Unmanned Aerial Vehicles Swarm-Based Distributed Phased Arrays for Grating Lobe Mitigation and Collision Avoidance

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ABSTRACT Distributed phased arrays based on unmanned aerial vehicle (UAV) swarm with small antenna elements on each micro-UAV are expected to achieve much better performance than the traditional phased arrays due to a large amount of swarm mobile individuals and deployment flexibility. To avoid the possible collisions of the flying UAVs, a large separation distance between UAVs is required, but grating lobes can appear when the array element spacing is larger than one-half wavelength. To solve this issue, array antennas with aperiodic element placement are normally used to mitigate the grating lobes, while suffering from a high collision risk for UAVs due to the reduced array element separation in the aperiodic array. This paper proposes a novel 3-D aperiodic array design by adding an additional degree of freedom in the optimization of array configuration. The sidelobe levels can be largely reduced from the planar periodic arrays. In addition, the collision risk for UAVs represented by the minimum separation distance between array elements can be largely decreased from the planar aperiodic arrays. This work provides a feasible strategy for the design and optimization of the UAV swarm-based phased arrays for practical applications.

INDEX TERMS Phased arrays, UAVs, grating lobe mitigation, collision avoidance, aperiodic arrays, optimization.

I. INTRODUCTION

UNMANNED aerial vehicles (UAV) swarm technology has garnered great interest for wireless communications [1], [2], [3], [4], remote sensing [5], [6], [7], radars [8], [9], [10], [11], and many other applications. Traditional phased arrays are based on single platform combing the signals from each array element through the analog feeding network. In contrast, distributed phased arrays connecting each node through the wireless network enable the distributed beamforming by accurately controlling the phase states of the individual nodes of the arrays. A UAV swarm-based distributed phased array is a combination of a swarm of flying micro-UAVs, each of which is equipped with a single small wireless system. Due to a large number of swarm distributed mobile platforms and deployment flexibility, it is expected that such a distributed phased array can achieve much better performance than a traditional phased array based on a single solid platform [12], [13], [14], [15]. In recent years, UAV swarm-based distributed sparse array systems have been proposed as aerial basestations [16], [17], data aggregators [18], air-to-air communication system [4], Internet of Things (IoT) data harvesting and dissemination [19], physical layer secure communications [20], and for many other applications.

Since the UAV swarm-based phased array systems enable distributed beamforming through the coherent combination of many separate transceivers, the structure of such systems are normally based on the traditional planar array configurations, rather than using reflectarrays [21] or transmitarrays structures [22] with closely spaced passive resonant elements. Due to the limitations of physical dimension of UAVs, the minimum array element spacing would be larger than one-half wavelength, resulting in grating lobes. Recently, several techniques have been proposed to mitigate the grating lobes of the UAV swarm-based planar distributed phased arrays. References [12], [23] developed robust beamformer and planar tiled arrays to mitigate positional errors for grating lobe mitigation. Reference [24] uses
However, the large support structures for deploying array antennas and complex feed network may limit their applications in solid aperture-based phased arrays. Due to the flexibility of distributed system configuration and deployment, the UAV swarm-based phased arrays provide a unique platform for the development of the volumetric arrays.

To achieve both the low sidelobe level and the low collision risk for the flying UAVs, a UAV swarm-based 3-D aperiodic phased array is proposed in this paper. Schematic diagrams of UAV swarm-based phased arrays are shown in Fig. 2(c). Different from the planar aperiodic array, an additional degree of freedom in the z direction is included in the design of a 3-D aperiodic array element position. Compared to the planar periodic array in Fig. 2(a), the side-lobe levels for the optimized 3-D aperiodic array can be largely decreased due to the aperiodic element distribution. Compared to the planar aperiodic array in Fig. 2(b), the additional degree of freedom in the z direction for the optimized 3-D aperiodic array helps to increase the minimum element spacing and keep the same low sidelobe levels. The real 3-D aperiodic array can be considered as a basic strategy for the design and optimization of the UAV swarm-based phased arrays.

