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Acoustic Network for UAS Detection, Tracking, and Classification

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ABSTRACT

Stevens Institute of Technology (SIT) is conducting research for the Air Force Research Laboratory (AFRL) for creating an expandable networked distributed counter UAS (CUAS) system. This system provides UAS detection, tracking, and classification based on passive acoustic sensing. A previous version, the Drone Acoustic Detection System (DADS) [1] used multiple microphone nodes, each equipped with a four-microphone array. The digitized microphone data is transferred over radio in real-time to a central computer, where it is processed. A new version, DADSV2 is under development and includes a larger number of nodes with a 10-microphone array. In the improved system, the initial stages of processing, detection, direction finding, and feature extraction are performed locally on a single-board computer built into the sensor node, while the localization and classification are performed on a central computer that processes data collected from all sensors. This significantly reduces the stream of data required for a centralized location, thus reducing the demands for radio performance.

SIT has developed and tested signal processing methods for improving acoustic UAS detection, tracking and classification. These methods include spatial filtering (such as adaptive beamforming), various methods of ambient noise suppression, and the incorporation of beamforming for classification algorithms. Investigation of the acoustic array with seven microphones was conducted in a field test at ARFL tests facilities in NY and at a NJ local airport. The test demonstrated a significant increase in detection and classification distances using nodes with seven microphones and new methods of signal processing.

SIT built the DADSV2 10 microphone node with digital microphones and onboard signal processing and is testing its performance. The new network with 8 similar nodes will be built in the nearest time.

SIT also collected a library of acoustic UAS signatures recorded in previous tests conducted over the course of several years. SIT acoustic database contains several hundred sounds for more than ten small UAS. The database has also acoustic data for ambient noise, various vehicles, and aircraft. This database can be used for the development of modern Machine Learning (ML) classification algorithms.

Keywords: signal processing, passive acoustics, UAS detection tracking, and classification

1. Introduction

As was stated by the Department of Homeland Security (DHS) [2] : “Militant groups across the globe increasingly use technologies that were either crude or unavailable to consumers at the time of the 9/11 attacks. One example is unmanned systems. Improvements in the range and payload of unmanned aerial systems (UAS) have allowed terrorist groups like the Islamic State of Iraq and Syria (ISIS) to use consumer drones to drop explosives on security forces; surveil enemies; and use airborne video capabilities to film propaganda. The Department requires a sound understanding of technological advances that attackers will employ, and those that can help to counter terrorism and targeted violence.”

The small Unmanned Aerial Systems (sUAS) field continues its rapid development of new technology, thereby creating new, exciting, and readily accessible applications for hobbyists, commercial industry, and military users. The advancement in computing power and the miniaturization of components has improved the functionality for legitimate applications across the globe. These applications include uses such as agricultural applications, disaster management, photography and movie filming, and simple recreational fun. The expansion of legitimate sUAS applications simultaneously creates new risks and the potential for state, non-state, and nefarious actors to utilize drones for operations that could be hazardous to not only the Departments of Defense and Homeland Security personnel and facilities, but also to airports, prisons, nuclear facilities, and other components of critical infrastructure. A large list of UAS incidents around the World was organized by AARONIA [3].

Many UAS were detected flying in sensitive and secured areas. For example, the counter-drone company Dedrone reported that they observed at least 7524 drone flights around the Reichstag in Berlin from the beginning of January to the end of August of 2020 [4]. However, special drones, especially from the security and military sectors, cannot necessarily be located with the existing system.

One of the most recent developments in drone technology is the ability to build low-cost custom-made UAS and coordinate multiple drones simultaneously. These so-called “swarms” can overwhelm defensive capabilities. In 2018, a drone swarm attacked a pair of Russian bases in Syria. In the attack, 13 fixed-wing simple homemade drones attempted to deliver aerial bombs from a distance of more than 31 miles [5], [6]. These homemade drones were low-tech, when compared with commercial off-the-shelf systems.

The Russian invasion of Ukraine has shown a huge increase in the importance of UAS military applications, and many experts believe that UAS change the rules of the war. According to CNET [7] : “The US Defense Department has given Ukraine's military more than 700 AeroVironment Switchblade drones, a "loitering munition" model that can circle a battlefield then become a missile aimed at a target. AeroVironment said it has donated to Ukraine more than 100 Quantix drones, reconnaissance models that take off vertically like a quadcopter but then level off and fly faster with a fixed-wing design to survey for up to 45 minutes per battery charge”.

In Ukrainian forces, sUAS are used by small military units for aerial surveillance. Even though Ukraine has military drones, they use thousands of DJI and other commercial sUAS. sUAS with thermal cameras are used for finding military equipment and soldiers at night and concealed in vegetation. Even snipers employed sUAS for surveillance [8].

Counter drone systems have been developed to detect, classify, and mitigate this threat using various sensor technologies including radar, lidar, optical, radiofrequency, and acoustics. These sensors are combined into fusion systems to take advantage of the various benefits they offer.

The DHS Congress report [9] provides an assessment of the current state and perceived future advancements over the next 3-10 years that could pose a threat to the security of the United States, as well as recommendations for mitigation. This report suggested the development of Best Practice UAS Defense protocols at the FOUO level and deployment at mass gathering venues to provide necessary guidance for

mitigating UAS threats. This will most likely involve a layered approach consisting of passive RF detection, short-range radar for active detection, EO/IR cameras for ID and tracking, RF mitigation (C2 or GPS signal jamming if permitted by statute), and kinetic mitigation.

The counter-drone systems database developed by the Center for the Study of the Drone at Bard College [10] contains 537 products from 277 manufacturers from 38 countries. This database was built in 2019 and since then, the number of CUAS systems increased significantly.

