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ADVANCING DIRECTION ESTIMATION FOR DRONE DETECTION IN NOISY OUTDOOR ENVIRONMENTS

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ABSTRACT

Accurate localization of drones is crucial for surveillance and security. Microphone arrays, paired with advanced signal processing, provide a promising approach to this challenge. However, outdoor environments present significant difficulties, including high noise levels, interference, and dynamic acoustic conditions. These challenges intensify when sensors operate on moving platforms, complicating reliable detection and direction-of-arrival (DOA) estimation. This study aims to enhance the detection and DOA estimation, in both azimuth and elevation angles, of drone-specific sounds, such as rotor noise, in realistic, noisy outdoor scenarios. The approach employs adaptive time-space filtering in combination with the Fraunhofer FKIE's patented coherent broadband beamforming technique, whose performance is compared to the conventional delay-and-sum beamformer. Experimental data were collected in free-field environments with sensors mounted on noisy platforms to simulate real-world conditions. It is demonstrated that the proposed method significantly enhances robustness in detecting sound sources, as detection and localization are sometimes impossible without the space-time filter. Additionally, the proposed beamforming technique reduces sidelobe levels, outperforming traditional methods. These findings highlight the potential of advanced beamforming techniques to improve drone detection capabilities, even in challenging environments, and could prove essential for applications requiring reliable acoustic monitoring in noisy, dynamic conditions.

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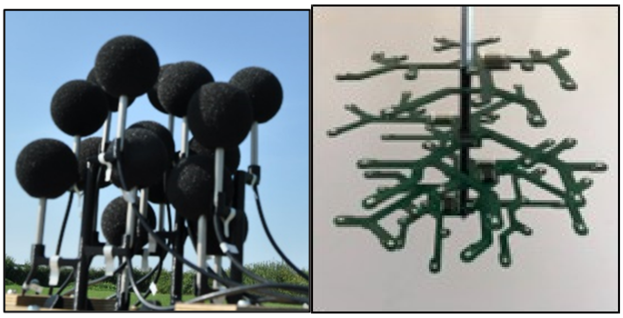

(a) N = 10 (b) N = 64

Figure 1: Volumetric microphone arrays called Crow's Nest Arrays with N elements.

Keywords: *Drone detection, Direction-of-Arrival (DOA) estimation, Coherent broadband beamforming, acoustic surveillance, space-time filtering*

1. INTRODUCTION

The detection, bearing estimation, and localization of drones are critical tasks in various applications such as search-and-rescue, security, and surveillance. Microphone arrays have proven effective in providing spatial resolution for detecting sound sources, but real-world conditions introduce challenges such as background noise, competing sound sources, and platform motion. To improve the reliability and accuracy of DOA estimation for drone detection, advanced signal processing techniques such as coherent beamforming must be employed. Traditional beamforming techniques [1-2], such as delay-and-sum [3], suffer from high sidelobes, reducing their effectiveness in noisy environments. In contrast, coherent broadband beamforming [4-7] offers significant advantages [8-9], particularly in scenarios requiring precise localization under challenging conditions. This paper presents a novel approach that integrates adaptive time-space filtering with coherent broadband beamforming [4],[10] to improve the detection and localization of drone sounds.

2. METHODOLOGY

2.1 Microphone Array Configuration

The study utilizes a volumetric microphone array known as the Crow's Nest Array (CNA) to enhance the accuracy and reliability of acoustic drone detection. This array consists of multiple microphones distributed randomly within a spherical volume (see Figure 1a and 1b)[11-14], which offers a significant advantage in terms of spatial resolution. Unlike linear or planar arrays, the CNA's volumetric configuration allows for nearly uniform beamforming performance in all directions. This means that the array can detect and localize sound sources with minimal bias toward any particular direction, making it highly effective for omnidirectional surveillance. The spatial distribution of microphones ensures a narrow main beam across a wide range of angles, reducing distortions that typically arise from directional sensitivity limitations in conventional arrays.

2.2 Beamforming Techniques

To analyze and compare drone localization performance, two different beamforming techniques are implemented: delay-and-sum beamforming and coherent broadband beamforming [4], [7], [10].

The delay-and-sum beamforming method is a conventional technique used for estimating the direction of arrival (DOA) of a sound source. It operates by aligning and summing signals received at different microphones based on their relative time delays. While this approach is straightforward and computationally efficient, it has significant drawbacks. One of the main limitations is the presence of high sidelobes (see Figure 2), which can cause false detections by creating misleading peaks in the spatial response. These sidelobes degrade the accuracy of DOA estimation, especially in noisy environments where interference can be mistaken for a legitimate signal.