An analytical model is introduced to analyze the array antenna radiation performance. A genetic algorithm uses to optimize the array element position for the lowest peak side-lobe level (PSLL) in the array radiation pattern and the minimum distance between the array elements. The PSLL for a planar aperiodic array with different minimum array element spacing is analyzed. The embedded element radiation pattern for a 3-D array influenced by the surrounding array elements is studied using a full-wave model. The PSLL and the minimum element spacing are compared for a planar periodic array, the corresponding optimized planar aperiodic array, and the corresponding optimized 3-D aperiodic array.

II. ANALYSIS METHOD

In this section, an analytical model is introduced to analyze the array antenna radiation performance. To simplify the array model and speed up the evaluation of the cost function in each iteration during the optimization, the array embedded element radiation patterns are approximately equal to the radiation pattern for a single isolated antenna. This approximation is valid when $d_0$ of the sparse array is larger than one wavelength and the accuracy of this approximation was verified by comparing it with a full-wave phased array model in [27].

A. ELEMENT RADIATED FIELDS

In the model, square patch antennas in the $x$-$y$ plane with the same linear polarization are used as the array elements. The normalized radiated electric fields $\overline{E}_{\text{ant}}(\theta, \phi)$ for a single $x$-polarized standalone square patch antenna are

$$|\overline{E}_{\text{ant},\theta}| = \cos \theta \cdot \sin \phi \cdot X \frac{Y}{Z} \tag{1}$$

$$|\overline{E}_{\text{ant},\phi}| = \cos \phi \cdot X \frac{Y}{Z} \tag{2}$$

FIGURE 1. Schematic diagram for grating lobe mitigation by a planar aperiodic array. For a planar periodic array, a grating lobe is observed when the element spacing $d_0$ is larger than $0.5\lambda$. This grating lobe can be mitigated by aperiodically placing the array elements with an offset vector $(\Delta x, \Delta y)$ applied to the original element position. However, the minimum element spacing $d_{\text{min}}$ for the optimized planar aperiodic array can be less than $d_0$, which increases the collision risk for UAVs.
where

\[ X = \cos \left( \frac{k_0L}{2} \sin \theta \cos \phi \right) \]  
\[ Y = \sin \left( \frac{k_0L}{2} \sin \theta \cos \phi \right) \]  
\[ Z = \frac{k_0L}{2} \sin \theta \cos \phi. \]  

\( L \) is the width of the square patch antenna and \( k_0 \) is the wave number in free space.

For an \( N \times N \) square planar periodic array, the \((m, n)\)th array element is excited with current \( I_0 \) and the radiated field in the \( \vec{r} \) direction is

\[ \vec{E}_{\text{ele}, mn}(\vec{r}) = \vec{E}_{\text{ant}}(\vec{r}) \cdot \exp(jk_0(\hat{r}x_{mn} + \hat{r}y_{mn} + \hat{r}z_{mn})) \],

(6)

where

\[ x_{mn} = md_0 \]  
\[ y_{mn} = nd_0 \]  
\[ z_{mn} = z_0. \]  

\((x_{mn}, y_{mn}, z_{mn})\) represents the \((m, n)\)th element position in the array and \( d_0 \) is the cell spacing in the \( x-y \) plane.

The element position for an aperiodic array can be implemented by adding an offset vector \((\Delta x_{mn}, \Delta y_{mn}, \Delta z_{mn})\) to the \((m, n)\)th element position in the periodic array by

\[ x_{mn} = md_0 + \Delta x_{mn}, \]  
\[ y_{mn} = nd_0 + \Delta y_{mn}, \]  
\[ z_{mn} = z_0 + \Delta z_{mn}. \]  

The minimum array element spacing \(d_{\text{min}}\) related to the collision risk of UAVs can be calculated from the distance between the two elements \((x, y, z)\) and \((x', y', z')\) by

\[ d_{\text{min}} = \min \left( \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2} \right). \]  

\(B. \ \text{ARRAY RADIATED FIELDS}\)

