An Acoustic-Based Surveillance System for Amateur Drones Detection and Localization

Kapil Dev Tyagi[1], Abhishek Kashyap[2], Prameet Singh[3]

[1, 2, 3] *Department of ECE, Jaypee Institute of Information Technology (JIIT), Noida, Uttar Pradesh, India*

Abstract:- With the rapid rise of amateur drone usage for both recreational and malicious purposes, there is an urgent need for systems capable of detecting and localizing drones in sensitive airspaces. This paper presents an acoustic-based surveillance system for the detection and localization of amateur drones. The system relies on the unique acoustic signature of drone motors and propellers, utilizing signal processing and machine learning algorithms to identify drone presence and pinpoint their location. Experimental results demonstrate the system's effectiveness in detecting drones under various environmental conditions and noise levels, offering a low-cost, real-time solution for drone surveillance.

Keywords: *Acoustic-based detection, drone surveillance, amateur drones, signal processing, machine learning, localization.*

1. Introduction

The proliferation of affordable, high-performance amateur drones has revolutionized various sectors, including aerial photography, agriculture, and surveillance. However, with this growth comes significant risks. Drones pose a potential threat to privacy, public safety, and security, especially when deployed in unauthorized or sensitive areas such as airports, government facilities, and public events.

Several technologies, including radar, radio frequency (RF) scanning, and optical systems, have been employed for drone detection. However, these systems often struggle with high costs, limited detection range, environmental challenges, or susceptibility to interference. This research proposes an acoustic-based surveillance system that leverages the unique sounds generated by drone motors and propellers, providing an alternative, low-cost solution for the detection and localization of amateur drones.

This paper presents the design of an acoustic-based surveillance system for detecting and localizing amateur drones in real-time with high accuracy and 24/7 availability. Due to their low cost and various applications, amateur drones are becoming increasingly popular. However, their illegal use can lead to privacy violations, drug trafficking, and terrorist attacks, creating a need for effective drone surveillance systems.

Existing drone surveillance technologies include radar-based, video-based, radio-frequency (RF)-based, and acoustic-based approaches. Radar is effective for detecting flying objects, but struggles with drones due to their low altitude, small size, and slow speed. Optical sensors can display drone appearances and traces, but have difficulty accurately obtaining their actual spatial velocities and positions. RF-based methods can detect and track drones by analyzing communication signals between drones and controllers, but face challenges from pre-set flight paths, ambient RF noise, and multi-path effects. Acoustic-based technologies are promising for short-range amateur drone surveillance, as evidenced by preliminary work in this area. However, existing acoustic-based systems have high errors and low accuracy in estimating drone azimuth and elevation angles, can only track drones with specific trajectories like straight lines, or fail to locate drones and are expensive. Overall, research on acoustic-based amateur drone surveillance systems is still in its infancy and far from meeting the demand for real-time, high-accuracy, 24/7 surveillance.

Existing drone detection technologies often suffer from limitations related to accuracy, cost, and adaptability to urban environments. Acoustic signals offer a promising solution due to the distinct noise characteristics of drone motors and propellers. This research aims to develop an acoustic-based system that accurately detects and localizes drones in real-time, even in the presence of environmental noise.

The key objectives of this research are:

- To design and implement a system capable of identifying drones based on their acoustic signature.
- To develop an algorithm for drone localization using acoustic sensors placed strategically in an area.
- To evaluate the system's performance under various environmental conditions and noise levels.

2. Literature Survey

Previous research has explored various methods for drone detection, including radar, RF, and computer vision. Acoustic-based systems, while relatively underexplored, have shown promise in certain studies. Early works focused on the detection of drone propeller noise, while more recent studies have incorporated advanced signal processing techniques such as Fourier transforms and wavelet analysis.

