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Unmanned Aerial Vehicle Swarming

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***Abstract*— Unmanned Aerial Vehicles (UAVs) is a special case of the ad-hoc network, as it is categorized from the Flying ad-hoc network (FANET), which is a subcategory from the ad-hoc network. The massive widely used applications for UAVs through the variety of missions leads the researchers to deep through enhancing such systems by equipping different technologies and techniques for UAVs. Adding swarming facilities for UAVs was our case research interest in Drone Hopper research center, to gain the accurate and powerful usage through a swarm of drones to be used in different applications such as firefighting and agriculture. In this paper, a perspective study for UAVs swarming is highlighted through the FASTER project, under H2020 Grant Agreement 833507, showing the problems that face such techniques and technologies, and giving a clear accurate solution.**

Keywords—UAV, FANET, Swarming, FASTER, Drone Hopper

I. Introduction

Ad-hoc network is a special case of wireless network, in which each node act as a router or access point by itself without the aid of the infrastructure. The power of ad-hoc networks leads the research center in Drone Hopper to highlight the huge benefits for UAVs, where UAVs are a part of FANET, which is one of the main categories for the ad-hoc network. The research aims to highlights UAVs benefits when adding the swarm capabilities to the UAVs missions in real-time applications.

Also, the word swarm comes from the natural systems, such as bee colonies showing a large group of bees going to attack, so swarm can be thought of as precision that deals with systems composed of many participants, sharing a mission using decentralized control and self-organization. Where, the communication process in such networks using swarms is the most critical issue due to the circumstances of using such networks in both military and civilian applications, through a lot of researchers work it was found that the common communication techniques used between the entities are wireless Lan, blue tooth, and infrared, where a lot of communication problems exist due to many aspects such as Line-of-Sight (LoS), and the direct communication requirements when using such techniques. The communication process through swarming depends upon wireless communication, where various limitations and technical problems may affect the wireless technologies to work properly, and it can be observed in two main aspects respectively the entities (UAVs) limitations and the incompatible standards that are used. Almost, all researchers during their research work depend on IEEE 802.11 (WIFI), to build the systems they want to examine and measuring results, but in reality, these communications process is only standard for the indoor purpose, as it is designed for local area networks, which is not suitable for designing such a swarm for UAVs in the reality. Fig.1 gives a brief description of nodes working in a WIFI environment, considering two Basic Service Sets (BSS) respectively BSS#1 with nodes N1, N2, N3, and BSS#2 with nodes N10, N20, N30. These BSSs can be isolated or connected to the distribution system (DS) as shown in Fig.1, the DS acts as a backbone through the access points (APs), it is noticed that nodes into the BSS cannot communicate directly with each other, so if N1 which is a part of BSS#1 wants to send data to N2 which is in the same BSS#1, the mac frame will be sent first to the AP of BSS#1 and then from the AP to N2.

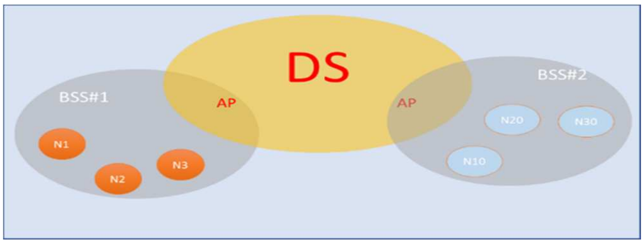

Fig. 1. Wireless Network in WIFI environment.

Also, if N1 wants to send data to N10, which is a part of BSS#2 (remote communication), then the mac frame will be sent to the main BSS#1 and relayed by the AP over the DS to the AP in BSS#2, then to N10. This is a fact when using a wireless network, but using ad-hoc networks is totally different, because each node act as a router or access point by itself, so the communication process with the ad-hoc network is simpler and more accurate than the ordinary wireless networks. This paper is organized into six sections, section two discusses in detail the overall of the FASTER project, section three deals with challenges of the communication technologies through swarming, section four analysis the swarming problems, section five discuss the results, and finally, section six conclude the paper.