Currently, it appears that the main tools for sUAS detection are Passive RF drone detection systems. The most widely used in the Ukrainian-Russian war is AeroScope [11]. Russia bought and deployed a large number of AeroScope receivers that can detect DJI UAS at distances up to 31 miles. The application of RF CUAS detection systems is limited by their RF signatures that are in CUAS databases. Numerous jammers and Electronic Warfare (EW) systems disturb and prevent UAS detection in the battlefield.

Passive acoustic systems are not affected by jammers and by EW systems. They are stealthy and have low SWaP-C (Size, Weight, Power, and Cost). They are passive and do not require illumination. Acoustic CUAS can provide target classification [12], [13] that many other systems cannot.

The drawback of acoustic systems is that they often have lower detection distances compared to counterpart technologies, and they are vulnerable to ambient noise.

A detailed review of acoustic methods for UAS detection was presented in Martinez-Carranza et al. [14]. Most methods do not provide UAS localization. Busset et al. [15] used a 120-element microphone array (acoustic camera) for localization and demonstrated tracking for distances up to 250 m. Acoustic cameras are expensive, with camera cost exceeding \$10K and their parameters are not optimized for UAS detection.

To solve an increasing need for a low-cost and portable counter-UAS detection system, the Stevens Institute of Technology built and developed the Drone Acoustic Detection System (DADS), a multi-nodal four-microphone system capable of detecting and tracking drones [1]. We are continuing to improve this system by adding a number of microphones and a number of nodes.

This paper presents a brief review of SIT's progress for the development of acoustic sensors for UAS detection, tracking, and classification.

2. Previous Stevens Work on Low-Flying Aircraft and UAS Detection

Stevens Institute of Technology's work in air acoustics started with the development of the Acoustic Aircraft Detection system (AAD), a passive acoustic wide area surveillance system. Stevens, with funding from the Science and Technology Directorate of DHS, developed and built the AAD system [16]–[18] that can detect, track and classify small planes, helicopters, and ultralight aircraft based on their acoustic signatures. It was designed to create a low-cost, reliable system that can be powered autonomously while communicating using a radio link or network over long distances. The deployed system consists of 4 nodes located between 1 and 4 km apart in mountainous terrain. Each node is comprised of a pyramid-shaped volumetric cluster of 5 microphones, an embedded computer, and a pan-tilt-zoom camera steered to detect targets in real-time (Figure 1). A communication device was used to transfer data to a centralized location. Each node estimates the direction of arrival toward the sound sources and sends it along to a central processing computer. The central computer combines the data from all nodes to generate tracks and classify targets. The station fuses the data from sensors for finding the direction of arrival of aircraft sounds, then uses triangulation techniques for target localization. Calculated tracks were used for steering the cameras to the acoustically tracked target to capture pictures. An extended test spanning more than three years has uncovered many challenges that are part of such deployment including the impact of weather, natural and human-made interfering sources of noise, effects of terrain, and the variety of types and modes of operation of the targets of interest. During the deployment period, the system detected a significant number of targets of interest. Several control tests with different aircraft providing ground truth GPS for comparison with the acoustic tracking were also conducted. Examples of target tracking are shown in Figure 2.



Figure 1 Acoustic field station of the low flying aircraft detection system

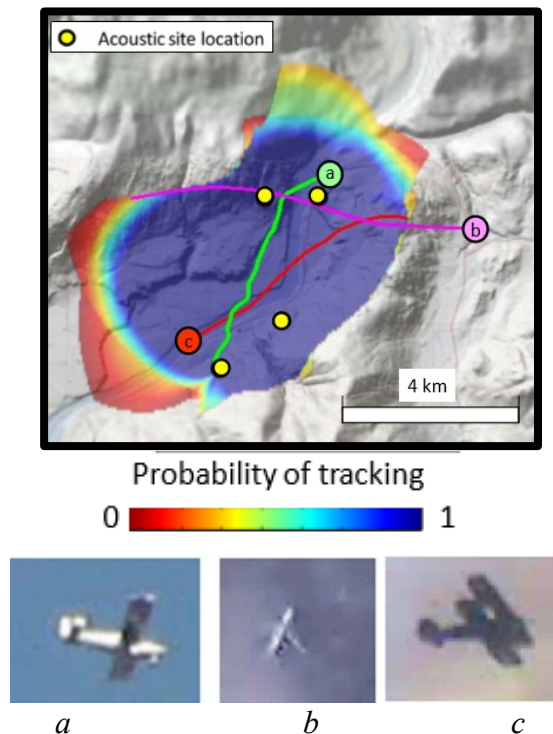


Figure 2. Acoustic tracks of targets of opportunity and photos made by the ADD camera: a – small plane, b– large jet aircraft c – a biplane. The color scale shows the predicted probability of tracking.

Experience acquired in the development of AAD, was has formed the basis for the development of the Drone Acoustic Detection System (DADS). Previous information on the development and testing of this system by SIT is published in [1], [19], [20]. During the work, several experimental acoustic arrays were built and evaluated. In the tests conducted, the prototype demonstrated small UAS detection and 3D target tracking by a network of acoustic sensors in real-time out to 390 m. Figure 3 shows one of the sensor nodes of DADS deployed in the field, while Figure 4 depicts the prototype GUI showing real-time detection and tracking of a small UAS (DJI Inspire 2).

