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A Novel Flying Robot Swarm Formation Technique Based on Adaptive Wireless Communication using MUSIC Algorithm

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ABSTRACT - This paper presents a novel technique to address the challenge of coordinating swarm flying robots in a leader-follower configuration. A combination of the Multi Signal Classification (MUSIC) estimation algorithm, based on a wireless MIMO array antenna, along with onboard robot control are used for precise route tracking of an individual robot. Employing an array antenna reduces energy consumption for followers in passive mode and reduces computational complexity when measuring the angles of leader angle interferences, which depends on the phase difference of the impinging signal on the antenna elements of the array. Additionally, the angles estimation and beamforming processes, utilizing MUSIC algorithm, form an inner loop that furnishes orientation angles in 3D (Azimuth and elevation angles) for both the leader and potential interference sources. The outer loop, contingent on the onboard controller and the robot's GPS system, enabling fine adjustments in angle and position relative to the leader's location. The simulation results illustrated the efficiency of the proposed technique in estimating the orientation angles of the leader and the interference sources. The technique robustness is confirmed through testing the performance on different trajectories. Where the follower perfectly generates a main radiation beam directed towards the leader, effectively mitigates interference signals from neighboring group leaders, and successfully tracks the leader path.

Keywords: Beamforming, Flying robot, leader–follower, Signal estimation, Swarm formation.

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1. INTRODUCTION

Under-actuated vehicles (UAV) have several mechanical systems to perform a variety of functions that are dependent on a smaller number of control inputs. These systems are used in numerous of applications due to their lightweight design, simple construction, improved dependability, and efficiency. Flying robots are among the most important UAV systems for performing a wide range of civil and military tasks [1-5]. Researchers focused on group of flying robots flight control in the previous decade because they perform tasks more efficiently than a single one [6]. Dudek et al. specified the basic axes which are utilized to generate various configuration of multi-robotic systems according to tasks and applications [7]. This classification demonstrates seven axes as configuration size, communication (range, topology, and bandwidth), organization reconfiguration, process, and types of robots. During this specification, the range of communication among the group members is set to be short [8]. locchi et al. defined different classification depends on four levels (cooperation, knowledge, coordination, and organization) [9]. According to this definition the robots carry out a task through applying these four levels, where in the first level cooperation together, in the second level the robots have two options (aware, or unaware) to existence of other robots, in the third level the robots have three options of coordination types (strongly, weakly, and not coordination) to deal with the action of other robots. The last level depends on the organization of robots, which divided into two systems type, centralized system where there is a leader robot for configuration which called Leader- follower system, and decentralized system with no leader for the configuration.

This paper proposed a new technique of multi - flying robots formation flight based on leader follower cooperation system with awareness to the neighboring robots using strongly coordination depends on adaptive wireless communication based on angle of arrival estimation technology. The leader and the followers of the group are equipped with multi antenna (MIMO). The multi antenna beamforming reduces the power consumption by half compared to Omni antenna transmission [10-11]. According to use beamforming technique the antenna system becomes smart and can estimate and detect the signal transmitted by group's leader signal while ignore other signals even the signal of leaders for other neighboring groups in the large formation system. Steering vector is generated by estimation process due to the received signal phase on each antenna element with low computational process and low power consumption while the multi antenna in passive mode. The signal of the neighboring groups' leaders is mitigated and considered as interferences signals. The group robots are equipped with GPS sensor which indicate the location of each robot (leader and follower) in space of 3D (x, y, and z). According to steering vector and the locations information the follower moves toward the group's leader location. The proposed technique and objectives can be summarized as follow

- Flying robots of the configuration are equipped with GPS for location determination, along with XBee radio device to communicate with ground station. The distance between the follower and the group's leader is predetermined prior to the mission, and the XBee radio device is employed solely in the event of a fault or if the station modifies the mission settings. This streamlined approach reduces the monitoring process compared to other proposed systems as that in [12].

- All flying robots equipped with a multi antenna array to direct the radiation beam. This technique reduces power consumption by leader when send information to the followers, and also by followers when they use this antenna in passive mode. Computational complexity is reduced where the estimation angles in 3D (Azimuth and elevation angles) for leader and interferences, and steering vector generation depend only on the phase differences for the received signal on each antenna element. The onboard built-in controller uses by leader to track the mission trajectory, while the followers use it to make the fine tuning for location when following the leader.

This paper is structured as follows. *Section 2* presents the relative work. The proposed work and overall control structure is presented in *section 3*. Section 4 presents the proposed trajectory tracking system and its methodology based on leader's angle estimation/beamforming algorithm, and onboard built-in controller. *Section 5* illustrates the simulation results. Conclusion is given in *section 6*.

2. RELATIVE WORK

Leader-follower is one of considered formation techniques to guide the swarm of robots. Cai and Huang [13] were proposed a nonlinear control theory to deal with the leader – follower unanimity for swarm formation. The proposed system is based on bidirectional communication between neighboring followers while all followers receive leader's information. Lyapunov theory is used to achieve the stability for angular velocity tracking and maintaining the attitude. While, the stability of the team's formation is achieved by using the saturation function and a single integrator consensus algorithm in [14]. Fixed topology of multi–agent system of two protocols is proposed by [15] , the first deals with the global information of communication to guarantee multi – robot system to connect to the formation in exponential rate. The second depends on local information for each follower, and provides the distribution information. The second protocol is designed to deal with a certain degree of failure. Damer et al. [16], proposed algorithms to disperse very small robots to cover an unknown environment without central control. These algorithms were based on wireless signal intensity to communicate with neighboring robots or with backbone. The dispersion due to neighboring robots is based on consideration one robot is stationary while the second robot moves away until reach the distance with less communication according threshold limitation which preset before the mission. While for the Scenario of backbone dispersion some robots should connect with the information backbone and the others communicate with them continuously, in case one robot miss the connection it starts a search process to find the nearest backbone node to communicate with it. The results show that the robots can cover the unknown area effectively by using the wireless signal intensity. Wu, Han. et al. [17] proposed a leader follower method to achieve precise multi-robot configuration and localization. To solve the localization problem a combination between dead reckoning and two wireless network is used. ZigBee wireless network is used to evaluate the position of each robot in the formation based on Kalman filter method. While, the travel coordination of robot is provided by the electronic tag floors located in the corners of the floor to maintain smooth turning. The radio frequency identification is a wireless technology which consist from three components (tag, reader, and an antenna). The tag with exclusive code is fixed on the robot body, the reader installed at the corner of the floor transmitted the radio frequency to the robot. the electronic tag is start to transmit information only when robot become close to the tag, then the robot calibrate the motion angle according to the received information. The passive tag is utilized to minimize the power consumption because it uses the radio frequency power which transmit from antenna. To ensure the perfect robot swarm formation a lot of techniques have been proposed, many of them depend on combining the wireless communication with controlling methods or gave more interest to the neighboring robot and create long computational process continuously.

