# Impact of UAV Swarm Density and Heterogeneity on Synthetic Aperture DoA Convergence

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***Abstract*—This paper reports on the impact of UAV swarm density and heterogeneity on synthetic aperture DoA convergence. The synthetic aperture is derived from the displacement of distributed UAVs (agents) operating in a sparse volumetric swarm. Heterogeneity arises from the changing orientation of an agent's antenna and receiving pattern function as it swarms in the distributed cluster of agents. This alters the agents' antenna pattern function(s) over time and alters the convergence and overall performance properties of vector-space direction of arrival techniques. The goal of this work is to evaluate the impact of the swarm density and orientation in this framework and study the convergence and error using this technique under different SNR conditions using the MUSIC algorithm. Simulation and measurements for up to sixteen elements on a thirty-two-location test platform are provided and comparisons are made to benchmark their performance with theoretical expectations.**

***Keywords*—Direction-of-arrival estimation; Unmanned aerial vehicles; Quaternions; Swarming; Aperiodic arrays**

## I. INTRODUCTION

Direction-of-arrival (DoA) estimation has been a topic of discussion for many years [1]-[3]. Even though a number of algorithms have been proposed to provide the estimation for DoA, the multiple signal classification (MUSIC) algorithm remains quite prevalent since it offers a very robust eigen-based decomposition of the signal space. Furthermore, most of investigations are limited to either linear (one-dimensional) or planar (two-dimensional) array configurations. The three-dimensional volumetric antenna array structure based on cubic and spherical configurations have demonstrated the ability to overcome aliasing and improve the accuracy of DoA estimation using MUSIC algorithm [4], However, mutual coupling and shielding effects among the compact array gives rise to serious problem in real world applications.

This work proposes a pragmatic method to leverage this type of volumetric sampling using sparse UAV swarms as a distributed signal collection platform. This swarm morphs over time to create a synthetic aperture, which alters the position and orientation of agents in the swarm. This work evaluates the performance of these unstructured volumetric distributions under different SNR conditions. Simulations are used to evaluate convergence as a function of sparsity, swarm volume, and heterogeneity derived from rotated pattern functions.

## II. SWARMING UAV SYNTHETIC APERTURE

Fig. 1 shows a graphical representation of a UAV swarm as it morphs in time. Each of the $N$ agents in the swarm has a location, orientation, and trajectory. Notionally, these have position $P_{n,t}(r,\theta,\phi)$, where $n$ is the agent's index and $t$ is the 'snapshot' time parameter. During swarming, the agents undergo rotations and translations, where a dual quaternion framework provides a convenient mechanism to handle this behavior. This motion rotates the agents' local $(u,v,w)$ coordinate systems that describes the spatial orientation of their antenna radiation pattern with respect to the global coordinate system and incoming signal if interest $S(\theta_0,\phi_0)$. The collection of these $M$ measurements over time creates a synthetic aperture that can be used to calculate the parameters of interest $(\theta_0,\phi_0)$.

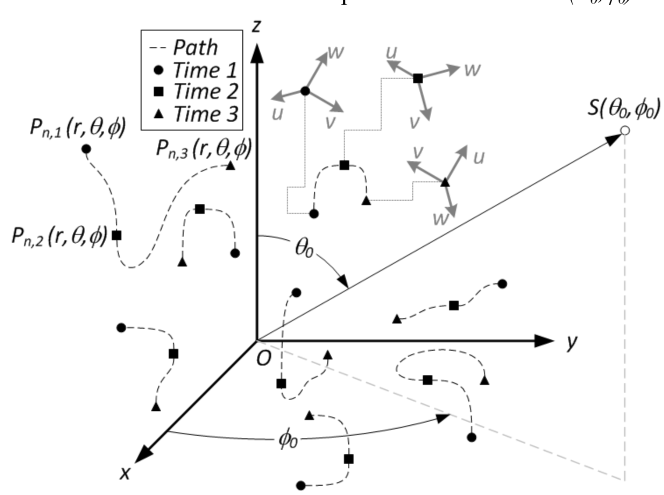


Fig. 1 Volumetric Random Antenna Arrays Configuration

## III. SIMULATION AND EXPERIMENT

The data collection process assumes the target is stationary and narrowband, and that one or more of the agents of the swarm can process the information (or accomplished remotely). This also assumes the agents have connected wirelessly. The conjecture assumes that the MUSIC algorithm can estimate the DOA easily with high SNR, and numbers of iterations are needed for the system to converge with low SNR. To study this, a test-bed is constructed with thirty-two possible locations that an agent can occupy. The iterative data collection process begins at time $t = 1$ (the circles in Fig. 1), when all $N$ agents record the incident signal and report their position $P_{n,1}(r,\theta,\phi)$ with this information. This is used to make the first estimate of the DoA. The process iterates for $M$ snapshots times until the convergence criteria is met or some other instruction is received. Fig. 1 shows this iteration moving from circle, to square, to triangle (each represents a different location in time).