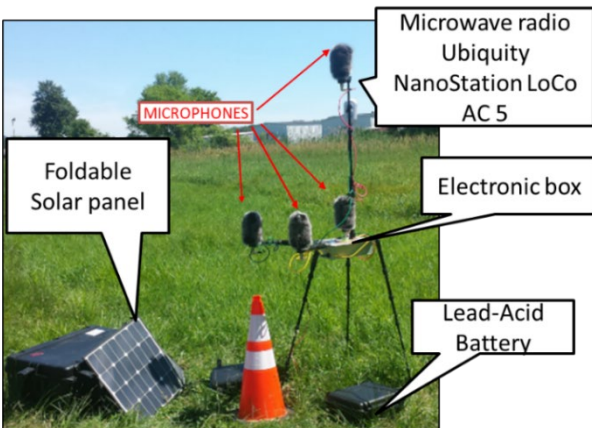


Figure 3. One of the DADS nodes deployed in the field

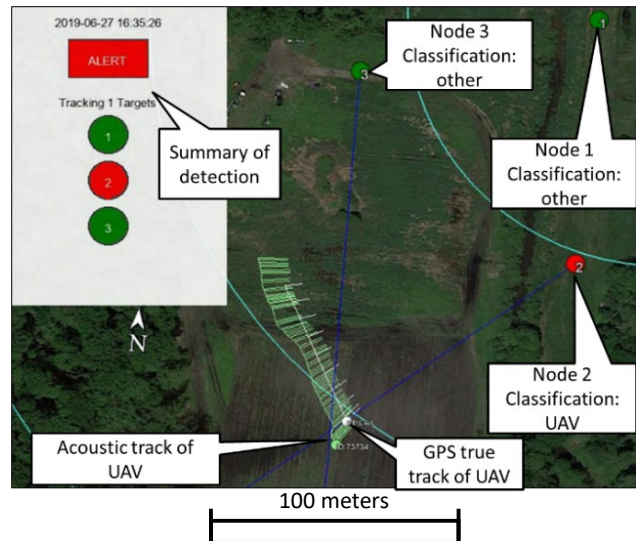


Figure 4. Real-time map display of DADS detecting and tracking a UAV

3. Progress in DADS Development

Stevens Institute of Technology is continuing the development of a distributed networked acoustic detection system against UAVs based on compact acoustic arrays.

The overall goal for the development is the creation of a UAS detection system network of low-cost acoustic sensors, with each having several microphones. A concept of the overall system is presented in Figure 5. Initial stages of processing, detection, direction finding, and feature extraction will be performed locally on a single-board computer built into each sensor node. The modifications will reduce the stream of data required for a centralized location, requirements for radio performance, and the overall system cost.

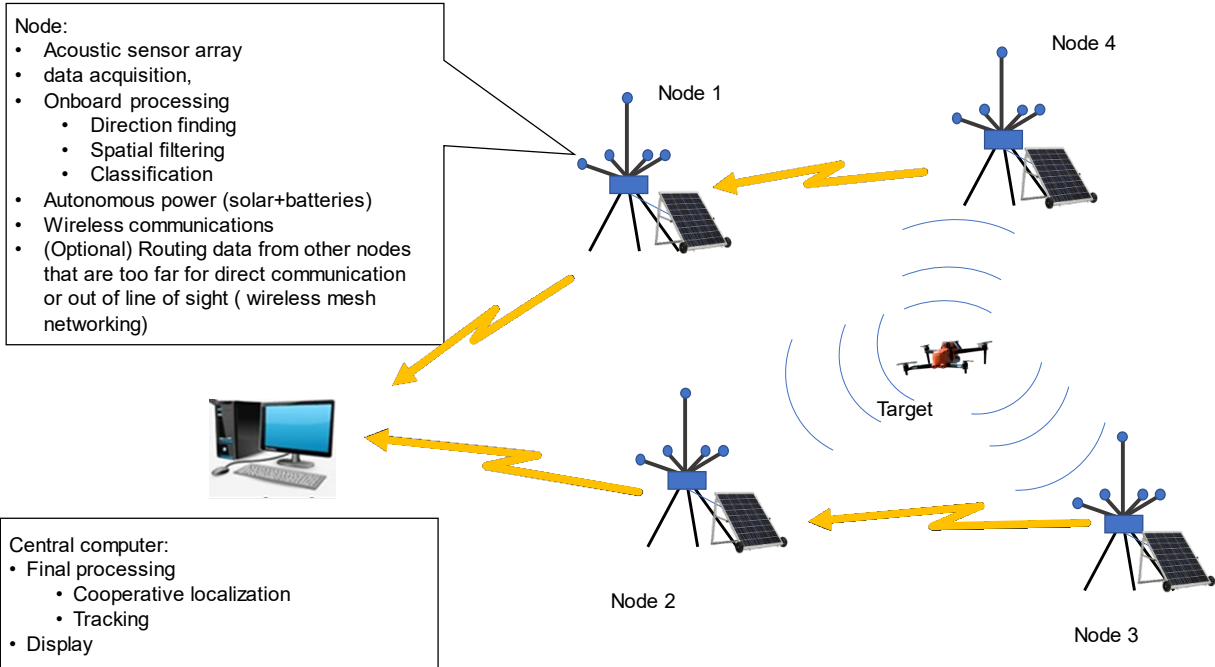


Figure 5. Concept of the overall system

Several versions of the acoustic array have been developed, built, and tested. This includes the Drone Acoustic Detection System (see Figure 6, the intermediate system Drone Acoustic Recorder System [20] (DARA, a development recording system with added real-time audio streaming capability, see Figure 6), and DADS version 2 (DADSv2).