In this paper the proposed technique depends on MIMO antenna system angle estimation technology. The leader of the configuration sends its preset code to the follower which estimates the leader's angle by using passive antenna system without extra energy consumption. The follower antenna system measures the angle of arrival according to phase difference of received signal by different antenna with simple calculation process. Hence, the flower moves toward the leader after generate a steering vector by weighting the antenna array.

3. PROPOSED WORK

In this section, the problem of interest is first illustrated. Then a simplified model of an individual swarm robot is given and the formation control strategy is described.

3.1 Statement of the Problem

An The proposed work is addressed the formation and trajectory tracking of multi robotic system, using the MIMO wireless system and the inboard controller to ensure smooth trajectory tracking. For many applications, each robot in the formation should has an accurate information for the other

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robot's positions in the space of waypoints to carry out its mission efficiently. Practically, the primary issue with numerous swarm robot localization methods is the absence of precision, leading to persistent defects. In this paper the proposed method utilized to enhance the accuracy of trajectory tracking for flying swarm robots without adding a complexity to computation process. The proposed homogeneous flying robot's formation with leader – follower configuration may consist of large number of robots. Hence, two codes are used to ensure accurate tracking. The first code is *Air Traffic Control Code* (ATCC) which generates by all robots (leaders and followers) and sends to the ground station to recognize the (x, y, and z) position for each robot in the flying space. The second code is *Identification Friend Code* (IFC) which generates by leaders and sends to the followers to recognize the group leader.

3.2 Overall Control Structure

The control strategy is based on increase the efficiency through overcome the limitation of the sensing range of individual flying robots within a large group of robots [17]. This strategy uses the linear hierarchy [18], through depending the tire distribution as shown in the *Figure 1*. These tiers are distributed to represent the configuration levels. The first tire represents the leader of the swarm, the second tire represents the group's leader, and the reset tiers consider as followers robots. According to this distribution the swarm's configuration can contains large number of robots because the control strategy is simple. Where each robot knew it works level by the presetting provided at the ground station. Hence, the group's leader in the first level sends the IFC_{TG} signal through the wireless MIMO antenna, where the lower-case letters *T* and *G* represent the tire (the level) and group number respectively. Thus, the group's leader sends IFC_{10} which represents the signal of leader in the first tire and zero group because it's the leader of whole configuration which represent group zero. While all robots detect the incoming signal through their array of antennas, only the robots with a second tire take action in response to the signal as they are situated in the second level and must follow the group's leader. Next, the second tire's robots transmit their IFC_{2G} which is received by the antenna array of third tire's robots, G didn't mark here because it depends on which group number represents. Furthermore, the remaining robots transmit their identification friend code to enable each robot to identify which leader in the upper level it should follow. When a robot receives multiple signals simultaneously, its response depends on two conditions. The first is the preset configuration that determines its role as a follower or leader before the mission, or can be modified instantly by the ground station via the XBee wireless network. The second is the beamforming process, which is generated by the MIMO antenna array. This process measures the phase difference of each signal on the individual antennas of the array, as shown in *figure 2*. Hence, the beamformer of each robot calculates the angles of all the robots in the upper tier and generates a beam pattern. This pattern directs the main beam towards the leader that the robot should follow based on its IFC and creates null points towards other robots that transmit different IFC. The beamformer uses the null points in the beam pattern to ignore the effects of leaders of the other groups and treat them as interference sources. At the same time, all robots send ATCC signal to the ground station through XBee radio. The ground station has the capability to alter robot's role by modifying its IFC_{TG}, enabling it to function as either a leader or a follower. According to this capability, the swarm configuration can include a considerable number of robots that are either led by a single leader or split into sub-groups each with its own distinct leader.

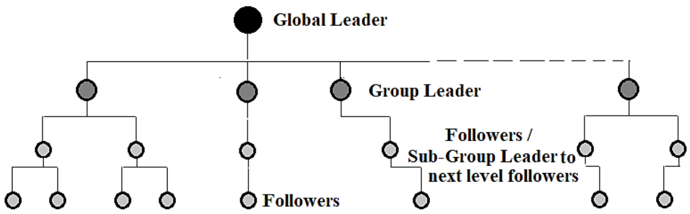

Figure 1. Tire Distribution Levels for Formation Configuration (Some of Possible Scenarios)