The total radiated electric field from the array antenna can be found from the element radiated field \(\vec{E}\) and the beamformer weight \(\vec{w} = (w_1, w_2, \ldots, w_N)\) using the linearity of the radiated field with respect to element excitations. The total radiated electric field is

\[ \vec{E}(\vec{r}) = \frac{1}{|I_0|^2} \sum_{m=1}^{N} \sum_{n=1}^{N} w_n^* \vec{E}_{m,n}(\vec{r}). \]  

(14)

To account for the first-order mutual coupling between array elements, the array directivity is calculated by the overlap matrix method. The element pattern overlap matrix \(A\) with elements is given by

\[ A_{ij} = \frac{1}{2\eta} \int_{\Omega} \vec{E}_{\text{ele},i}(\vec{r}) \cdot \vec{E}^*_\text{ele,j}(\vec{r}) \, d\Omega, \]  

(15)

where \(\Omega\) is the spherical angle of \(\vec{r}\). The array total radiated power is

\[ P_{\text{rad}} = \frac{1}{|I_0|^2} \vec{w}^H \vec{A} \vec{w}. \]  

(16)

where \(H\) represents conjugate transpose. The total radiated power density of the array antenna at the steered direction \(\vec{r}_0\) is

\[ S(\vec{r}_0) = \frac{1}{|I_0|^2} \vec{w}^H \vec{B}(\vec{r}_0) \vec{w}, \]  

(17)

where \(\vec{B}(\vec{r}_0)\) represents the array signal response matrix with elements given by

\[ B_{i,j}(\vec{r}_0) = \frac{1}{\eta} \vec{E}_{\text{ele},i}(\vec{r}) \cdot \vec{E}^*_\text{ele,j}(\vec{r}). \]  

(18)

By combining the total radiated power and the total radiated power density at the steered direction \(\vec{r}_0\), the array directivity can be expressed by

\[ D(\vec{r}_0) = \frac{4\pi r^2 \vec{w}^H \vec{B}(\vec{r}_0) \vec{w}}{\vec{w}^H \vec{A} \vec{w}}. \]  

(19)
FIGURE 3. Minimum distance limit for element positions optimization in swarm-UAVs.

The PSLL of the array radiation pattern is calculated by

\[
\text{PSLL (dB)} = -10 \log_{10} \left( \frac{D(r_0)}{D(\bar{r}_g)} \right)
\]

(20)

where \( \bar{r}_g \) is a point with spherical angles in the direction of the peak sidelobe level.

C. BOUNDARIES FOR ELEMENT POSITIONS

The element offset distances from the element in a planar periodic array are optimized using a genetic algorithm. The array element position in the optimization is confined in a box with dimension of \( L_{\text{limit},x} \times L_{\text{limit},y} \times L_{\text{limit},z} \) in Fig. 3. The element offset distance vector \((\Delta x_{mn}, \Delta y_{mn}, \Delta z_{mn})\) is limited by

\[
-0.5L_{\text{limit},x} < \Delta x_{mn} < 0.5L_{\text{limit},x}
\]

(21)

\[
-0.5L_{\text{limit},y} < \Delta y_{mn} < 0.5L_{\text{limit},y}
\]

(22)

\[
-0.5L_{\text{limit},z} < \Delta z_{mn} < 0.5L_{\text{limit},z}
\]

(23)

where \( L_{\text{limit},x} \) equals to \( L_{\text{limit},y} \). Then the minimum spacing constraint of array elements in the optimization becomes

\[
d_{\text{min,limit}} = d_0 - L_{\text{limit},x,y}.
\]

(24)

D. ELEMENT PHASE ERROR

The array model described above is based on an ideal distributed array model where the radiated fields from each array element add together coherently in the expected direction. In practice, however, there are several major factors that can lead to severe degradation of the incoherent radiation pattern. These include the relative frequency offset and phase error of the oscillators on each array element, the relative timing offset, the drone positional estimation errors, the channel delays from each node to the destination, and element’s tilt angle [15], [33]. To account for the practical application requirements, a uniform distributed random noise \( \Delta \) with a maximum amplitude of \( \Delta_{\text{max}} \) is added to the beamformer weights for each array element by

\[
w'_{m,n} = w_{m,n} e^{j2\pi \Delta m n \lambda}.
\]

(25)

The incoherent radiation pattern of the distributed array antenna can be calculated by applying (25) to (19).