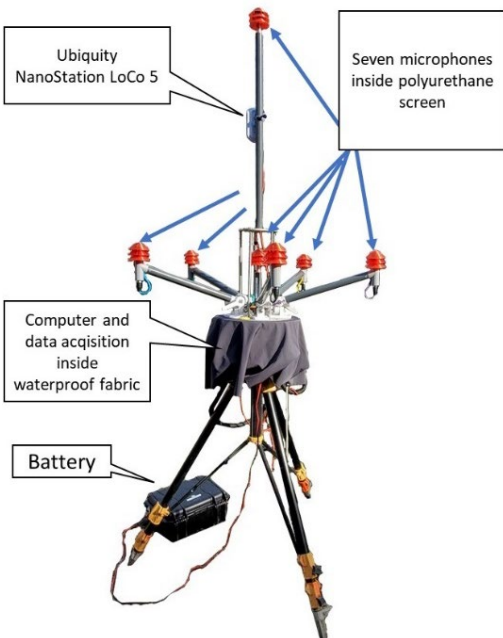


Figure 6. -Drone Acoustic Recorder System with real-time streaming– DARA-RT

The DADSv2 (see Figure 7) includes digital MEMS (Micro-electromechanical Systems) microphones, allowing an increase in the number of microphones at a lower cost and power consumption. DADSv2 is equipped with an array of 10 digital MEMS microphones in a pyramid-shaped configuration with a baseline of 1 meter. Weatherization of the microphones has been demonstrated using soft polyurethane canopies. The DADSv2 acoustic sensing node includes onboard processing for detection, direction finding, and classification of targets detected using their sound. Within the overall distributed system, each node finds the direction of arrival of the UAV sound (DOA) and communicates the data to a centralized location, where it is used for localization and tracking the targets using UAV in 3D.

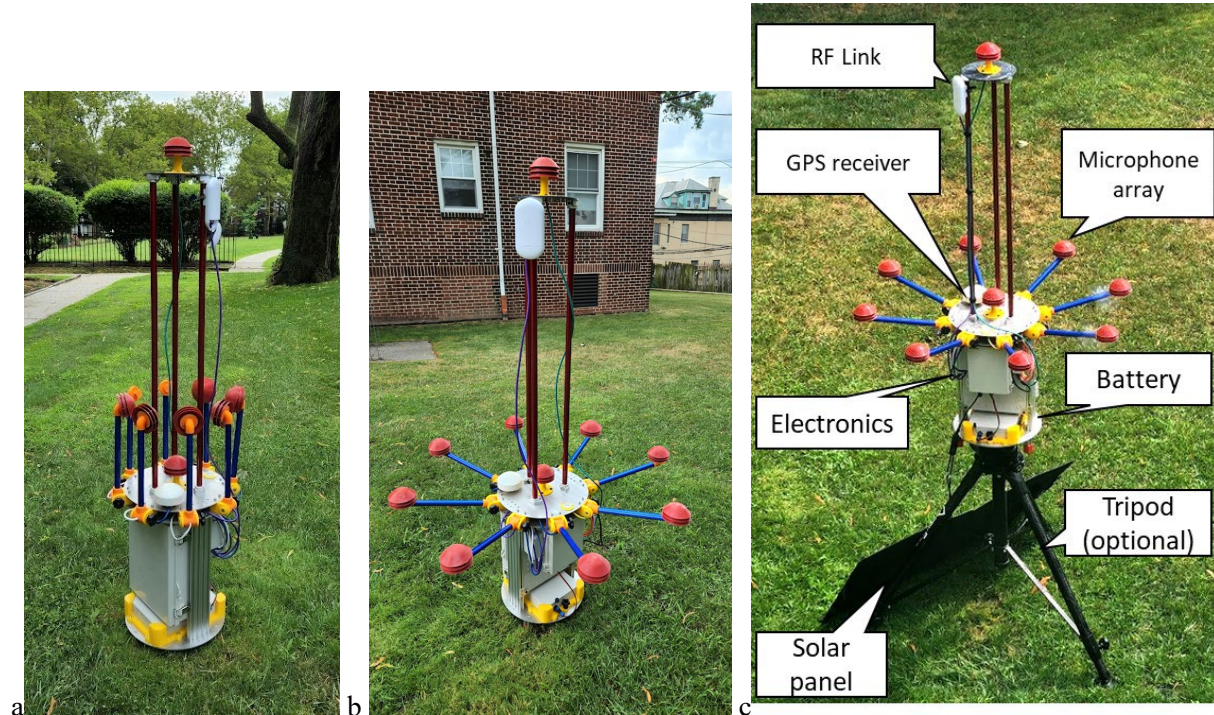


Figure 7. DADSv2 revision B prototype: a – folded, b – assembled on the ground, c – assembled on a tripod with a solar panel connected

4. DADS Software Improvements and Test Results

Recent work led to a significant signal processing software improvement provided by longer detection and classification distances with more accurate bearing. This section presents progress in the software developed with examples received in the field tests. Extensive testing of a distributed network of acoustic sensors over multiple days was conducted at an airport against variously sized commercially available UAVs including DJI Mavic, DJI Phantom, and DJI M600, and Inspired Flight IF1200.

During the field test, six nodes were deployed: three DARA nodes and three DADS nodes. Such deployment demonstrates coverage of the area with localization capability, alongside other data collecting equipment such as cameras, auxiliary acoustic recorders, and weather stations.

The ground truth of the UAV activity was acquired by interpreting the UAV autopilot data and the aircraft activity was controlled using ADS-B (Automatic Dependent Surveillance-Broadcast) receiver providing tracks over time.

4.1. Principles of direction-finding using acoustics

Steered-Response Phase Transform (SRP-PHAT) [21] was used for direction finding. It is based on computing and adding up the GCC-PHAT (Generalized Cross-Correlation Phase Transform) output. It is equivalent to finding steered response power (SRP) traditional filter-and-sum beamformer in a wide band. For a compact array, the SRP for each possible direction of arrival can be formed which is referred to as Global Coherence Surface (GCF), a maximum in GCF represents a direction.