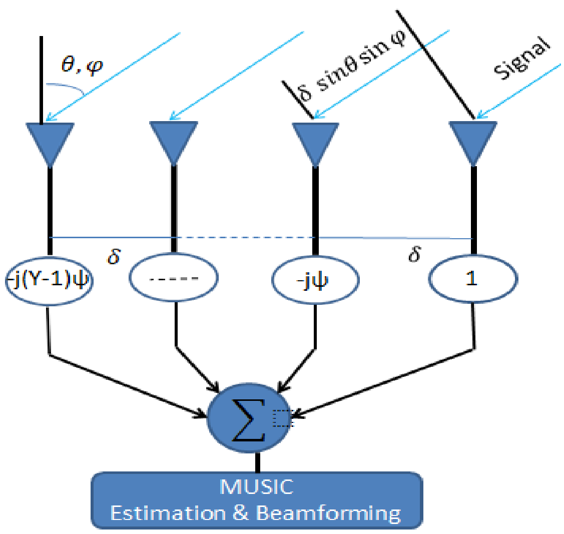

Figure 2. Array of Antenna configuration and phase estimation

4. TRAJECTORY TRACKING

The proposed technique is applied to both the leader and follower flying robots within the system. The control system of trajectory tracking system is divided into two control loops: Inner loop and Outer loop as in *figure 3*.

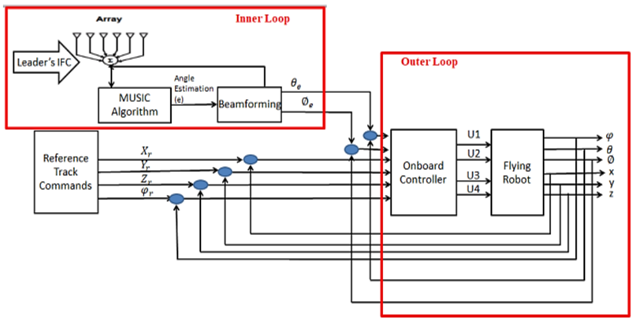

Figure 3. Flying Robot Control System

4.1. Direction Estimation and Beamforming (Inner- loop)

Once the follower receives the IFC from the leader, the process of angle estimation begins, which involves tracking the leader's location in three-dimensional space (*x*, *y*, and *z*) using the angles of pitch (θ), roll $(\emptyset)$, and yaw (φ). This is accomplished by analyzing the phase difference generated by the impinging signal on the antenna array [19], which can be a linear array, square array, or circular array configuration based on MUSIC algorithm. The weight assigned to each antenna is determined based on this measurement, enabling the beam of radiation to be directed towards the leader electronically. Thus, the robot is directed by the beamformer to move up or down in the z-x plane based on the disparity between the received azimuth signal angle and the presetting azimuth angle specified in *equation (1a)*. This presetting angle refers to the angle designated at the ground station for the follower to follow up the leader. Concurrently, the beamformer guides the robot to move left or right in the x-y plane to achieve the limitation defined in *equation (1b)* which eliminates the difference between the received elevation signal angle and the presetting angle.

$$\lim_{t\to\infty}\|e_\theta\| = \|\theta_r - \theta\| \quad (1a)$$

$$\lim_{t\to\infty}\|e_\varphi\| = \|\varphi_r - \varphi\| \quad (1b)$$

Where, e_θ and e_φ are the angle tracking error in azimuth and elevation axes respectively. The MUSIC algorithm estimates the direction of the leader due to estimation the direction of arrive of the wireless signal transmitted from leader at instant time *t* as :

$$x(t) = \sum_{m=1}^{M} a(\theta_{m,}, \varphi_m).s_m(t) \quad (2)$$

Where *t* = 1,2,……,k , while k represents the total number of snapshots captured by the estimation algorithm. $S_m(t)$ represents the $M\,x\,1$ vector of source signals, where M is the number of signal sources which transmit signals that impinge on the antenna array consisting of Y elements. $a(\theta)$ is represents the $Yx1$ array vector as

$$a(\theta,\varphi) = [1 \quad e^{-j\psi} \;\dots\dots\dots\dots\; e^{-j(Y-1)\psi}]^T \quad (3)$$

Where T is the transposition operator, and ψ is the electric phase shift of each array element according to its position from the reference element of the array, which can be define by

$$\psi = \left(\frac{2\pi f}{c}\right)\delta \sin(\theta) \sin(\varphi) \quad (4)$$

Where, f is the signal frequency, while C is the light speed, and δ is the space between adjacent antenna element. Thus, the received signal information in *equation (2)* can rewrite in a matrix form

$$x(t) = A \,.\, s(t) \quad (5)$$

According to *equation (5)* the signal is represented as $(Yx1)$ vector, while the A is (YxM) matrix of steering vectors for M sources $A = [\,a(\theta_1,\varphi_1), \dots\dots a(\theta_m,\varphi_m)]$, and $S(t)$ is a vector of size $(Mx1)$.

In practical scenarios, the received signal encompasses not only the transmitted signals from the leaders through the antenna array but also accompanying noise.

$$x(t) = A\,.\,s(t) + n(t) \quad (6)$$

This represented in matrix form as

$$X = A.S + N \quad (7)$$

Where, $S = [S(1) \;\dots\dots S(k)]$ is an $(M\,x\,K)$ matrix of source of signals, and $N = [\,n(1) \;\dots,.n(k)]$ is an $(N\,x\,K)$ white Gaussian noise. Then, the spatial information of the impinging signal is collected in the spatial correlation matrix R as in *equation (8)*,

$$R_x = E[X(t), X(t)^H] = AR_sA^H + \sigma_n^2 I \quad (8)$$

The matrix R_s represents the covariance of the source, with its diagonal elements denoting the source's power and the off-diagonal elements indicating the source correlation.

$$R_s = E\,[ss^H] \quad (9)$$

Where R_s is a full rank matrix with M equal to the number of sources. The AR_sA^H is a Y-by-Y matrix, with M positive real eigenvalues an $N - M$ zero eigenvalues. The positive eigenvector related to the positive eigenvalue represent the signal subspace $V_s = [v_1, \dots.., v_M]$ and eigenvectors related to the zero eigenvalues represent the null subspace $V_n = [v_{M+1}, \dots\dots, v_N]$. According to the signal eigenvectors and null space eigenvectors as in [20], the MUSIC algorithm generate the estimation MUSIC pseudo-spectrum as in *equation (10)* to estimate the direction of leader's signal with low power peak and the direction of interferences with high power peak.