E. OPTIMIZATION PROCESS

Using the above array model, the element offset distance vector \((\Delta x_{mn}, \Delta y_{mn}, \Delta z_{mn})\) are optimized using a genetic algorithm [27], [34] to minimize PSLL and maximize the minimum array element spacing. Since the maximum PSLL usually occurs when the beam is steered to the largest angle from the zenith direction, to simplify the optimization process, the PSLL is optimized to a minimum when the zenith angle \( \theta \) is \( 30^\circ \) by the azimuth angles \( \phi \) at \( 0^\circ \), \( 45^\circ \), and \( 90^\circ \). To ensure statistical reliability of the optimized results, the population number was set at 100. The cost function is defined as the reciprocal of the maximum PSLL in dB plus the minimum array element spacing in wavelengths with a scaling factor of 10. The optimization is terminated when the average relative change in the fitness function values over 50 generations was less than \( 1 \times 10^{-4} \). The flow chart of array optimization procedure using the genetic algorithm is shown in Fig. 4. Fig. 5 shows the cost function over iteration for the example of optimizing a \( 6 \times 6 \)-element 3-D aperiodic array.

III. PLANAR ARRAY LIMITS

For a UAV swarm-based phased array, it is necessary to keep a large distance between UAVs to avoid the potential collision of flying UAVs. For a UAV swarm-based planar periodic phased array, however, grating lobes occur when the array element spacing is larger than one half wavelength. To mitigate the grating lobes that appear for the planar periodic arrays, the arrays generally require aperiodic element placement. In this section, a tradeoff between the PSLL for the
array radiation pattern and the minimum array element spacing correlated to the collision risk of UAVs will be presented for an optimized planar aperiodic array. In the array model, the array element number is 36 and the mainlobe is steered to $\theta = -30^\circ$. For the planar periodic array, the array element spacing is $d_0 = 2\lambda$.

A. APERIODIC ARRAYS FOR GRATING LOBE MITIGATION

As shown in Fig. 1, for a beam-steered planar periodic array, when the element spacing $d_0$ is larger than $0.5\lambda$, the element radiated fields can be in-phase superposition in the mainlobe and grating lobe directions. For an aperiodic array, the element radiated fields are in-phase superposition in the main lobe direction, while are out-of-phase superposition in the grating lobe direction due to the aperiodic array element distribution. The grating lobe can be mitigated by optimizing the offset vector $(\Delta x, \Delta y)$ from the corresponding periodic array.

B. COLLISION RISK FOR PLANAR APERIODIC ARRAYS

Through the above analysis, we have found that the PSLL for the optimized planar aperiodic array can be largely decreased compared to the planar periodic array. As shown in Fig. 1, the minimum element spacing $d_{\text{min}}$, however, can be much less than that for the planar periodic array. Due to the complicated circumstance, reduced distance between flying UAVs could largely increase the collision risk for UAVs and make the optimized aperiodic array configuration impractical. Thus, the $d_{\text{min}}$ in practice should be large enough to keep a safe distance between UAVs, while the PSLL for the array radiation pattern can be increased.

Fig. 6 shows a comparison of array radiation pattern for a $6 \times 6$ planar periodic array and the corresponding optimized planar aperiodic array. Due to the large element spacing, grating lobes are observed when $\theta$ at $0^\circ$ and $30^\circ$. For the planar aperiodic array, the array element positions are optimized using a genetic algorithm to minimize the PSLL of the array radiation pattern. The grating lobes at $0^\circ$ and $30^\circ$ observed from the planar periodic array can be mitigated by the optimized planar aperiodic array.