Improvement of sound source separation was achieved using Region-zeroing (RZ), the approach used for multi-source separation in GCF, whereas after locating a global maximum a fixed region of direction is assigned the value of zero in the GCF and the search is performed again. This algorithm is effective in finding multiple maxima regardless of the shape of the peak, with the only required assumption being the size of the region.

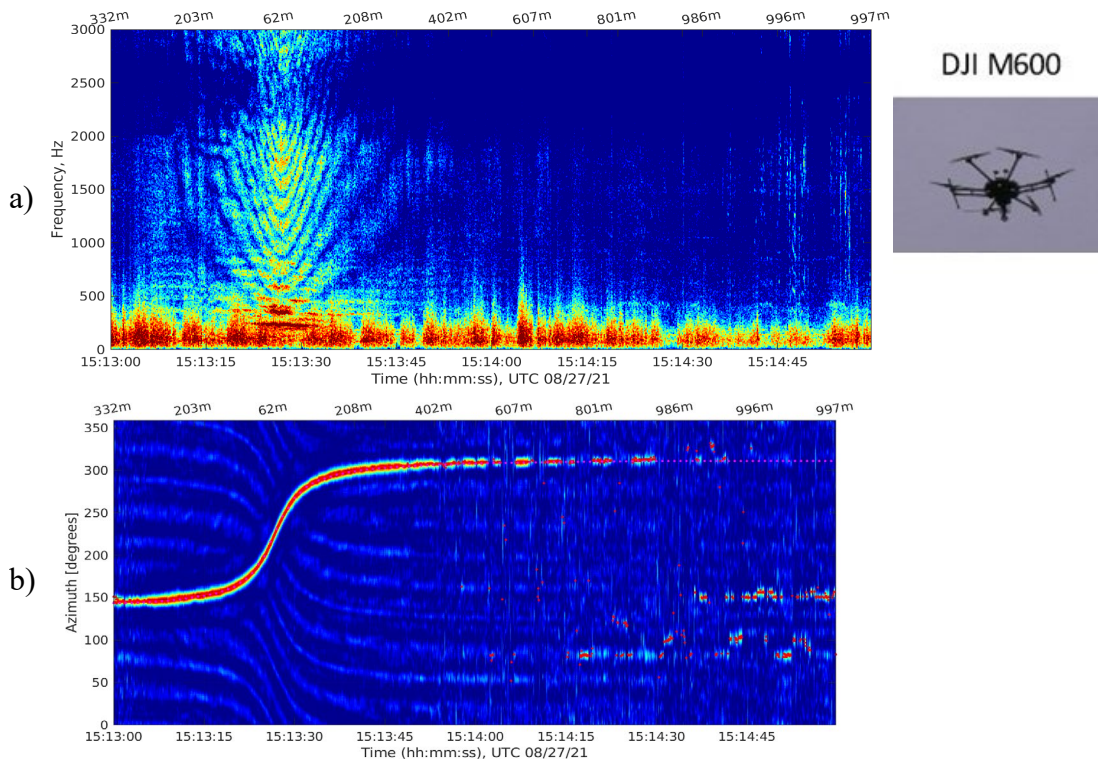


Figure 8. 2021-Aug-27 15:13. Result from one of the DARA arrays. Target is a DJI M600. a – spectrogram – b - SRP-PHAT azimuth slice (seen approximately out to 600 meters), intermittently out to 700 meters

4.1. Expected DADSv2 beamforming performance

Theoretical beamforming performance can be derived from the microphone placement and processing method and can help understand the expectations from the performance of each intermediate system. We present beam patterns of each array, the graphs in

Figure 9a-c show the amount of energy from each direction retained after applying conventional beamforming, steering the beam at azimuth 25 and elevation of 10 degrees.

The original DADS used only 4 microphones, which enabled broadband direction finding, however, the beamforming performance was limited as can be seen from the normalized response shown in

Figure 9a, with most frequencies over 300 Hz having strong grating lobes, comparable in strength with the main lobe. The DARA with 7 microphones has an improved beam pattern (

Figure 9b), with sidelobes starting to appear above 1 kHz. The DADSv2 (

Figure 9c) array has 10 microphones which result in slightly higher gain yet and similar sidelobe performance.

The broadband pattern has been computed for a series of frequencies between 300 and 1500 Hz at 100 Hz intervals (pattern characteristic of SRP-PHAT processing) of the DARA and DADSv2 can be shown to be comparable, while the original DADS has strong ambiguities as shown in

Figure 9b.