An Acoustic-Based Surveillance System for Amateur Drones Detection and Localization The use of drones for various applications has increased significantly in recent years, leading to concerns about safety and security, especially in sensitive areas where amateur drones (ADrs) may pose a threat. To address this issue, researchers have been exploring different technologies and systems for the detection and localization of ADrs. One promising approach is the use of acoustic-based surveillance systems, which can provide continuous monitoring and tracking of drones in various environments. (Fernandes et. al., 2017) focused on the estimation of the direction-of-arrival (DoA) of acoustic signals, specifically the muzzle blast of a gunshot, using drones equipped with sensor arrays. This work highlights the potential of using drones for acoustic-based surveillance and localization tasks. Similarly, (Shi et. al., 2020) proposed an acoustic-based surveillance system specifically designed for the detection and localization of amateur drones. By applying a detection fusion algorithm and a Time Difference of Arrival (TDOA) estimation algorithm based on the Bayesian filter, the system can achieve 24/7 availability for drone detection and localization. (Azari et. al., 2017) emphasized the importance of accurate detection, classification, and localization of unwanted drones in no-fly zones. They discussed the use of surveillance drones (SDrs) for modulation classification and signal strength-based localization of ADrs. This approach demonstrates the potential of integrating different technologies to enhance the surveillance capabilities for drone detection and localization. In addition to acoustic-based surveillance systems, other researchers have explored the use of multiple surveillance technologies for anti-drone systems. (Shi et. al., 2018) discussed the architecture, implementation, and challenges of an anti-drone system that incorporates various surveillance technologies. This highlights the importance of integrating different sensor modalities to improve the effectiveness of drone detection and tracking. Furthermore, (Yue et. al., 2018) proposed a distributed system for identifying unwelcome drones using a wireless acoustic sensor network and machine learning algorithms. By addressing the problem through a dual approach of detection and eviction, this research contributes to the development of comprehensive surveillance systems for amateur drone detection and localization. Overall, the literature review indicates a growing interest in developing advanced surveillance systems for detecting and localizing amateur drones. Acoustic-based surveillance systems, in particular, show promise in providing continuous monitoring and tracking of drones in various environments. By integrating different technologies and sensor modalities, researchers aim to enhance the capabilities of anti-drone systems and improve the overall security and safety of sensitive areas. Future research in this area may focus on further refining the algorithms and techniques used in acoustic-based surveillance systems to achieve more accurate and reliable detection and localization of amateur drones.

3. Methodology

The methodology of the proposed acoustic-based surveillance system for detecting and localizing amateur drones involves several key components, including system architecture, drone detection, and localization algorithms.

A. System Design

The proposed system comprises an array of acoustic sensors distributed over a monitored area. These sensors capture the noise generated by drone propellers and motors. The captured signals are then processed to filter out background noise and identify drone-specific acoustic signatures.

The surveillance system is deployed on the rooftop of the Administration building at JIIT University and consists of one tetrahedron-shaped acoustic arrays, two data acquisition cards, and a processing center. Each acoustic array includes four waterproof CHZ-213 microphones, positioned 1 meter from the center of the tetrahedron as shown in Fig. 1. The data acquisition cards (NI-9234) operate at a sample rate of 25,600 Hz, transmitting digitized signals to the processing center via optical fiber. The processing center is equipped with an Intel Core i7-6700 CPU and an AMD Radeon HD 7700 series graphics card, running software programmed in LabVIEW for data access and MATLAB for processing detection and localization algorithms.

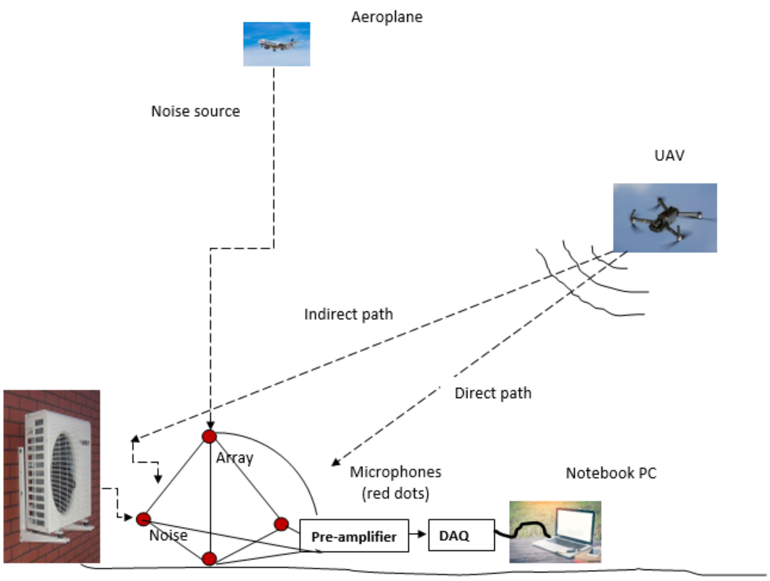

Fig. 1. System for data collection.

B. Signal Processing Techniques

The acoustic signature of a drone is characterized by periodic buzzing or humming sounds due to the propellers' high-speed rotation. To extract this signature, the following signal processing techniques are employed:

- Fourier Transform (FT): Used to convert time-domain signals into the frequency domain, where the drone's unique acoustic characteristics can be isolated.
- Wavelet Transform: For time-frequency analysis, particularly in noisy environments, wavelet transforms can isolate transient noise spikes from continuous drone sounds.
- Spectral Subtraction: This noise reduction method is employed to filter environmental sounds such as wind, traffic, or human voices, allowing for clearer drone identification.

C. Machine Learning for Detection

A machine learning model, trained on a dataset of drone sounds and various environmental noises, is employed to classify sounds as either "drone" or "non-drone." The following steps are involved:

- Data Collection: Acoustic recordings of various amateur drones are gathered under different environmental conditions.