II. FASTER Project

The presented system was developed as part of a larger project, the EU-funded FASTER [14], which aims to develop innovative technologies for first responders (FRs). The overall FASTER project system architecture is IoTbased, with the principles of scalability and modularity, having individual modules and services. The main project components: edge devices modules, broker modules, processing modules, and Human Machine Interface Systems modules are depicted in Fig. 2. The system includes a host of technologies and applications for FRs, including drone applications, augmented reality situational awareness, wearables, communication aids, AI modules, and more, as well as a command center front end to display all data and provide a front end for various tasks, including UAV mapping.

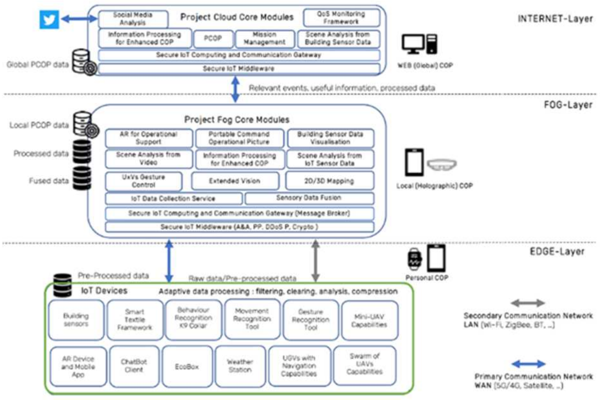

Fig. 2. FASTER Project Architecture [14].

The FASTER project has multiple UAV-related applications, including extending communication capabilities, aerial transportation of tools, and 2D mapping, among others. UAV applications, as seen in Fig. 3, are deployed in the EDGE Layer, while sensor data is transmitted and processed through the upper layers, where each of the UAVs can make one or more tasks depending on its architecture.

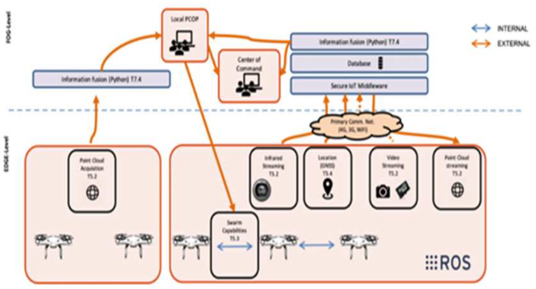

Fig. 3. Swarm of UAVs tasks during FASTER Project [14].

III. COMMUNICATIONS TECHNOLOGIES CHALLENGES IN UAVS

Choosing the suitable communication process in Unmanned Aerial Systems (UAS) depends on selecting the right communication modules and protocol used, and taking into account the antenna design, the platform used, and the network architecture. Also, the selection for the type of communication technology should consider a lot of parameters respectively, the range, bandwidth, mobility, signal frequencies, compatibility, speed, and payload. Table.1, shows different wireless protocols characteristics where it is noticed that the most powerful protocols to be used with UAS are WiMAX and GSM/GPRS, due to their communication range, frequency band, bandwidth, Tx power, and the type of modulation with the digital transmission techniques, which lead to making them more secure for such applications. The communication through UAS could be affected by many facilities such as the Doppler effect, communication failure, jamming, and antenna direction. These effects may impact the packet delivery quality with high packet losses, but the aim is to have communication with efficient, low latency, and reliable communication into the system. Through [5], the researchers hint at the main points in UAVs communication respectively the channel model, antenna model, UAV energy consumption model, UAV communication performance metric, and the mathematical formulation for UAV communication and trajectory co-design. These main fundamental points were represented in a mathematical formula, showing the safety reliable communication for UAVs to be used to have efficient, safe, and reliable flight missions. The channel model was represented by a modified log-distance path loss model to account for the UAV direction, represented as shown in the equation.1 [5].