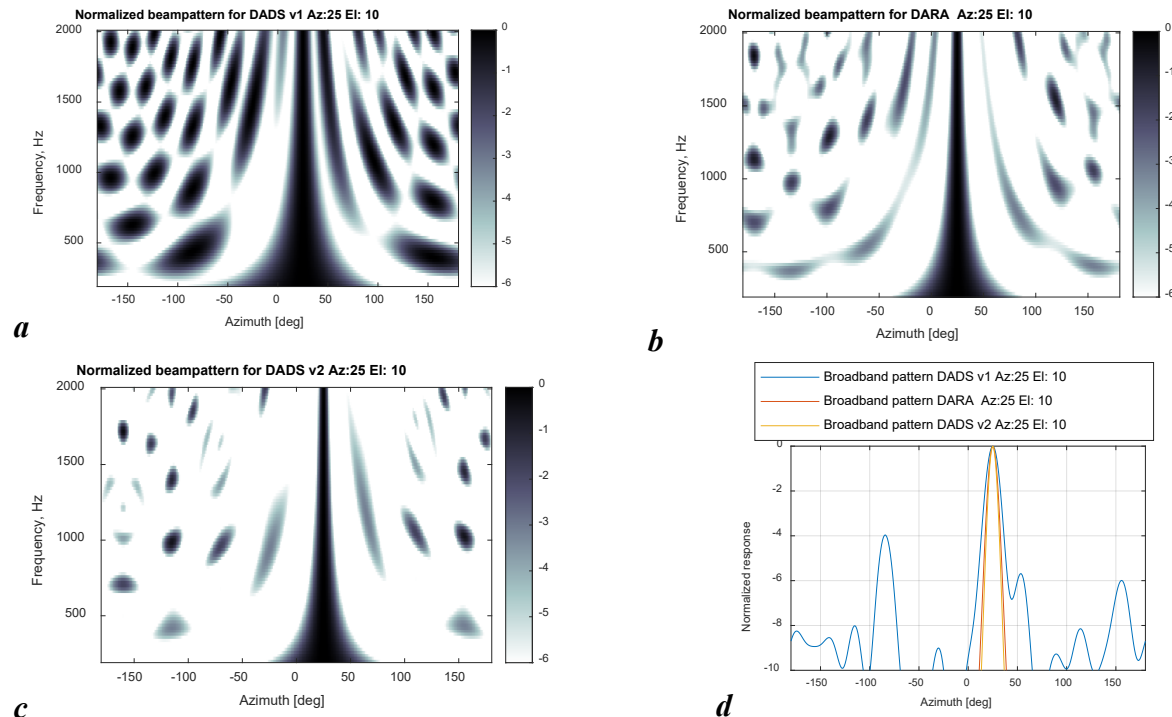


Figure 9. Normalized beampatterns of the arrays within the intermediate systems at several frequencies: a – DADS, b- DARA, c- DADSv2, d – broadband response

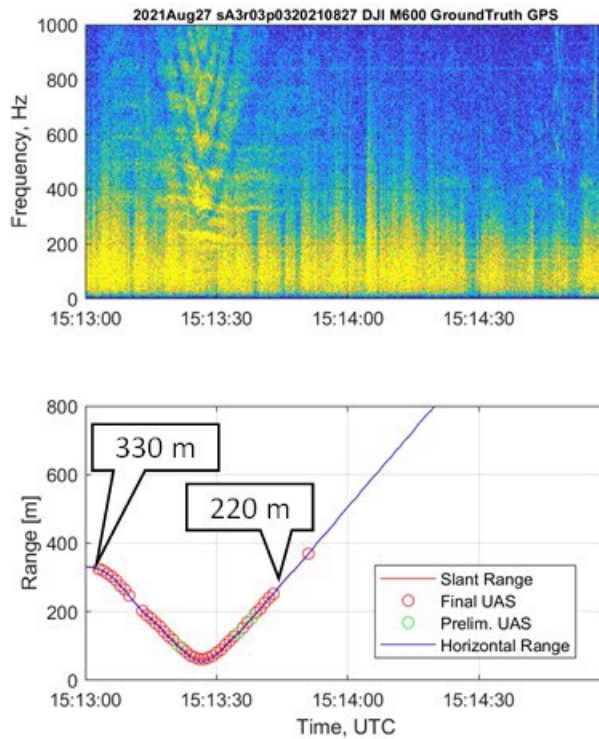
4.2. Improvement of acoustic classification by spatial filtering

This classification algorithm is based on the fact that groups of motors in a multi-rotor UAS rotate with different RPM (Revolutions Per Minute) speeds. RPM in UAS front and rear groups of motors must be different to provide a thrust force in the horizontal direction. Also, motors' RPM must be different to provide a steady flight or hovering in windy conditions. That feature translates into more than one set of harmonic lines in UAS acoustic signatures. On the other hand, the acoustic signature of non-UAS motorized vehicles has only one set of parallel harmonic lines. [1].

The module requires a window of 5 seconds of data at a time to be accumulated and can be performed on a sliding window. On an onboard computer, the processing (Pentium N3710) of one window can take 1-2 seconds and fully occupies 1 core of the CPU, thus classification can only occur consistently every 2 seconds.

The effect of classification distance improvement using beamforming is demonstrated on a particularly noisy distance run of DJI M600 shown in Figure 10. The application of beamforming provided consistent classification out to 410 meters (Figure 10b), by comparison, Figure 10a shows a single-channel spectrogram that is much noisier and results in reliable classification only out to 220-330 meters.

a (omnidirectional, single microphone)



b (beamformed on DOA found from SRP-PHAT)

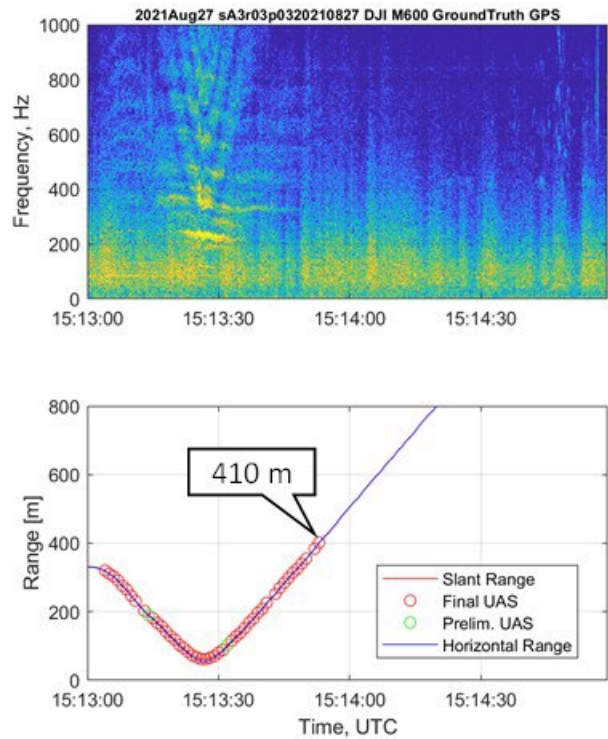


Figure 10. Comparison of classification output on the distance run of a DJI M600, a particularly noisy run. The classification results are plotted as colored circles against the true range to the UAV at the moment of classification. a – no beamforming (yields 220-330 m range), b- beamforming (yields consistent detection out to 410 m)

4.3. Acoustic tracking and direction-finding

The conducted field test using three DARA nodes and three DADS nodes demonstrated coverage of the area with localization capability, alongside other data collecting equipment such as cameras, auxiliary acoustic recorders, and weather stations.