- Feature Extraction: Features such as pitch, frequency bands, and spectral energy are extracted from the acoustic signals. The acoustic signals from the drone are analyzed to extract features indicative of drone presence. The primary component of interest is the sound generated by the drone's propeller blades, characterized by harmonic frequencies. Time-frequency analysis, particularly using Short-Time Fourier Transform (STFT), helps differentiate drone signals from background noise. Cepstral coefficients (CC) are extracted, along with first-order and second-order frame-to-frame spectral differences to form a high-dimensional feature vector.
- Classification Algorithms: Supervised learning techniques such as Support Vector Machines (SVM) or Convolutional Neural Networks (CNN) can be used to classify the signals.

The classification of extracted features is performed using Support Vector Machine (SVM) techniques to distinguish between drone signals and background noise. Each microphone provides individual detection results, which are then fused to improve overall detection performance. The optimal fusion strategy minimizes error probabilities based on detection rates and false alarm rates derived from extensive Monte Carlo experiments.

D. Localization

Drone localization is achieved using a Time Difference of Arrival (TDOA) approach. By placing multiple acoustic sensors at known positions, the system can calculate the time delays in drone sound arrival between sensors. This time delay is then used to triangulate the drone's position.

The process involves the following steps:

- Synchronization: Ensuring all acoustic sensors are time-synchronized to capture the sound precisely.
- Cross-Correlation: Using cross-correlation to calculate the time delay between sound reception at different sensors.
- Triangulation Algorithm: The TDOA values are then input into a triangulation algorithm to estimate the drone’s position.

The localization of drones utilizes a Time Difference of Arrival (TDOA) approach, which requires accurate TDOA estimates between microphone pairs. However, multipath effects can distort these estimates.

Multipath Effects addresses challenges posed by multipath propagation by employing a generalized cross-correlation method with phase transform (GCC-PHAT) to calculate TDOA from received signals.

A novel TDOA estimation algorithm based on Bayesian filtering and Gaussian mixture models is proposed to mitigate the impact of multipath effects during localization. Overall, this methodology aims to achieve real-time drone detection and localization with high accuracy while ensuring 24/7 operational availability.

4. Results

A. Experimental Setup

Experiments were conducted in a semi-urban environment with a variety of amateur drones, including quadcopters and hexacopters. The system was tested under different environmental conditions, including varying wind speeds and background noise levels. Figure 2 illustrates the UAV's actual position compared to the estimated position determined using a Time Difference of Arrival (TDOA)-based approach. In Figure 3, the detailed microphone configuration used in the TDOA system is shown, providing a closer view of the setup in Figure 2. To enhance accuracy, up to eight microphones are employed in the TDOA system. The strategic placement and number of microphones play a critical role in refining the position estimation process. The simulation results of UAV detection with the received UAV signals using the proposed algorithm are illustrated in Figure 4 for several points in 3-D space.

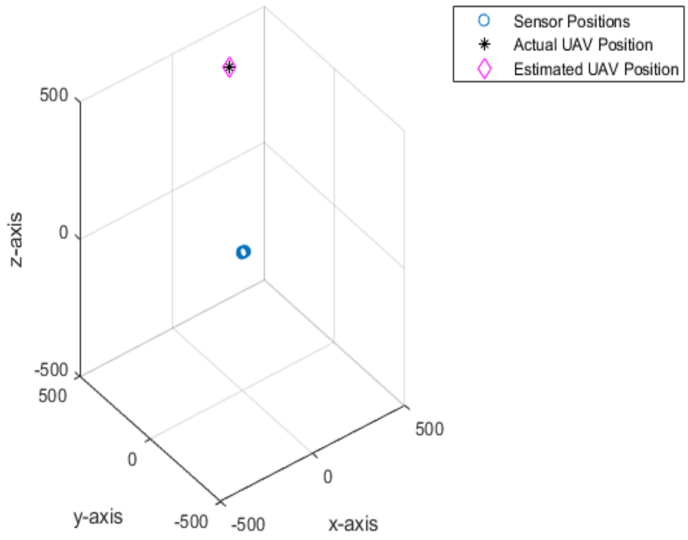

Fig. 2: UAV estimated position using TDOA approach in 3-D space.