$$P_{MUSIC}\,(\theta,\varphi) = \frac{1}{a^H(\theta,\varphi)V_n\,V_n^H a(\theta,\varphi)} \quad (10)$$

The covariance matrix in equation (8) allows beamforming to determine an optimal weight for the array antenna, as demonstrated in [21,22],emphasizing the focus on achieving unity gain in the leader's direction (θ_L) and nullifying the directions of leaders from other groups.

$$\mathrm{W_{opt}} = \frac{\mathrm{R_x^{-1}a(\theta_L,\varphi_L)}}{\mathrm{a^H(\theta_L,\varphi_L)R_x^{-1}a(\theta_L,\varphi_L)}} \quad (11)$$

4.2. Onboard Controller (Outer Loop)

The integrated onboard controller is responsible for coordinating the motion of the four-rotor flying robot. This robot's body-fixed frame encompasses four rotors symmetrically arranged around its center. To maintain balance and facilitate movement, pairs of rotors along the same axis rotate in unison [23,24]. Movement can be achieved as in [5]. The inertial fixed frame is employed to ascertain the flying robot's positions in the *x*, *y*, and *z* axes, as well as its orientation angles: pitch (θ), $roll$ ($\emptyset$), and yaw (φ) respectively. The onboard controller obtains the pitch and roll angles from the estimation and beamforming stage. The mathematical model for the equations of motion governing this flying robot is derived using the Newton Euler theorem. These equations are presented in *equation (12).*

$$\left.\begin{aligned}
\ddot{x} &= (sin\emptyset sin\varphi \cos\emptyset + sin\theta\cos\varphi).\frac{u_1}{m} \\
\ddot{y} &= \sin\emptyset\, sin\theta\cos\varphi - sin\emptyset\, cos\,\varphi).\frac{u_1}{m} \\
\ddot{z} &= -g + (\cos\emptyset\cos\,\theta).\frac{u_1}{m} \\
\ddot{\emptyset} &= \dot{\theta}\dot{\varphi}\left(\frac{I_{yy}-I_{zz}}{I_{xx}}\right) - \frac{L}{I_{xx}}u_2. \\
\ddot{\theta} &= \dot{\emptyset}\dot{\varphi}\left(\frac{I_{zz}-I_{xx}}{I_{yy}}\right) - \frac{L}{I_{yy}}u_3 \\
\ddot{\varphi} &= \dot{\emptyset}\dot{\theta}\left(\frac{I_{xx}-I_{yy}}{I_{zz}}\right) - \frac{1}{I_{zz}}u_4
\end{aligned}\right\} \quad (12)$$

Where m, g represent the mass of the robot and the gravity respectively, $I_{xx}, I_{yy}, and\ I_{zz}$ represent the inertias around the $x, y, and\ z$ axis. whereas $u_1, u_2, u_3, and\ u_4$ represent the control input to the flying robot which can be determined as in [4] as follows:

$$\left.\begin{aligned}
u_1 &= f_1 + f_2 + f_3 + f_4 \\
u_2 &= l\ (f_3 - f_4\ ) \\
u_3 &= l\ (f_1 - f_2\ ) \\
u_1 &= \mathrm{k}\ (\ f_1 + f_2 - f_3 - f_4\ \ )
\end{aligned}\right\} \quad (13)$$

Where f_i , $i = 1 \ldots . k$ represent the thrust produced by the rotors, l represents the distance from the center of the flying robot to the rotors. Whereas k represents the propellers thrust due to the yaw moment. *Equation (1)*, and *(2)* utilized to design the control strategy of the flying robot by minimizing the error which is the deference between the desired and actual ordination.

5. SIMULATION RESULTS

This section presents the simulation results of two formation's scenarios for identical flying robots by using MATLAB. The simulation parameters are described in Table 1. During the simulations the leaders sent the IFC modulated on the carrier frequency signal as shown in *Figure 4*. While, the received signal by follower's antenna array shown in the *Figure 5*. Table 2 is prepared to illustrated a comparison between the proposed technique and other algorithms in terms of requirements, energy consumption, and computational complexity.

Table 1: Simulation Parameters

Fly Robot Parameters	I_{xx} and I_{yy}	1.25 kg.m^2
	I_{zz}	2.5 kg.m^2
	Mass (m)	2 Kg
	l	0.25 m
Antenna Parameters	Antenna Type	ULA
	Carrier Freq.	2.4GHz

