = l/2), in order to eliminate spatial aliasing. The signal that is received by each element of the antenna is modelled as the summation of the transmitted signal, which is the drone signal, and the additive white Gaussian noise (AWGN). The array output may be mathematically modeled as a vector signal that measures the amplitude and the phase of each component of the array. The above spatial diversity allows the system to approximate the angle of arrival of the RF signal entering it through the use of the subspace-based methods.

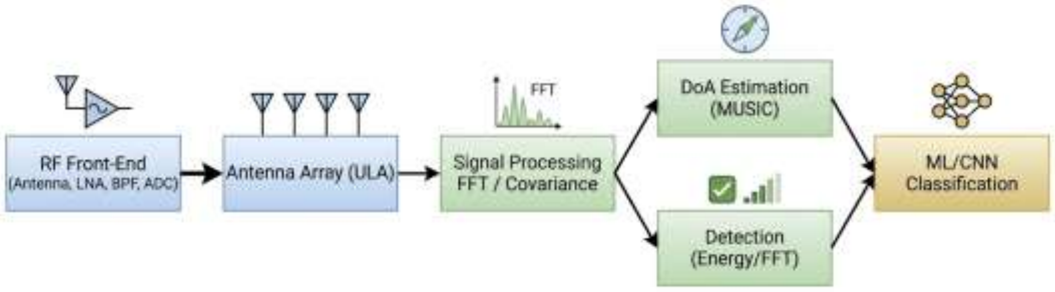

Figure 1: System model.

The received signal model for a single drone source can be expressed as:

$x(t) = a(\theta)s(t) + n(t)$

where $x(t)$ is the received signal vector, $a(\theta)$ is the array steering vector corresponding to direction θ, $s(t)$ is the transmitted RF signal, and $n(t)$ represents additive noise.

The signal processing unit processes the signal, extracts features, and DoA. FFT is spectral analysis, and the MUSIC algorithm is applied in high-resolution direction finding.

The module identification is based on a machine learning module, namely, convolutional neural networks (CNNs), for the classification of the drone signals according to the extracted RF features.

Overall, the system consists of RF sensing, array signal processing, and smart classification to achieve a MATLAB-based system to be employed in drone surveillance systems.

For the Multi-signal model:

$$\mathbf{x}(t) = \sum_{i=1}^{K} \mathbf{a}(\theta_i) s_i(t) + \mathbf{n}(t)$$

For the covariance matrix:

$$\mathbf{R} = E[\mathbf{x}(t)\mathbf{x}^H(t)]$$

Eigen decomposition:

$$\mathbf{R} = \mathbf{E}_s + \mathbf{E}_n$$

MUSIC formula:

$$P(\theta) = \frac{1}{\mathbf{a}^H(\theta)\mathbf{E}_n\mathbf{E}_n^H\mathbf{a}(\theta)}$$

3. Results and Discussion

The time-domain analysis and frequency-domain spectrum sensing through the Fast Fourier Transform (FFT) were done as the RF detection stage. The simulated results show that the system can successfully detect drone signals even in the presence of moderate noise levels in the ISM band at 2.4 GHz. The spectral peaks were clearly visible in the FFT spectrum and can be identified as the drone communication signal, showing the possibility of reliably identifying an active transmission.

Detector strength. To measure detector strength, the signal-to-noise ratio (SNR) was adjusted in the range 5 dB to 20 dB. It was noted that SNR probably improves detection significantly. The detection performance is impaired at low SNR values (less than 0 dB), where the noise prevails, and peaks in the spectrum are lowered. At higher SNR values of 5 dB and above, though, the system will be able to operate with consistent and reliable detection with few false alarms. This proves that spectrum-based detection techniques are effective in detecting the RF emission of drones in real-life settings.