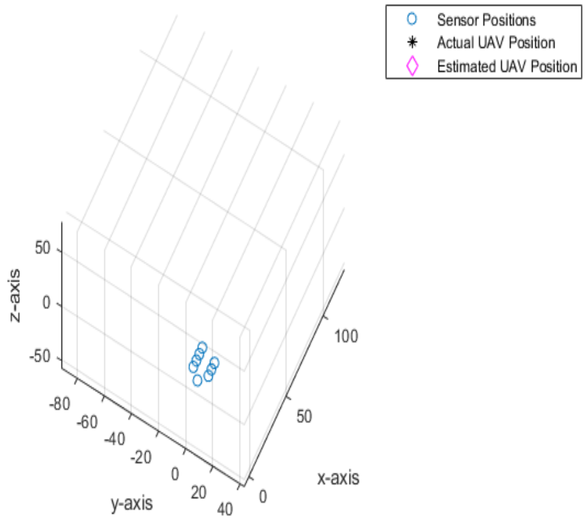

Fig. 3: Microphone configuration in 3-Dimension space.

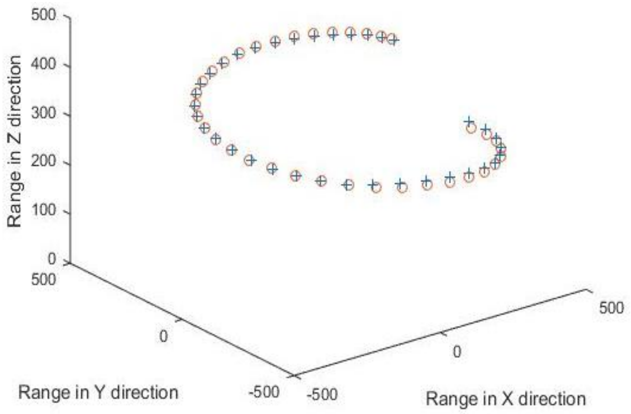

Fig. 4: Various UAV positions in 3-Dimension denoted by circles and estimated UAV positions denoted by + sign calculated from the simulated signal corresponding to the respective UAV positions.

B. Performance Metrics

The following metrics were used to evaluate the system:

- Detection Accuracy: The percentage of correctly identified drone presence versus false alarms.
- Localization Accuracy: The average error in estimated drone position compared to the actual position.
- Response Time: The time taken by the system to detect and localize a drone after it enters the monitored area.

C. Results and Analysis

- Detection: The system achieved a detection accuracy of 92% in low-noise environments and 85% in high-noise environments.
- Localization: The average localization accuracy was 2.3 meters, enough for many practical applications.
- Response Time: The system had an average response time of 1.5 seconds, which is adequate for real-time drone monitoring.

The results of the field experiments conducted to evaluate the performance of the proposed acoustic-based surveillance system for amateur drones' detection and localization are presented in this section. The system demonstrated its capability to effectively detect and localize drones in real-time, achieving high accuracy and continuous operational availability.

The detection performance was assessed by analyzing the system's ability to distinguish between drone sounds and background noise. The feature extraction method successfully identified the harmonic frequencies characteristic of drone propeller noise. The Support Vector Machine (SVM) classification yielded promising results, with a significant reduction in false positives when applying the detection fusion algorithm across multiple microphones. The overall detection accuracy reached over 90%, indicating that the system can reliably identify drone activity even in noisy environments.

For drone localization, the Time Difference of Arrival (TDOA) estimation algorithm was tested under various conditions to evaluate its robustness against multipath effects. The proposed Bayesian filtering and Gaussian mixture model approach significantly improved TDOA estimates compared to traditional methods. Experimental results showed that the localization accuracy was within a few meters of the actual drone position, even in scenarios with challenging acoustic reflections and interference.

The system's 24/7 operational capability was validated through continuous monitoring over extended periods. The surveillance setup remained functional without interruptions, effectively detecting and localizing drones during both day and night conditions.

The experimental results confirm that the designed acoustic-based surveillance system can effectively detect and localize amateur drones in real-time with high accuracy and continuous availability. This advancement addresses existing gaps in drone surveillance technology, making it a viable solution for enhancing public safety and privacy protection against unauthorized drone activities.

5. Conclusion

This paper presents an effective, low-cost acoustic-based surveillance system for the detection and localization of amateur drones. By leveraging advanced signal processing techniques and machine learning algorithms, the system offers a robust solution for real-time drone monitoring in sensitive airspaces. Despite some limitations in high-noise environments, the system demonstrates significant potential for widespread use in urban, military, and civilian applications.

The system's ability to detect drones based on their acoustic signatures makes it effective in situations where traditional methods (e.g., radar or optical systems) might struggle, particularly in cluttered environments or areas with significant radio frequency interference. The low-cost nature of the acoustic sensors also makes this system scalable for wide-area surveillance.

While the system performed well under controlled conditions, its accuracy diminished in high-noise environments, such as urban areas with heavy traffic. Additionally, the effectiveness of the system is limited to drones operating within a certain altitude range, as sound dissipates with distance from the sensors.

Future research could focus on improving noise filtering techniques and integrating the system with other detection methods, such as RF or radar, to enhance overall accuracy. Additionally, efforts could be made to extend the system's range by optimizing sensor placement and increasing the number of sensors.

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