In contrast, the coherent broadband beamforming technique improves upon the delay-and-sum method by phase-aligning signals across multiple frequency bands before summation. This phase-coherent summation results in significantly lower sidelobes (see Figure 3), which enhances detection reliability by reducing false positives. The method is particularly effective for detecting drones in the presence of strong background noise, as it improves the signal-to-noise ratio (SNR) while maintaining high spatial resolution. By suppressing unwanted noise components more effectively than traditional methods, coherent broadband beamforming allows for more precise and stable localization of drones.

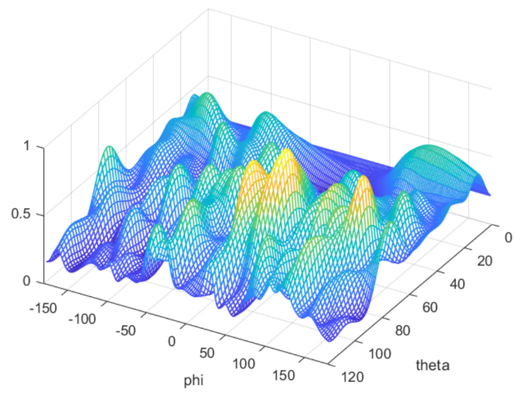

Figure 2: Directivity pattern of acoustic data containing drone and platform noise, using time-space filtering and incoherent beamforming.

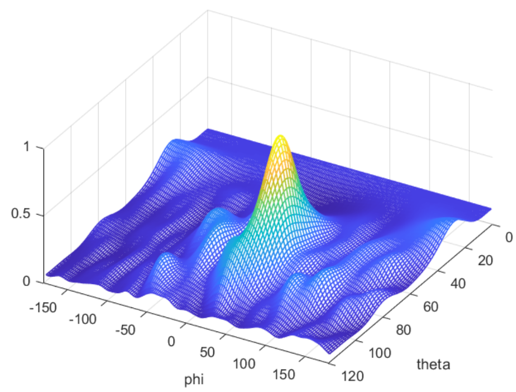

Figure 3: Directivity pattern of the same acoustic data as in Figure 2, using time-space filtering and coherent beamforming.

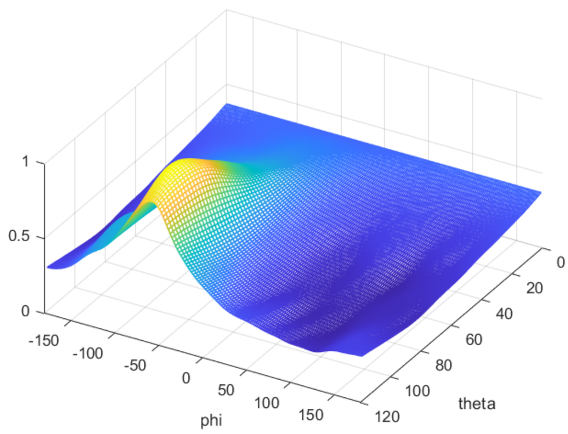

Figure 4: Directivity pattern of the same acoustic data as in Figures 2 and 3, using coherent beamforming without time-space filtering.

2.3 Adaptive Time-Space Filtering

To further enhance detection performance in complex and noisy environments, an adaptive time-space filtering technique is integrated into the system. This filtering approach dynamically adjusts both temporal and spatial signal components to maximize the strength of the drone's acoustic signature while suppressing background noise and environmental interference [15]. Unlike static filtering techniques that apply the same filtering parameters regardless of conditions, adaptive time-space filtering continuously analyzes incoming signals and modifies its filtering characteristics accordingly.

The primary advantage of this method is its ability to isolate the target signal from unwanted noise sources, such as wind and platform noise. Figure 3 shows an example where the space-time filter is applied, and Figure 4 shows the case without the filter. In Figure 3, a clear beam is directed towards the drone, accurately pinpointing its location within acoustic data that contains drone sounds alongside loud platform noise. The beam successfully identifies the drone's position due to effective filtering. In contrast, Figure 4 illustrates a scenario where no filtering is applied. In this case, the drone's location becomes indistinguishable, and the beam points to an erroneous position that corresponds to the platform noise, rather than the drone's actual location. This highlights the importance of filtering for distinguishing the desired signal from background noise.

2.4 Experimental Setup

To validate the effectiveness of the proposed approach, outdoor field experiments were conducted under realistic operational conditions. The experiments involved deploying drones at varying distances and altitudes to evaluate the system's ability to detect and localize targets under different scenarios. The microphone arrays were mounted on platforms that introduced additional noise, simulating real-world conditions where acoustic sensors are often placed on moving or vibrating surfaces.

The experimental design aimed to replicate practical deployment challenges, including fluctuating background noise levels, varying wind conditions, and changes in drone flight dynamics. By testing the system in these conditions, the study ensured that the results accurately reflected its performance in actual operational environments. Data collected from the field tests were analyzed to evaluate the impact of different beamforming techniques and filtering strategies, providing quantitative insights into the system's detection accuracy, robustness, and overall effectiveness.