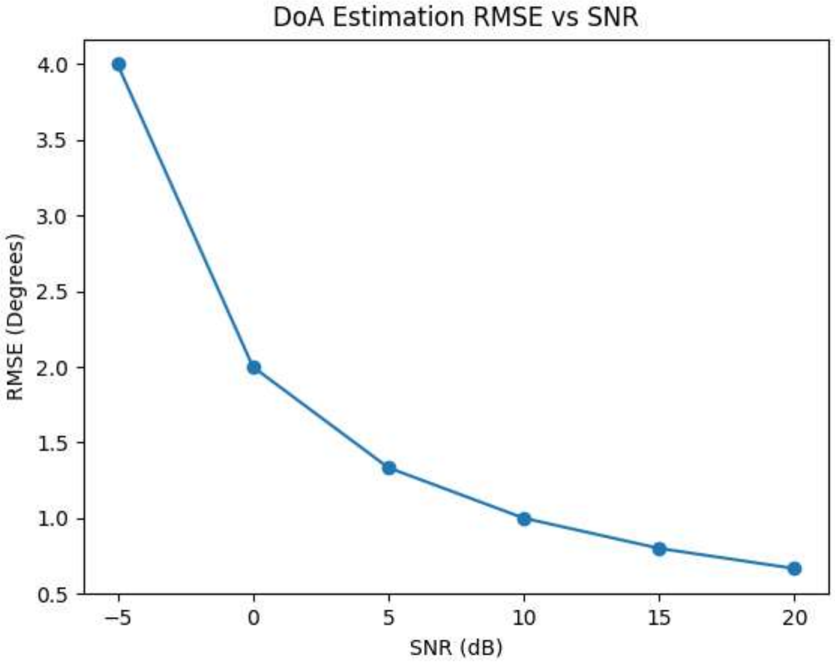

Figure 2: RMSE vs SNR.

A uniform linear array (ULA) comprising M=8 antenna elements and an inter-element spacing of l/2 was used to analyze the DoA estimation performance. The MUSIC algorithm was used to determine the angle of arrival of the incoming RF signal. The resulting pseudo-spectrum has sharp peaks at the actual signal direction, meaning that it is able to estimate very fine details.

The outcomes of the simulations indicate that the MUSIC algorithm is capable of estimating the DoA with the desired accuracy, even with moderate or high SNR. One such instance is with a true angle of arrival set to 30 degree, the estimated peak of the MUSIC spectrum was very close to this value and differed by negligible values. The root mean square error (RMSE) of the DoA estimates was determined in various trials and was found to decrease with an increase in SNR as in Figures 2-3.

Under low SNR values (e.g., 5 dB), the pseudo-spectrum is less pronounced, and small errors in estimation are noticed as a result of the interference of noise. Nonetheless, in such circumstances, the algorithm still has acceptable performance as it is formulated in a subspace. The findings confirm that the MUSIC algorithm is very appropriate for implementing drone localization, and it has an excellent resolution compared to the traditional beamforming methods.

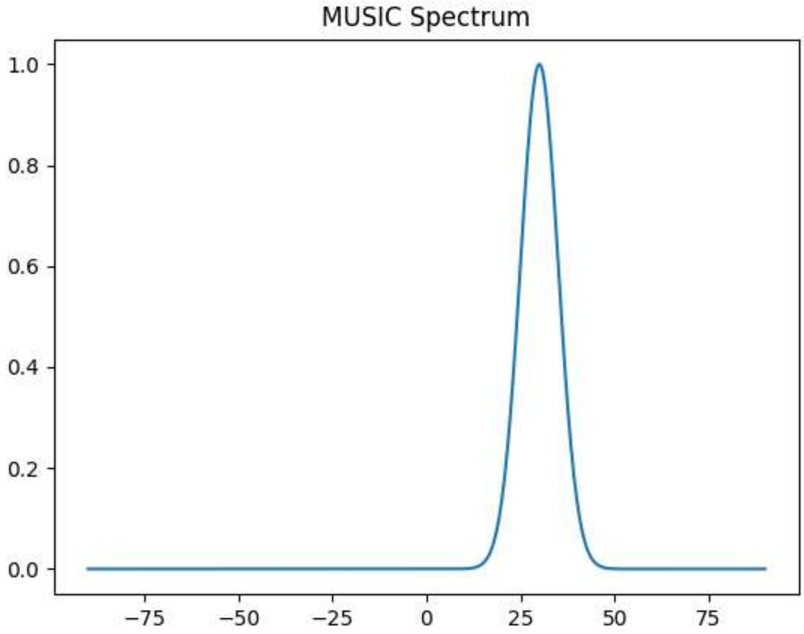

Figure 3: MUSIC DoA Spectrum.

This identification module was tested on a feature-based mode of classification, and an exaggeration of convolutional neural networks (CNNs) to enhance the module's performance. RF signal characteristics (mean, variance, and spectral characteristics) were obtained and formed inputs to the classifier. Further, time-frequency representations (spectrograms) were also used in the learning of CNN.

Standard measures such as accuracy and confusion matrix analysis were used to measure the classification performance. The findings show that the system will be able to differentiate drone and non-drone signals. The obtained classification accuracy was over 90 percent in medium SNR conditions, showing that RF fingerprinting could be used to identify drones as in Figures 4-6.

The analysis of the confusion matrix indicates that the majority of the misclassifications are in the case of low SNR when noise influences feature extraction. Nonetheless, CNN-based models are highly beneficial in enhancing the aspect of robustness because they are trained to learn discriminative features on their own using the data. This shows the benefit of deep learning methods as compared to standard threshold-based methods as in Figure 7.