The ground truth of the UAV activity was acquired by interpreting the UAV autopilot data and the aircraft activity was controlled using ADS-B (Automatic Dependent Surveillance-Broadcast) receiver providing tracks over time.

An example showing acoustic tracking for M600 is shown in Figure 11. This track represents the cooperative tracking for both DADS and DARA.

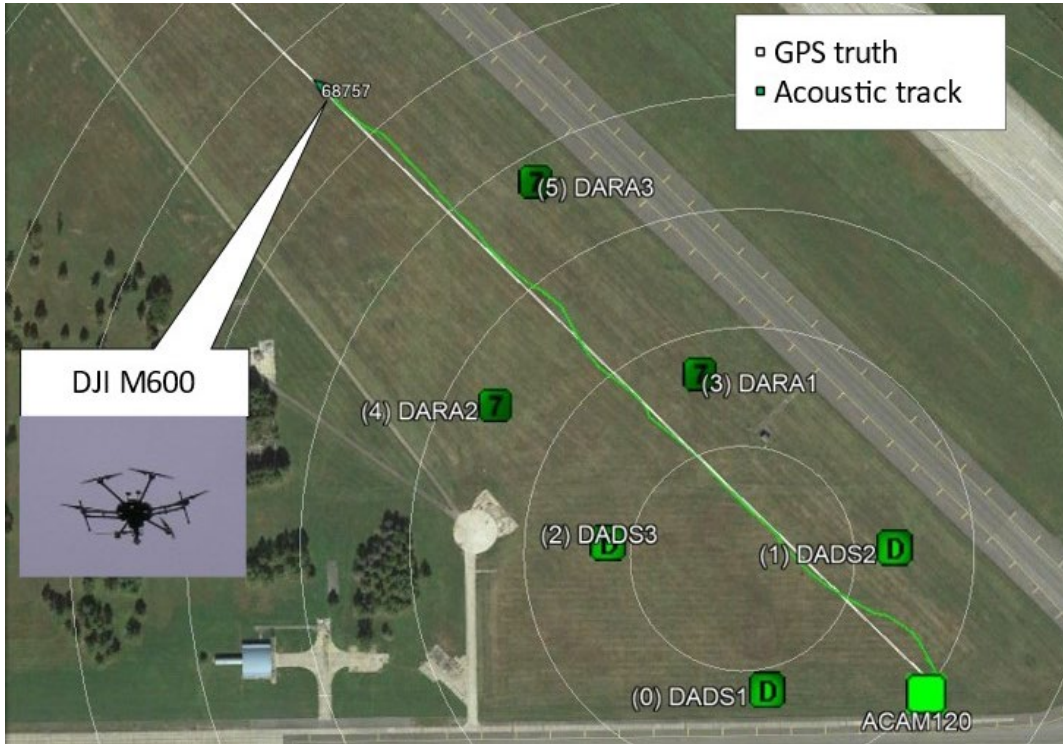


Figure 11. An example of tracking a single target (DJI M600) traveling in a straight line, the range circles are spaced at 100 meters

Analyzing a single-node performance, based on the examples from DARA#1 and DADS #2 is presented in Table.1. The direction-finding to M600 is consistent out to approximately 700 meters (see Figure 8a and Figure 8b).

Table 1. A sampling of performance for DARA (#1) and DADS (#2) sensors placed at approximately the same point in a typical target trajectory

Sensor	Region zeroing	Noise suppression	Target	Az. RMSE 200m-500m [degrees]	Rate of outliers	Detection range [meters]
DARA	RZ	NS	DJI M600	1.2	0.12	470
DADS		NS	DJI M600	1	0.05	410
DARA	RZ	NS	DJI Phantom 4	1.7	0.09	400
DADS		NS	DJI Phantom 4	1.7	0.07	240

5. Stevens Acoustic Database

The Stevens Acoustic Database (SAD) provides a method of generating a parametric dataset of audio files and metadata collected by the Stevens STAR Center for the intended use of acoustic data analysis and machine learning applications.

Each test features different run log information and GPS data that describes the movement of defined targets recorded by a range of different sensors. The sensors have varying standpoint positions, a number of channels, and record files in different formats and sample rates. This package, written in Python, normalizes the data to samples of specified lengths, and sample rates, and populates the target, GPS metadata, and aircraft Automatic Dependent Surveillance-Broadcast (ADS-B) logs as features that describe information about the recording. The package also provides commentary and areas for the user to input necessary processing functions for their applications - whether to write new audio files, generate and save spectrogram images, or directly input the generated array into their model.

The aggregated database features 650 hours of UAV, aircraft, vehicle, and environmental noise recordings. 450 hours of the recordings feature drones of different models and sizes including the DJI M600, DJI Phantom, DJI S1000, and DJI Mavic as well as Intel Falcon, Freefly ALTA, Autel EVO, and 3DR Solo.