3. RESULTS AND DISCUSSION

3.1 Performance Comparison

Experimental results clearly demonstrate that the proposed approach outperforms conventional detection and localization techniques, especially in challenging environments. One of the key findings is that, in the absence of the space-time filter (see Figures 4 and 7), detecting and accurately localizing drones in high-noise conditions was impossible. In fact, the DOA of a static noise source was predominant instead of the moving drone, and it was detected instead. This emphasizes the crucial role of the filtering mechanism in isolating relevant signals from background noise. Additionally, when comparing beamforming methods, the coherent broadband beamforming technique (see Figures 3 and 5) showed a distinct advantage over the conventional delay-and-sum method (see Figures 2 and 6). Specifically, the coherent broadband beamformer produced significantly lower sidelobes, resulting in clearer, smoother detections, more accurate true detections, and a more reliable detection signal. By reducing sidelobe levels, the method effectively minimized false alarms and improved the ability to distinguish drones from background noise.

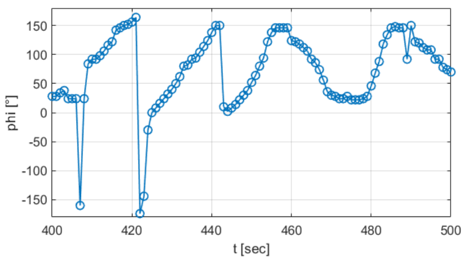

Figure 5: Temporal evolution of coherent beamforming estimation results plotted against azimuth for the detection of drone sounds in the presence of strong platform noise, filtered using a space-time filter.

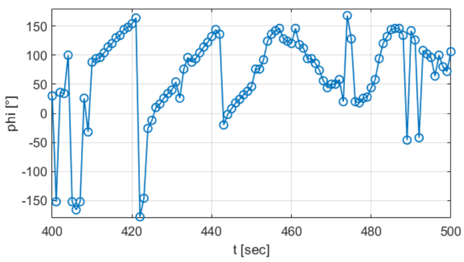

Figure 6: Temporal evolution of incoherent beamforming estimation results plotted against azimuth for the detection of drone sounds in the presence of strong platform noise, filtered using the same filter as in Figure 5.

3.2 Robustness to Environmental Noise

Environmental noise presents a major challenge in acoustic surveillance, as uncontrolled noise sources can mask or distort the signals emitted by drones. The proposed adaptive time-space filter effectively countered this issue by dynamically adjusting to the surrounding noise conditions. This adaptability allowed the system to successfully detect drones even in highly noisy environments, such as strong platform noise. The ability to reduce noise interference is particularly valuable for drone detection applications, where the acoustic signature of a drone may be weak or partially masked by ambient sounds. By ensuring robust performance under such conditions, the proposed method significantly enhances the reliability of acoustic surveillance systems.

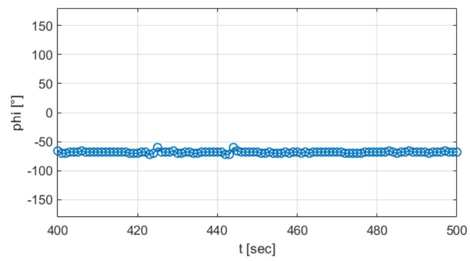

Figure 7: Temporal evolution of coherent beamforming estimation results plotted against azimuth for the detection of drone sounds in the presence of strong platform noise without filtering. The displayed DOA results correspond to a static noise source, not to the moving drone.

3.3 Applications and Implications

Beyond drone detection, the proposed approach has broader applications in acoustic surveillance. The ability to accurately track sound sources in real time makes it suitable for various scenarios. This capability is particularly useful in security and defense applications, where identifying and tracking unauthorized aerial vehicles or other moving targets is a critical task. Moreover, the method's effectiveness in challenging acoustic conditions suggests its potential utility in emergency response operations. For example, it could be deployed in search-and-rescue missions to locate people trapped in disaster-stricken areas by detecting their calls for help. Additionally, in law enforcement scenarios, the system could be used to monitor and track suspicious activities based on audio cues, thereby enhancing situational awareness. By improving the accuracy and robustness of acoustic detection and localization, the proposed method contributes to the advancement of intelligent surveillance technologies. These improvements have the potential to redefine how security agencies, military forces, and emergency responders approach real-time acoustic monitoring and threat detection.

4. CONCLUSION

This study presents a novel approach combining adaptive time-space filtering with coherent broadband beamforming to enhance drone detection in noisy outdoor environments. The experimental results confirm that the proposed method significantly improves detection robustness, even in challenging conditions where conventional methods fail. The time-space filtering effectively isolates drone acoustic signatures from background noise, while the coherent broadband beamforming significantly reduces sidelobe interference, ensuring more accurate localization. These findings highlight the potential of advanced signal processing techniques in addressing the critical challenges of real-world drone detection.

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