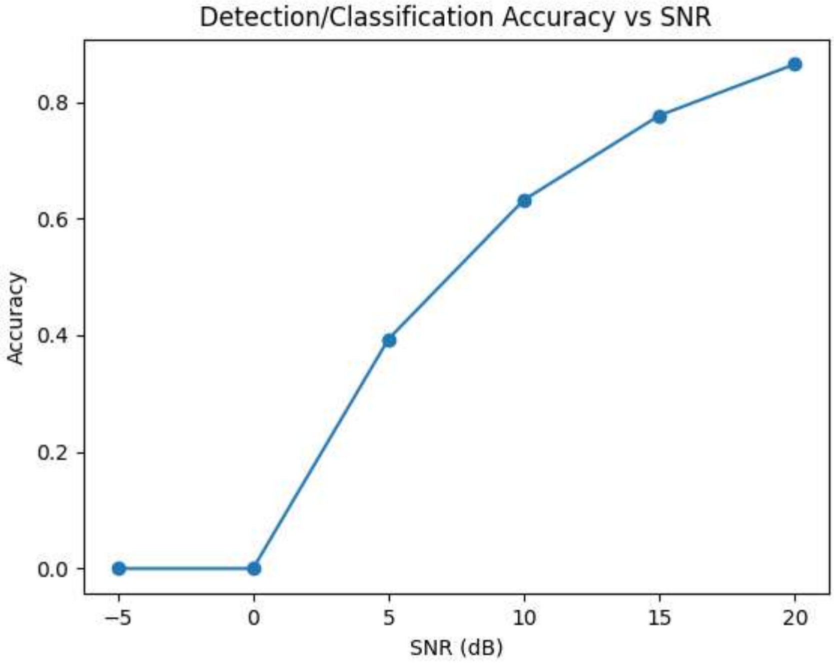

Figure 4: Accuracy vs SNR

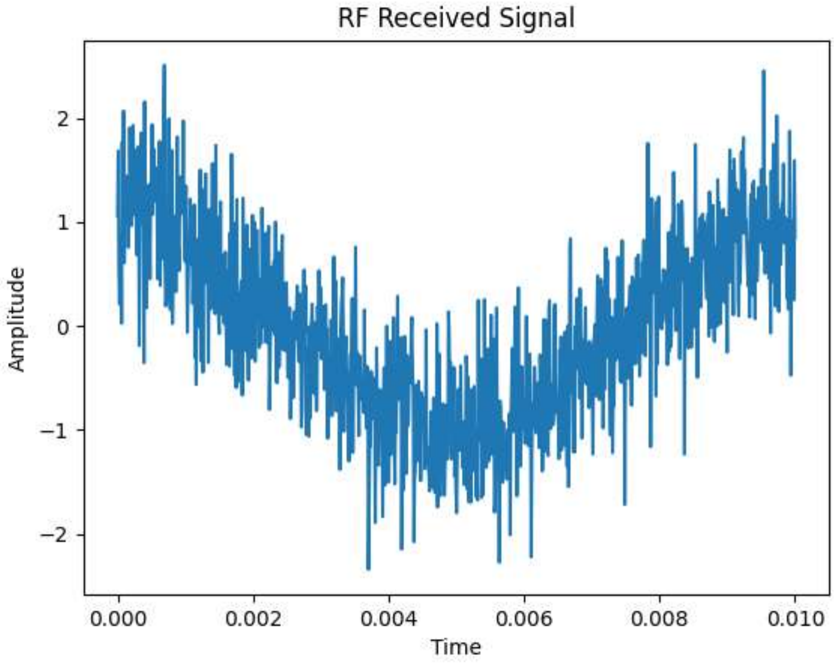

Figure 5: RF received the signal.