TABLE I. DIFFERENT WIRELESS PROTOCOLS CHARACTERISTICS.

Type of Protocol	Bluetooth [1],[2]	Ultra-wideband (UWB) [1], [2]	ZigBee [1], [2]	Wi-Fi [2], [3]	Wi-Max [1],[3]	GSM/GPRS [1],[4]
Frequency band	2.4 GHz	3.1-10.6 GHz	868-915 MHz; 2.4 GHz	2.4: 5 GHz	2.4: 5.1- 66 GHz	850-900: 1800-1900 MHz
Max signal rate	720 Kb/s	110 Mb/s	250 Kb/s	54 Mb/s	35-70 Mb/s	168 Kb/s
Communicati-on Range	10 m	10-102 m	10-1000 m	10-100 m	300m-49 Km	2-35 Km
TX power	0 -10 dBm	-41.3 dBm/MHz	-25 -0 dBm	15 - 20 dBm	23 dBm	0-39 dBm
Bandwidth	1 MHz	0.5- 7.5 GHz	0.3-0.6 MHz: 2 MHz	25-20 MHz	20:10 MHz	200 kHz
Type of Modulation	GFSK, CPFSK, 8-DPSK, π/4-DQPSK	BPSK, PPM, PAM, OOK, PWM	BPSK QPSK, O-QPSK	BPSK, QPSK, OFDM, M-QAM	QAM16/64, QPSK, BPSK, OFDM	GMSK, 8PSK
Digital Transmission Technique	FHSS	DS-UWB, MB-OFDM	DSSS	MC-DSSS, CCK, OFDM	OFDM, OFDMA	TDMA, DSSS

$$PL(d) = PL_{ter}(d) + \xi F \qquad (1)$$

Where $PL_{ter}(d)$ is the log-distance path loss model, $\xi = -1$ if the UAV fly towards the ground control station (GCS), and when it operates far from the GCS, $\xi = +1$, and F represent a tiny positive adjustment factor for the UAV direction. Also, the antenna model was represented by the mean of directional antenna gain, as shown in the equation.2 [5].

$$G(r) = \begin{cases} G, r \le H_U \tan(\psi) \\ g, \ \ other\ wise \end{cases} \qquad (2)$$

Where r is the distance between the GCS and the UAV, ψ represent the half beamwidth in radians, in the other hand, the UAV energy consumption model was represented in the form of equations 3,4 [5], showing two primary models one for the fixed-wing and the other for the rotary-wing as follow;

$$P(V) = c_1 V^3 + \frac{c_2}{V} \tag{3}$$

Where P is the propulsion power consumption at constant speed V m/s, c_1 and c_2 are two UAV parameters related to payload, wing area, the density of the air, etc.

$$P(V) = P_o\left(1 + \frac{3V^2}{U_{tip}^2}\right) + P_i\left(\sqrt{1 + \frac{V^4}{4v_o^4}} - \frac{V^2}{2v_O^3}\right)^{\frac{1}{2}} + \frac{1}{2} d_o \rho s A V^3 \tag{4}$$

Where $P(V)$ is the propulsion power consumption for the UAV rotary wing (Energy model), P_o and P_i symbolize the blade power profile and the induced power in the status of hovering depending on the UAV payload, total weight, air density (ρ), rotor area (A), also the tip speed of the rotor blade is represented as (U_{tip}), while the mean rotor induced velocity at the case of hovering is represented as (v_o), and the fuselage drag ratio, rotor solidity are represented respectively as (d_o) and (s) [5].

Whereas, UAV communication performance metric was classified into five performance metrics respectively link signal-to-interference-plus-noise ratio (SINR), outage coverage probability (P_{out}), communication throughput $\left(\hat{R}_{\ k}\right)$, energy efficiency ($EE_k$), orthogonal communication with isotropic antennas through missions with swarms of UAVs dealing with different ground control stations (mobility) or dealing with sensor nodes, where all nodes are equipped with isotropic antennas, these metrics is represented respectively through equations 5 to 9 [5].