6. Conclusions

Stevens Institute of Technology is developing a distributed acoustic sensing system capable of detecting and tracking UAS using the acoustic noise emitted by the propellers.

In the new DADSV2 system, each network node contains an acoustic array and has onboard processing that allows to find direction and classify the sound as coming from a UAS or other. Compared to the previous implementation, the sensing nodes have more microphones (up to 10) and provide beamforming capability that improves the specificity and maximum classification distance. During testing at an airport, the coverage by an intermediate system consisting of six nodes with various numbers of microphones was demonstrated.

Several nodes of the new DADSV2 system were built and functionally tested, with eight nodes planned to be built within the scope of the ongoing project.

The developed system and principles can be used for other military applications for detection, localization, and classification of various acoustic events such as: gunshots, artillery fire, vehicles, military equipment, planes, and helicopters. DADS has higher sensitivity and frequency band in comparison with currently used Unattended Ground Sensors (UGS) and other military acoustic systems that allows it to be used for detection of relatively quiet acoustic signals (ground vehicles, speech, etc.). These and other similar applications may require some modifications to the current DADS depending on the specific requirements of the task.

ACKNOWLEDGMENT

This work was funded by AFRL.

7. References

- [1] A. Sedunov, D. Haddad, H. Salloum, A. Sutin, N. Sedunov, and A. Yakubovskiy, “Stevens Drone Detection Acoustic System and Experiments in Acoustics UAV Tracking,” *2019 IEEE Int. Symp. Technol. Homel. Secur. HST 2019*, 2019.
- [2] Department of Homeland Security, “Strategic Framework for countering terrorism and targeted violence,” *Homel. security*, no. September, p. 40 pp., 2019.
- [3] “AARONIA Drone Incidents World Map.” [Online]. Available: <https://drone-detection-system.com/drone-incidents/>.
- [4] C. Brause, “Thousands of drones unnoticed over the government district.,” *Die Welt*, 11-Sep-2020.
- [5] K. Rempfer, “Did US drones swarm a Russian base? Probably not, but that capability isn’t far off.,” *Millitary Times*, 29-Oct-2018.
- [6] I. Ilijevski, Z. Dimovski, and K. Babanoski, “The Weaponisation of Drones-A Threat from Above Used for Terrorist Purposes Brezpilotni letalniki kot orožje-grožnja od zgoraj, uporabljena v teroristične namene The Weaponisation of Drones-A Threat from Above Used for Terrorist Purposes,” *VARSTVOSLOVJE J. Crim. Justice Secur. year*, vol. 23, no. 3, pp. 336–349.
- [7] “Ukraine Is Fighting Russia With Drones and Rewriting the Rules of War.,” *CNET*, 19-Apr-2022.
- [8] D. Hambling, “Small Quadcopters Rule The Battlefield In Ukraine — Which Makes Their Chinese Manufacturers Very Unhappy,” 29-Apr-2022.
- [9] “Homeland security advisory council. Final report of the emerging technologies subcommittee unmanned aircraft systems.,” 2020.
- [10] A. H. Michel, “Counter-Drone Systems,” *Bard Coll.*, vol. 19, no. March, pp. 10–12, 2019.
- [11] “Ukraine, and Russia — what we know about AeroScope,” *The Verge*, 23-Mar-2022.
- [12] J. Wang, Y. Liu, H. Song, and E. Aeronautical, “Tutorial : Counter-Unmanned Aircraft System (s) (C-UAS): State of the Art, Challenges , and Future Trends,” no. 10, 2021.
- [13] F. L. Chiper, A. Martian, C. Vladeanu, I. Marghescu, R. Craciunescu, and O. Fratu, “Drone Detection and Defense Systems: Survey and a Software-Defined Radio-Based Solution,” *Sensors*, vol. 22, no. 4, 2022.
- [14] J. Martinez-Carranza and C. Rascon, “A review on auditory perception for unmanned aerial vehicles,” *Sensors (Switzerland)*, vol. 20, no. 24, pp. 1–24, 2020.
- [15] J. Busset *et al.*, “Detection and tracking of drones using advanced acoustic cameras,” *Unmanned/Unattended Sensors Sens. Networks XI; Adv. Free. Opt. Commun. Tech. Appl.*, vol. 9647, p. 96470F, Oct. 2015.
- [16] H. Salloum, A. Sedunov, N. Sedunov, A. Sutin, and D. Masters, “Acoustic system for Low Flying Aircraft detection,” in *2015 IEEE International Symposium on Technologies for Homeland Security (HST)*, 2015, pp. 1–6.
- [17] A. Sedunov, A. Sutin, N. Sedunov, H. Salloum, A. Yakubovskiy, and D. Masters, “Passive acoustic system for tracking low-flying aircraft,” *IET Radar, Sonar Navig.*, vol. 10, no. 9, pp. 1561–1568, 2016.

- [18] A. Sedunov, H. Salloum, A. Sutin, and N. Sedunov, “Long-term testing of acoustic system for tracking low-flying aircraft,” in *2018 IEEE International Symposium on Technologies for Homeland Security (HST)*, 2018, pp. 1–6.
- [19] A. Sedunov and A. Sutin, “UAV Passive Acoustic Detection,” in *IEEE-HST*, 2018, pp. 3–8.
- [20] D. Kadyrov, A. Sedunov, N. Sedunov, A. Sutin, H. Salloum, and S. Tsyuryupa, “Improvements to the Stevens drone acoustic detection system,” in *The Journal of the Acoustical Society of America*, 2022, vol. 151, no. 4, p. 045001.
- [21] J. H. DiBiase, H. F. Silverman, and M. S. Brandstein, “Robust Localization in Reverberant Rooms,” in *Microphone Arrays*, 2001, pp. 157–180.