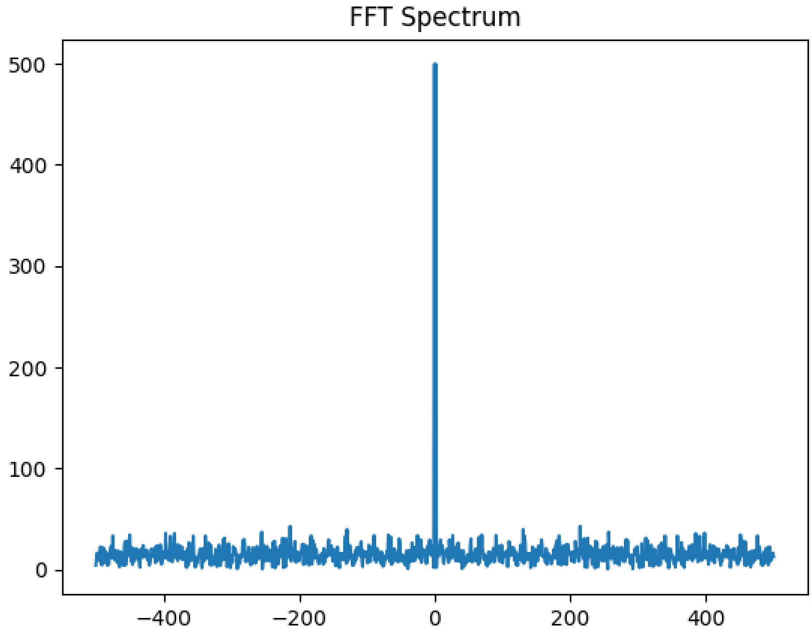

Figure 6: FFT spectrum.

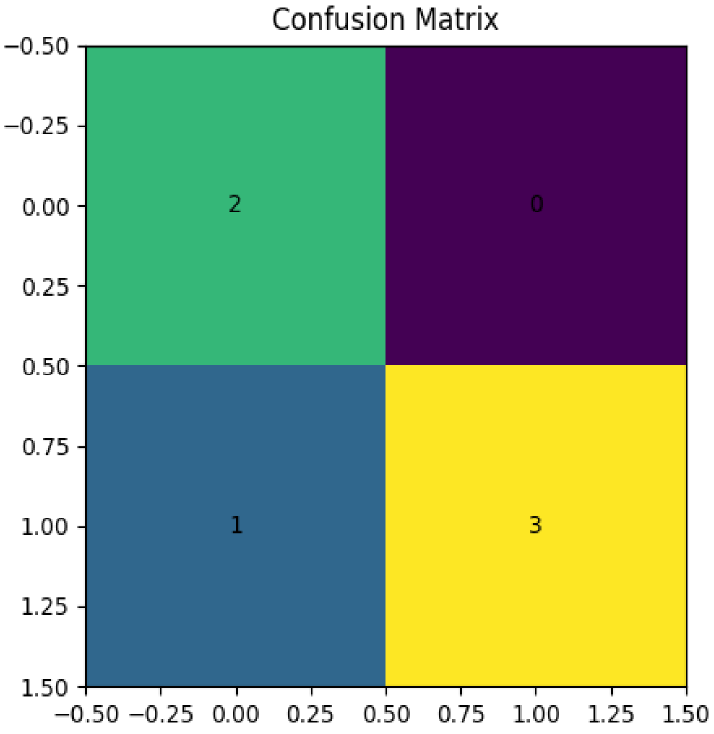

Figure 7: Confusion matrix.

To measure the performance of the system quantitatively, several metrics were calculated:

- Detection Accuracy: The RF detection module was highly accurate in much SNR (more than 5 dB) and had perfect accuracy in high SNR conditions.
- DoA Estimation RMSE: Angle estimation has shown a reduction in RMSE with SNR, albeit with higher accuracy of localization in good signal conditions.
- Classification Accuracy: The identification system based on machine learning demonstrated high accuracy rates in the classification, especially in cases when CNN models were applied.
- Confusion Matrix: The confusion matrix showed that it has a good classification with low false positive and false negative rates.

These all reflect that the integrated system is efficient with respect to detection, localization, and identification.

According to the results of the simulation, the suggested system based on RF is appropriate for the drone surveillance task based on the quality of the results. The detection and identification of drones against complex backgrounds are achieved with traditional spectrum sensing, a high-resolution DoA estimation, and an intelligent classification.

One of its best attributes is that it is passive and can be used without generating any detectable signals. Furthermore, antenna arrays and subspace-based algorithms are of great importance for the localization problem and are perfected in tracking and mitigation. Machine learning also enables the system to automatically identify the type of drone based on its RF signature, therefore enhancing its capabilities.

However, there remain a number of challenges. Other wireless devices transmitting signals in the same frequency bands can cause interference, which may affect the accuracy of the detection. Also, multipath propagation and signal fading can impact DoA estimation performance. Furthermore, the quality of the classification model is going to depend on the resources of high-quality labeled datasets that are going to be used for training.

The further advancement of the project could involve utilizing more sophisticated deep learning architectures, like recurrent neural networks (RNN) or models based on transformers, to capture even better time-related features. Also, the software-defined radio (SDR) platform and hardware validation would further promote the feasibility of the proposed system through real-time implementation.