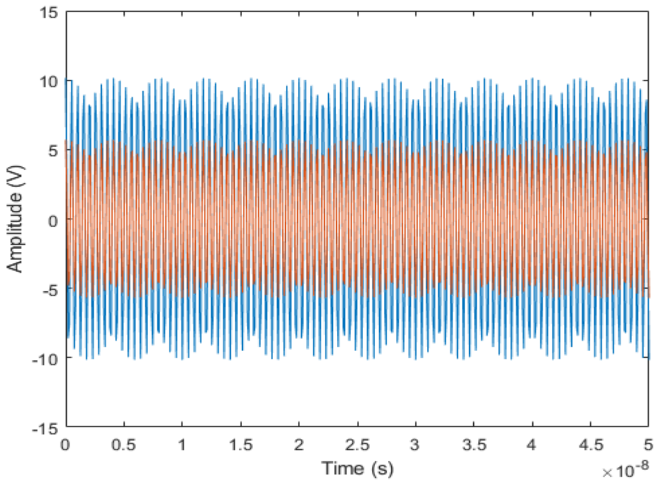

Figure 4. IFC Signal Modulated on Carrier Frequency

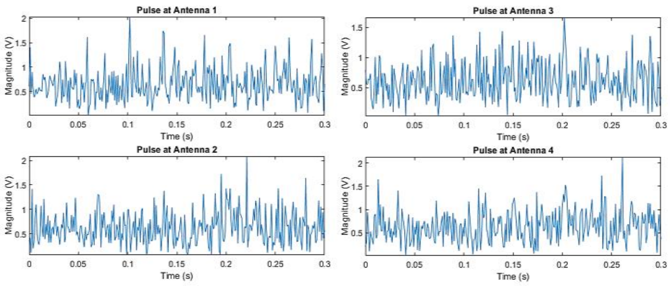

Figure 5. The Received Signal at each Antenna in the MIMO Array of Four Antenna

To demonstrate the dependability of the proposed technique, two simulation-based scenario cases have been executed as (*Case 1*: Arrow formation, *Case 2*: Straight- follow formation).

5.1. *Case 1*: Arrow formation

In this case, three flying robots are used to generate arrow formation (triangle configuration), one leader and two followers as in *figure 6*. The leader starts its route according to the way points that provided initially by the ground base station, start from initial position $(x0, y0, z0) = [0, 0, 0]^T$. While the two followers are set to follow up the leader in a distance, R_d (x, y, z) = (2, -2, z) and L_d (x, y, z) = (-2, -2, z). each follower is set to maintain an angle between with leader. the Right-side follower set to chase the leader with angle equal to 135^0 (R_{ang}= 135^0 = - 45^0), and the left side follower chase the leader with angle equal to 45^0 (L_{ang}= 45^0). The interference signals, the signal received from other groups leaders (neighbor groups), are assumed in this scenario at 60^0, and 150^0 for the group in the right side and the group in the left side respectively. Hence, the leader moves to perform the route and transmit the IFC via its MIMO antenna. The followers receive the leader's IFC by the array of antenna. According to the phase of the received signal with respect to each array antenna the MUSIC algorithm (Inner loop) estimates the direction of the leader and null the directions of the other group's leader and force the controller to keep the setting angle with leader, while the controller (outer loop) tries to keep the setting distance ($L_d\ and\ R_d$) with the leader by using the mounted distance sensors and GPS system. In *Figure*

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7a, the Music algorithm's estimation response in 3D is depicted for a single follower in relation to the directions of the group's leader and two interference signals from leaders of other groups. To ensure a clearer presentation, this article specifically emphasized showcasing the results in 2D. This was accomplished by demonstrating the response with respect to azimuth angle for both scenarios. Thus, *figure 7b* shows the response of MUSIC algorithm for the two followers to estimate the angles of the received signals. The blue curve represents the response of the follower in the left (*L* follower) and the red curve represents the response of the right follower (*R* follower). The response of MUSIC algorithm of left follower indicates the group's leader signal at angle equal to (45^0) in low power peak, and indicates the interference signals at 60^0 and 150^0. According to this estimation the algorithm beamformer consternates the main loop of the array antenna towards the leader's direction and neglected the interference directions with NULL power as shown in *figure 8* in polar form. *Figure 9* shows the radiation pattern in form of power against the radiation angle to provide reliable evidence for the adaptation response of followers to the IFC signals of the leader. *Figure 10* shows that the two followers are succeeded to trace the leader's route according to the presetting limitation set up by the ground station.

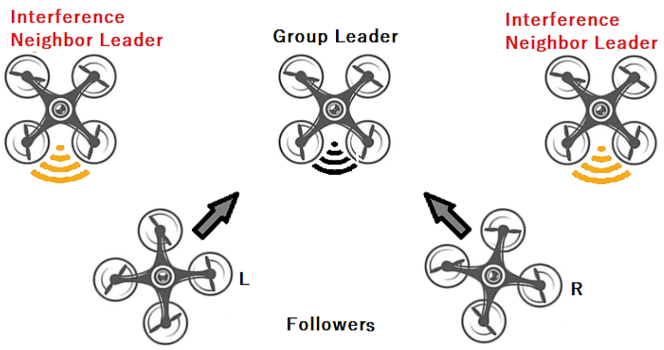

Figure 6. The Arrow Formation of Three Flying Robots

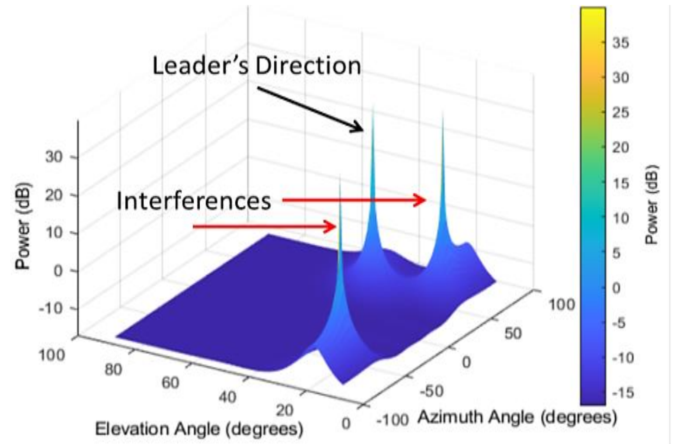

Figure 7a. The Response of Music Algorithm (Three Dimensions, Azimuth and Elevation)