Fig. 7 shows the optimization of a $6 \times 6$ planar aperiodic array for the lowest PSLL. The preliminary conditions for each array element position are represented by blue lines. The element positions are not allowed to be outside the blue boundary lines during the optimization. Smaller $L_{\text{limit},x}$ corresponds to a less degree of freedom of moving the array element from its original position. When $L_{\text{limit},xy}$ is 0, the array becomes a planar periodic array and a large grating lobe is observed. When the $L_{\text{limit},xy}$ is increased to $0.8\lambda$, the PSLL can be decreased from $1.4\text{dB}$ to $-8.5\text{dB}$, which is due to the more degree of freedom to randomize the aperiodic array element distributions. From the distribution of array elements, however, increase the limit of the maximum offset distance of array element leads to the decrease of the minimum element spacing and the increase of the collision risk for UAVs. Thus, it is necessary to find a way to reduce the PSLL for the aperiodic arrays, while maintaining...
IV. 3-D APERIODIC ARRAYS

Different from the traditional planar phased arrays based on solid apertures, the array elements for the UAV swarm-based phased arrays are more flexible to move in any direction. In this section, we will demonstrate that both the low PSLL and the low collision risk for UAVs can be achieved by the optimized 3-D aperiodic arrays. The element radiation pattern influenced by the surrounding elements in the 3-D aperiodic arrays will be studied. The PSLL and the minimum element spacing for the optimized 3-D aperiodic arrays will be compared to the corresponding optimized planar aperiodic arrays.

A. BLOCKAGE EFFECT

An example of the array layout for a 3-D aperiodic array is shown in Fig. 2. Compared to a planar aperiodic array where the element positions are optimized in the x and y directions, an additional parameter Δz is included in the optimization of the element positions for the 3-D aperiodic array.

In the analytical model for the planar arrays, to speed up the optimization process, we assume that the radiation pattern for the embedded array element is the same as that for an isolated array element. For the 3-D array analysis, however, the element radiation can be blocked by the surrounding elements due to the different positions in the z direction, which may have a large distortion of the element radiation pattern. In this section, the influence of the blockage by the surrounding elements on the embedded element radiation pattern is performed by the commercial software Ansys High Frequency Structure (HFSS) using Finite Element Method (FEM) solver. The 3-D structures of antennas and UAVs are included in the full-wave simulation model.

Fig. 8 shows a UAV swarm-based 3-element linear array, with a classical square patch antenna element on top of each UAV. The UAV is made of Polyester and has a length of 0.3 meters. The length of ground plane of the square patch antenna is 0.15 meters and the operating frequency is 1 GHz. The array element spacing in the x-y plane is $d_0$ and the offset distance of the center element is Δz. Fig. 9 shows the radiation pattern for the central element affected by surrounding elements at different $d_0$ and Δz. When $d_0$ is 0.6 meters, a distortion of radiation pattern for the center element is observed due to scattering effect. Increasing $d_0$ and decreasing Δz helps to reduce distortion of the radiation pattern. When $d_0$ is increased to 1.2 meters, the radiation pattern for the center element shows smaller changes at different Δz. Therefore, in the analytical model of array antenna, when $d_0$ is greater than 0.6 meters, the blockage effect by the other array elements becomes less significant, and the array embedded element radiation pattern is approximately equal to the isolated single element radiation pattern.

B. COMPARISONS

For the design of planar aperiodic arrays, the element offset distance Δx and Δy are optimized for the minimum PSLL and the maximum $d_{\text{min}}$. In the 3-D array analysis, besides Δx and Δy, the element offset distance in the z direction is included in the optimization. As indicated in Fig. 2, to make it consistent with the planar array model, $d_0$ in the 3-D aperiodic array model is defined as the average element spacing when projecting the 3-D array elements in the x-y plane. For the 6 × 6 array antenna, the element position is optimized at 1 GHz. The maximum offset distance in the...
Fig. 9. Embedded radiation pattern for the center antenna element in Fig. 8 over different element spacing $d_0$ and offset distances $\Delta z$. The antenna operating frequency is 1 GHz and radiation pattern and the array antennas are in the same cut plane.

$z$ direction $L_{\text{limit},z}$ is limited to $2d_0$ in the optimization of array element position for the 3-D aperiodic arrays.