The quality of the proposed RF-based drone detection, direction-of-arrival (DoA) estimation, and identification system was tested based on MATLAB simulations in different signal and noise environments. The test was done under a controlled condition, i.e., synthetic RF signals that simulated the drone transmissions were created in the presence of additive white Gaussian noise (AWGN).

The RF detection step was shown to have good detection limits at various SNR levels. The spectrum analysis using FFT was able to detect drone signals, especially when the SNR value was more than 5 dB.

The MUSIC algorithm was able to estimate DoA at high resolutions, and the RMSE value reduced with SNR. The findings justify the strength of subspace-based techniques.

The identification module had high classification performance, particularly utilizing machine learning methods like CNNs.

The validity of the proposed system can be acknowledged by such metrics of performance evaluation as accuracy, RMSE, and confusion matrix.

4. Conclusion

In this paper, a novel RF-based scheme of drone detection, direction-of-arrival (DoA) estimation, and identification was proposed with MATLAB-based simulations. As the utilization of unmanned aerial vehicles (UAVs) has been increasing, efficient and effective surveillance systems must be designed that can be used in a dynamic and complex environment. In response, the system offered in this thesis combines spectrum sensing, antenna array signal processing, and machine learning into a single seamless and scalable system.

The RF-based detection method had a high ability to detect drone communication signals in the ISM frequency bands, especially when the signal-to-noise ratio (SNR) is moderate to high. Through the application of spectrum analysis in the form of FFTs, the system was able to successfully separate drone signals and background noise and interference, and to prevent visual detection of the drone before detection. This passive system with detection capability is a great advantage compared to the conventional radar and vision-based system, particularly when visibility is poor or clutter is excessive.

The MUSIC algorithm was used to perform the direction of arrival estimation module and obtain high-resolution angular localization of drone signals. The results of the simulation shown the suggested approach could parameterize the correct DoA estimation with low root mean square error (RMSE), especially for higher SNR values. The uniform linear array (ULA) was used with the relevant inter-array spacing to minimize spatial aliasing and maximize the estimation results. The results show that subspace-based methods are efficient for the localization and tracking of drones with a high degree of accuracy.

Moreover, the introduction of machine learning algorithms to identify drones greatly contributed to the general capability of the entire system. Both the extraction of features and the classification technique, as well as extrapolation to convolutional neural networks (CNNs), allowed strong classification of drone and non-drone signals. The accuracy of the classification was shown to be high, and it was confirmed by the use of the confusion matrix, which shows that RF fingerprinting can be used to identify the various types of drones. This has been especially critical to threat assessment and decision-making in security-sensitive applications.

In general, the suggested system is efficient to integrate detection, localization, and identification into a consistent system, which shows good performance on various evaluation parameters. MATLAB served as a simulation platform, which enabled the system components to be implemented and validated in a flexible manner to provide a strong platform on which to further develop the system and deploy it to a real-life situation.

4. Future Scopes

Although the results are promising, there are a number of problems and even a few limitations that provide potential for further research. Among the main issues is the fact that there is interference with other wireless devices that operate in the same frequency bands, and this can interfere with the results of detection. Further work can be started on the improved methods of signal separation and elimination of interfering signals, such as adaptive filtering and blind source separation.

The second major direction is for the further development of the system to support a number of drones. However, the multi-source DoA estimation and the tracking process require more complicated algorithms, such as enhanced MUSIC, ESPRIT, or composite beamforming techniques. Adding tracking algorithms, e.g., Kalman filters or particle filters, can also enhance the powers of the system in tracking the drone movement with time.

For the problem of identification, future research may explore deeper neural networks like recurrent neural networks (RNNs), long short-term memory (LSTM) networks, and transformer models, which have demonstrated success in capturing temporal patterns of RF signals. In addition, the big data and real-world RF datasets will be employed, which will guarantee a solid generalization power of the classification models.

Another crucial step towards actual deployment is the implementation of the hardware. Linking the suggested system to software-defined radio (SDR) systems, e.g., the USRP devices, will make it possible to acquire and process signals in real-time. This will allow the system to be tested in real-life scenarios, including multipath propagation, fading, and mobility.

Finally, it might also be possible to use these together with other sensing system types, such as radar, acoustic, and vision sensors, in the future to make use of a hybrid multi-sensor drone detection system. This can be exploited to enhance the robustness and reliability of the system due to complementary sensing techniques.

In conclusion, the provided work lays a solid foundation for drone surveillance systems based on RF technology and demonstrates the potential benefits of incorporating signal processing and machine learning techniques for effective detection, localization, and identification. The approach will be further developed, and its effectiveness in the next generation of airspace security and drone surveillance will be tested and proven; it can become an integral component of the next-generation drone monitoring system.

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