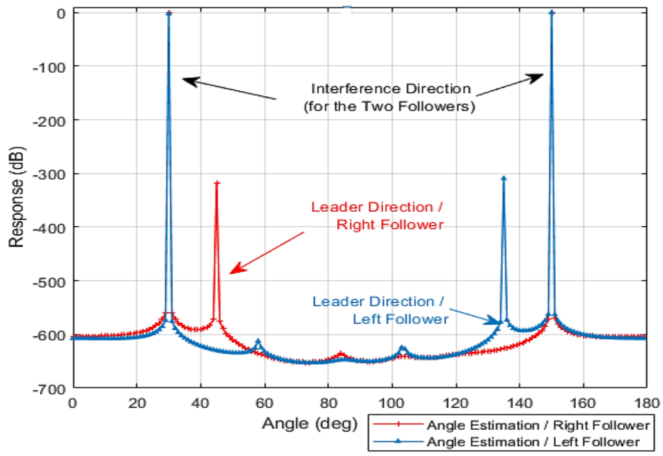

Figure 7b. The Response of Music Algorithm for Estimation the Angle of Received Signals (One Dimension, Azimuth plane)

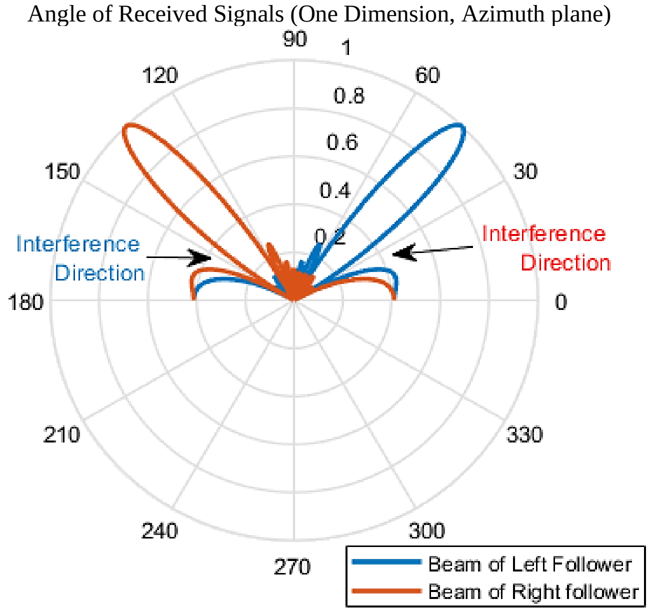

Figure 8. The Beamforming Response Main Loops directed to Leader Angle (45^0, 135^0) for Left and Right Follower respectively, the Direction of Interferences are Ignored with Null (Zero Power)

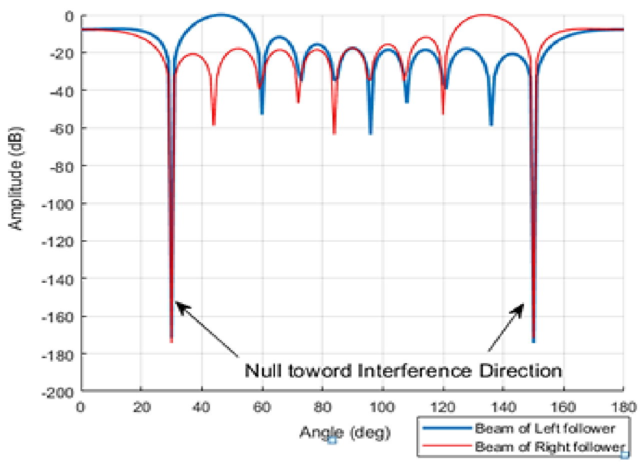

Figure 9. The Radiation Pattern of Two Followers

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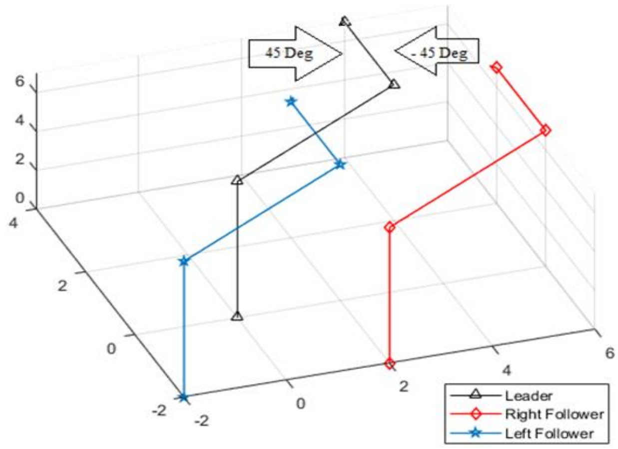

Figure 10. Arrow Formation Trajectory Tracking of three flying robots

5.2. *Case 2*: Straight- follow formation

The second formation case was implemented to ensure the robustness of the proposed technique in tracking the movement of leaders, taking into account their hierarchical distribution. The leader starts its route according to the way points that provided initially by the ground base station, start from initial position $(x0, y0, z0) = [0, 0, 0]^T$. While the two followers are set to follow up the leader in a distance, $F1(x, y, z) = [-0.5, 0, z]^T$ and $F2(x, y, z) = [-1,0, z]^T$. *Figure 11* illustrates this formation, where the sub-group leader and follower are aligned in a linear configuration with the group leader. The sub-group leader (first follower or F1) receives signals from both the group leader (IFC) and potential interference sources (IFC from neighboring leaders). Then estimates the angle of group's leader and the interferences sources. The sub-group leader's ($F1$) beamformer focuses the transmission power onto the main beam, directing it towards the group leader while nullifying the signals from the interference sources. In this scenario, the follower ($F2$) is tasked with tracking the signal from the sub-group leader ($F1$) and disregarding any signals originating from interference sources.