1) RADIATION AND INTER-UAV DISTANCE

Fig. 10 shows a comparison of PSLL and $d_{\text{min}}$ for planar periodic arrays, the corresponding optimized planar aperiodic arrays, and the corresponding optimized 3-D aperiodic arrays. As shown in Fig. 10(a), the PSLL for aperiodic arrays can be greatly reduced from the corresponding planar periodic array due to the aperiodic element distribution. The PSLL of the optimized 3-D aperiodic array is comparable to that of the optimized planar aperiodic array. Fig. 10(b) shows that the minimum element spacing for the optimized 3-D aperiodic array can be largely increased compared to the optimized planar aperiodic array, which helps to avoid collisions for flying UAVs in the red region, where the minimum element spacing is less than 0.65 meters [35]. The minimum element spacing for the optimized 3-D aperiodic array is close to that for the planar periodic array. As a result, the optimized 3-D aperiodic array shows the advantages of mitigating grating lobes and avoiding collisions.

Fig. 10. Comparison of $6 \times 6$ array antennas over different $d_0$. The threshold of the minimum inter-UAV distance for the collision avoidance sets to 0.65 meters [35].

Fig. 11. Peak sidelobe level for $6 \times 6$ arrays changes over different frequencies. The array element positions are optimized at 1 GHz.
2) BANDWIDTH

A comparison of PSLL with different frequencies are shown in Fig. 11. $d_0$ is equal to 0.6 meters, and the array element position is optimized at 1 GHz. Due to the periodic element distribution, the planar periodic array has the largest PSLL over a wide bandwidth. The PSLLs for the planar periodic array and the optimized planar aperiodic array decreases with decreasing frequency. Compared with the optimized planar aperiodic array, the PSLL for the optimized 3-D aperiodic array has a larger increment when the operating frequency of the array antenna deviates from the optimized frequency. This means that the array layout for the optimized 3-D aperiodic array is sensitive to frequency changes and should be considered in the practical applications.

3) ELEMENT PHASE ERROR EFFECTS

All of the above results are based on an ideal distributed array model where the radiated fields from each array element combine coherently in the expected direction with no phase errors. To account for the practical application, such as element positional estimation error, a uniform distributed random noise in (25) is applied to each array element. Fig. 12 shows 3-D radiation patterns for a $6 \times 6$ planar periodic array and corresponding optimized planar and 3-D aperiodic arrays at different random element phase errors limited to a maximum of $\Delta_{\text{max}}$. The mainlobe of the array radiation pattern is steered to $\theta$ at $-30^\circ$ and $d_0$ is 0.6 meters. When $\Delta_{\text{max}}$ is larger than $0.1\lambda$, a significant drop in the maximum directivity is observed, while the sidelobe level remains roughly the same for different phase errors. The mainlobe and sidelobes for the array radiation pattern of the optimized planar aperiodic array and the optimized 3-D aperiodic array are similar for different phase errors of the array elements. Therefore, when considering the practical applications, in order to maintain the high gain of the array antenna, the phase error of the array element in the distributed phased array system should be less than $0.1\lambda$.

V. CONCLUSION

Sidelobe levels and collision risk of flying UAVs represented by the minimum separation distance between array elements have been studied for planar periodic arrays, optimized planar aperiodic arrays, and optimized 3-D aperiodic arrays. Compared to the planar periodic arrays, the PSLL for the optimized 3-D aperiodic arrays can be largely decreased due to the aperiodic array element distribution. Compared to the optimized planar aperiodic arrays, the collision risk of flying UAVs can be largely decreased for the optimized 3-D aperiodic arrays due to the additional degree of freedom in the design of array element position. For the optimized 3-D aperiodic arrays, the blockage effect of the embedded array element radiation pattern by the surrounding elements can be ignored when the array element spacing $d_0$ is large enough. The 3-D aperiodic array layout can be considered as a feasible strategy for the design and optimization of the UAV swarm-based phased arrays when the UAVs are flying in complicated circumstances. For the future work, it would
be interesting to consider building such UAV swarm based 3-D aperiodic array system for many real applications.

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