## IV. Results

In experiments and simulations, the test fixture provides a convenient platform to study this morphing in time (using up to sixteen elements). In experiments, randomly positioned rectangular patch antennas designed for 2.45 GHz are used with a fixed morphing volume provided by a sphere with a 380 mm radius to estimate the DOA. Figs. 2-3 show examples of the simulated MUSIC spectrum for one and $M = 20$ iterations with SNR = -15 dB. Each of these assumes a direction of arrival with an azimuth of 300°and elevation of 60°.

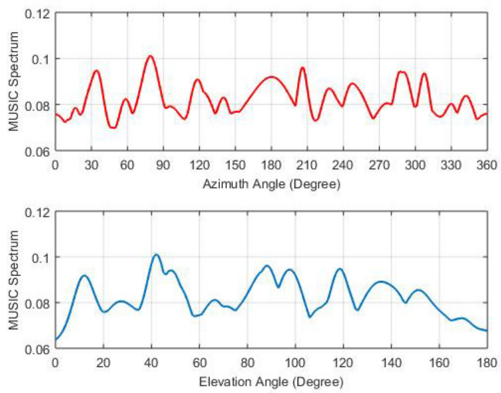


Fig. 2. Simulated MUSIC spectrum with number of iteration t = 1, an incident signal with a SNR = -15 dB, and a direction of arrival with an azimuth of 300° and elevation of 60°.

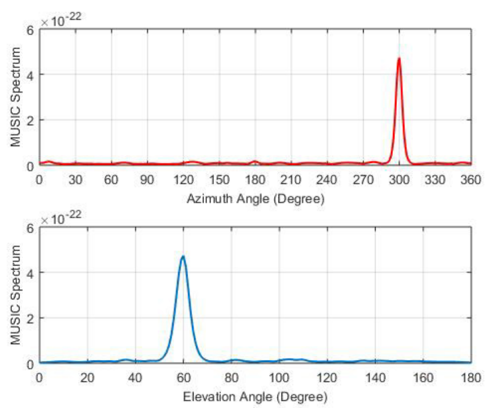


Fig. 3. Simulated MUSIC spectrum with number of iteration t = 20, an incident signal with a SNR = -15 dB, and a direction of arrival with an azimuth of 300° and elevation of 60°.

Figs. 4-5 show the results obtained from two of these experiments when the transmitting antenna was placed at pre-calculated locations with the azimuthal angles 14.7° and 37.4°, elevation angles 29.8° and 13.4°. A single iteration was used to estimate the incident angles and an accurate SNR was not available. The error between theoretical expectation and practical result is within 1 to 2 degrees.

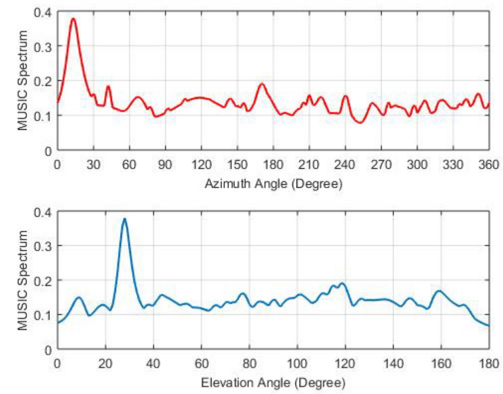


Fig. 4. Measured MUSIC spectrum with number of iteration t = 1, an incident signal of an azimuth of 14.7° and elevation of 29.8°.

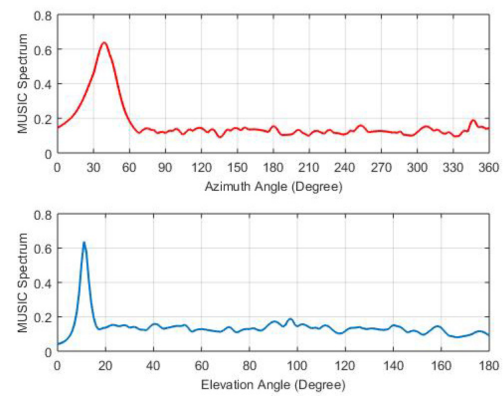


Fig. 5. Measured MUSIC spectrum with number of iteration t = 1, an incident signal of an azimuth of 37.4° and elevation of 13.4°.

## V. Conclusion

The estimation of DoA was examined using a UAV swarm to create a synthetic receiving aperture. The density and heterogeneity impact convergence, but simulations indicate that the technique may be effective in very noisy environments. Experimental observations show that the system can accurately capture the azimuthal and elevation angles of the source. Ongoing work is investigating the use of computer vision and machine learning techniques to augment the process.

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