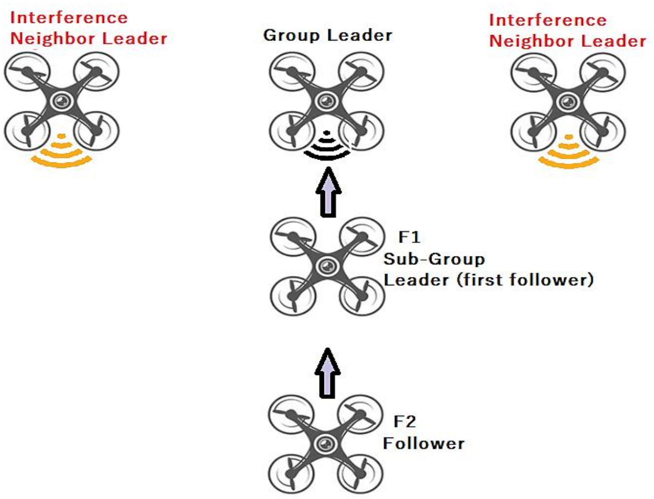

Figure 11. The Straight – Follow Formation Configuration

In *figure 12*, the MUSIC algorithm's output is depicted for both the sub-group leader (referred to as the $F1$) and the second follower ($F2$). The estimation process for both robots effectively determines the direction of the intended IFC. Specifically, the first follower aims for the IFC of the group leader, while the second follower targets the IFC of the sub-group leader. This choice is made in accordance with the desired configuration of moving all the robots in a straight line. The sub-group leader accurately determines the directions of the interference sources at 30^0 and 150^0, respectively. Meanwhile, the follower, adhering to a set distance behind the sub-group leader, estimates the interference sources' directions at 35^0 and 145^0, respectively. Consequently, there is a noticeable variance in angle measurements between the follower's estimation process and that of the sub-group leader.

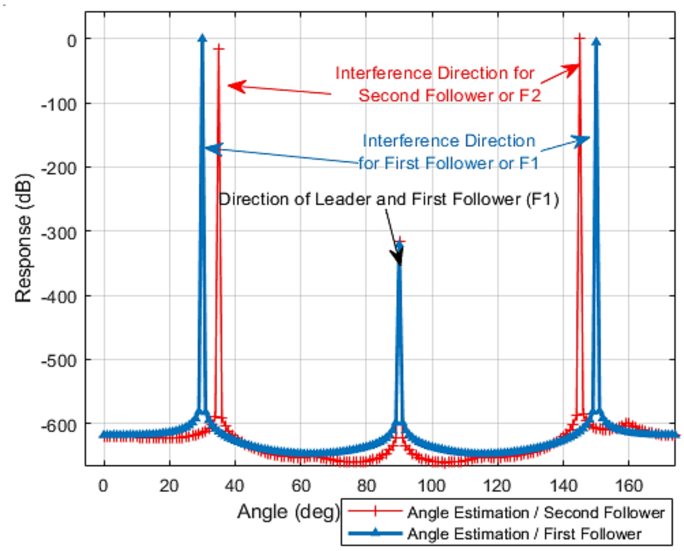

Figure 12. The Estimation Response for the Two Robots

In *Figure 13* and *figure 14*, the beamforming responses for two followers, F1 and F2, are depicted in polar form. The blue curve in *figure 13* represents the beamforming response of *F1*.

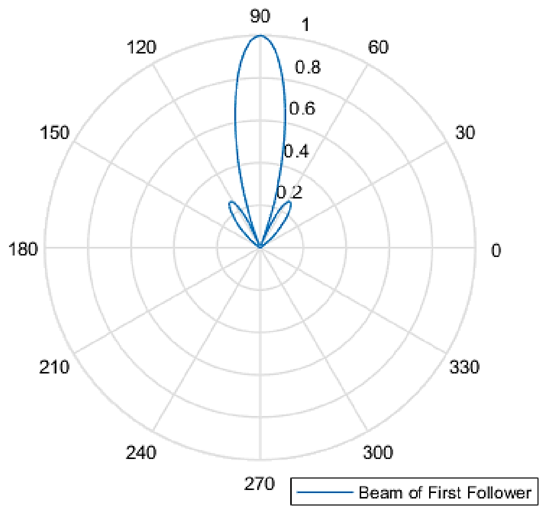

Figure 13. The Beamforming Response of the First Follower

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It demonstrates that the primary focus is on the directing the main beam to the group leader's location, disregarding the interference direction. This results in nulling the power interferences direction at 30^0 and 150^0, respectively. The red curve in *figure 14* showcases the beamforming response of *F2* as it accurately tracks the path of the sub-group leader, *F1*. The main beam directs precisely towards the location of *F1*, effectively nullifying the interference directions at 35^0 and 145^0, respectively.

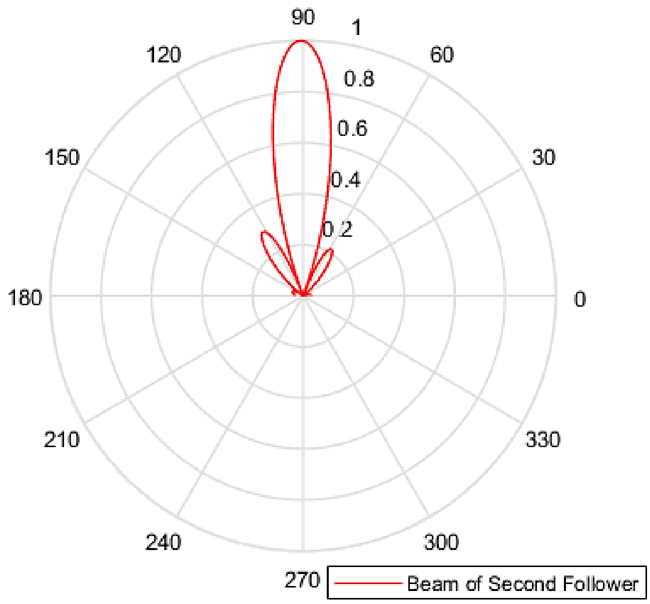

Figure 14. The Beamforming Response of the Second Follower

In contrast, *figure 15* and *figure 16* display the beamforming response by using the power magnitude response against the angle of response, aiming to enhance the reliability of the proposed technique's adaptive capabilities.

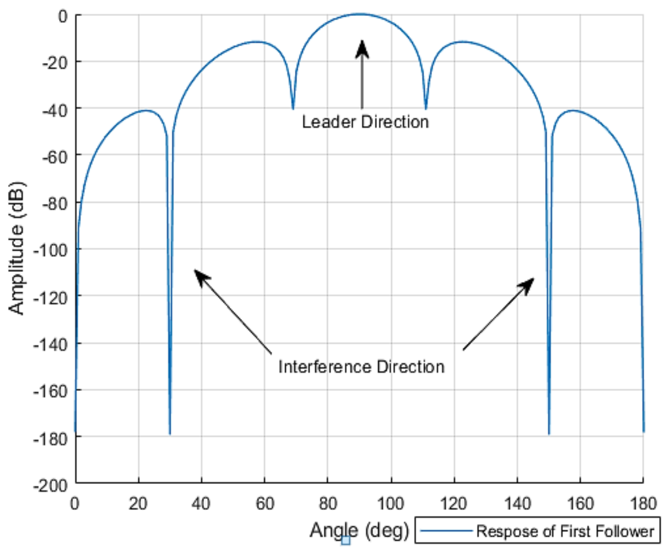

Figure 15. The Radiation Pattern of First Follower

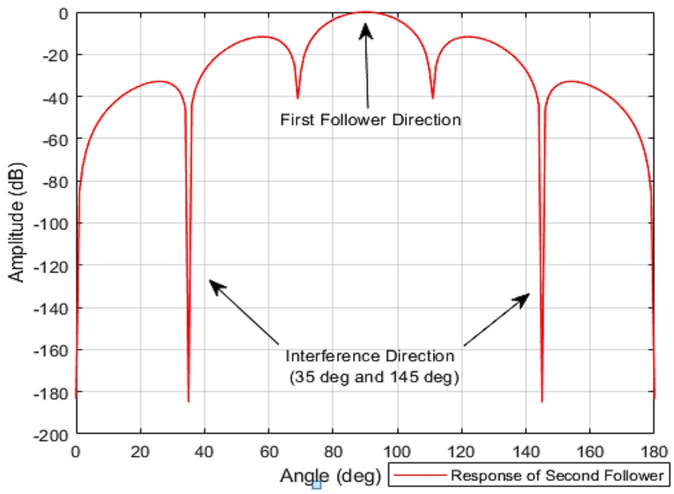

Figure 16. The Radiation Pattern of Second Follower

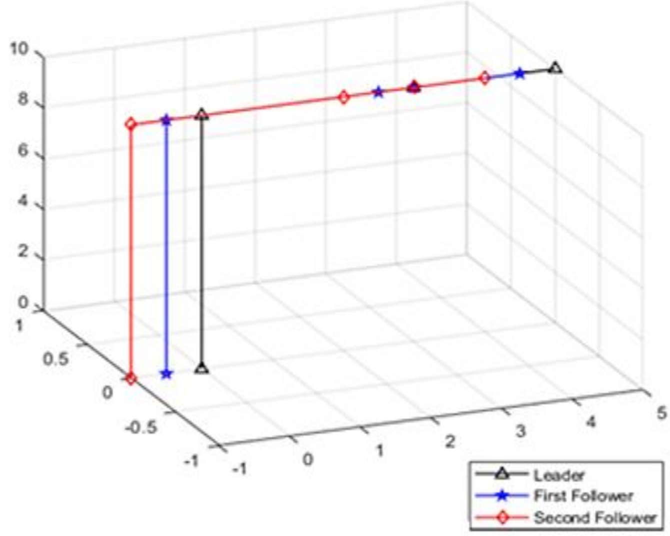

Figure 17. Straight- Follow Formation Trajectory Tracking of Three Flying Robots

7. CONCLUSION

In this paper, a swarm of multi-flying robot formation technique based on a leader-follower configuration was illustrated. The popular MUSIC estimation method was relied upon, utilizing a MIMO array of antennas to estimate the direction angle of the received signals from the group's leaders. The follower considered the received signal (IFC) from its own group leader as the signal of interest, while treating signals from other group leaders as interference signals. Beamforming algorithm was employed to generate the steering vector, which weighted the individual antennas in the array with suitable weights to direct the main beam toward the direction of the follower's own group leader while nullifying the direction of other group leaders. The tracking angle was sent to the follower's onboard controller to enable it to follow the leader according to mission requirements. The simulation results indicated that the proposed technique was successful in resolving the trajectory tracking challenge for two distinct formation scenarios, all while maintaining system robustness in the face of interference signals from neighbouring groups' leaders. These results underscore the follower's ability to adeptly track the leader, while keeping computational demands at a minimum through phase difference analysis of the received signal. *Table 2* demonstrates the effectiveness of the proposed technique in accomplishing the mission across different formation shapes, based on robot's role in outdoor or indoor workspace, with varying number of homogeneous or heterogeneous flying robots. The follower relying on the existing components of the system, including the onboard controller, sensors, and GPS system without adding extra instruments for guidance. Additionally, the follower decreases energy consumption by relying on passive reception of leader information through an array of antennas.

Table 2: Comparison between Swarm Formation Algorithms

	No.of controller	Extra instruments	No. of robots in formation	Robots Type	Formation shape	Workspace	Information of other robots	Power consumption	Monitoring process	Complexity
Proposed	one	Not needed	Small / large	Homogeneous / heterogeneous	Any shape	Indoor / outdoor	Not needed	Low	Low	Low
Ref. [13]	Two	Needed	Small / large	Homogeneous	Non linear	Indoor/ outdoor	Needed	Large	Medium	Large
Ref. [15]	Two	Needed	Medium	Homogeneous	Non linear	Indoor / outdoor	Needed	Large	Low	Large
Ref. [17]	two	Needed	Small	Homogeneous	Any shape	Indoor	Needed	Large	Low	Large

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