Through the uplink, when UAV x is sending data to the ground control station or any other entity, the SINR can be calculated as;

$$\gamma_x(\varrho) = \frac{S(q_x)}{I_{ter} + I_{aer}(\varrho_{\bar{x}}) + \sigma^2} \tag{5}$$

Where, the desired received signal power $S(q_x)$ changes with the UAV x location, the aggregate interference is given by I_{ter} for the ground control station, and the aggregate interference from other transmitting UAVs is given by $I_{aer}(\varrho_{\bar{x}})$ and it is changed by their locations, and the receiver noise power is given by σ^2, while at the down link equation.6 showes the data sent from the ground control station to the UAV, and at this situation the SINR can be calculated as;

$$\gamma_x(\varrho) = \frac{S(q_x)}{I_{ter}(q_x) + I_{aer}(\varrho) + \sigma^2} \tag{6}$$

Through both situations the desired signal power can be calculated as;

$$S(q_x) = P_t G_t(q_x) G_r(q_x) \beta(q_x) \widetilde{g^2} \tag{7}$$

Where, the transmission power is represented as P_t , the transmitter and receiver antenna gains are represented by G_t and G_r respectively, while $\tilde{g}$ represent a random variable for the fading [5]. In the other hand the outage probability can be given as;

$$P_{out\ ,x}(\varrho) = P_r(\gamma_x(\varrho) < \Gamma) \tag{8}$$

Where, Γ represent the threshold for the SINR, this equation is with respect of both LoS and NLoS probabilities [5]. While, the communication throughput can be thought as obtaining the average throughput for the success communication over a random channel realization as;

$$\hat{R}_x(\varrho) = \mathbb{E}[\log_2(1 + \gamma_x(\varrho))] \tag{9}$$

Also, the energy efficiency is measured in bits for the data that can be surely transmitted per unit consumed energy, and it is measured in bits/joule [5], through this the link energy efficiency for the UAV x can be calculated as;

$$EE_x\big(\varrho(t)\big) = \frac{\bar{R}_x(\varrho(t))}{E(q_x(t)) + E_{com}} \tag{10}$$

Where, $\bar{R}_x(\varrho(t))$ represent the average communication throughput for the given UAV x, and $E\big(q_x(t)\big)$ represent the propulsion energy consumption, and E_{com} represent the communication energy consumption [5]. Finally, calculating the orthogonal communication with isotropic antennas especially through missions with swarms, where all the links for the UAVs are assumed to be interference-free, so with the isotropic transmitter and receiver antennas, the transmitted and the received gain can be given as;

$$G_t(q_x) = G_r(q_x) = 1, \forall q_x \tag{11}$$

Through equation. 11 the communication throughput for each UAV x_s' link is given by;

$$\bar{R}_x(\{q_x(t)\}) = \mathbb{E}\left[\int_0^T \log_2(1 + \frac{P|g_x(t)|^2}{\sigma^2}) dt\right] \tag{12}$$

Where, the transmitted power is given as P and the instantaneous channel between UAV x and the ground control station is given by $g_x(t)$ [5].

IV. Analysing Unmanned Aerial Vechicle Swarming Problems

Through section.3, the communication requirements were discussed to model a powerful UAV swarm, also we clarify that it is essential to choose the desired wireless technology that can maintain the communication with all the UAVs into the system in a secure, uninterrupted wireless communication, that is capable for real-time interaction between UAVs. However, UAV swarms involve the integration of two main aspects, respectively networking system, and computing system. Through the networking system, the network demands especially for the control, coordination, and command traffics are the most critical issues, since UAV swarms demand a real-time distributed coordination and processing to fulfill the system requirements, using powerful wireless communication techniques, and in other hand dealing with the decision making for the UAVs itself through the swarm mission involve the main purpose of the computing system [6]. There are two types of swarm architectures, centralized and decentralized as shown in Figure.4.

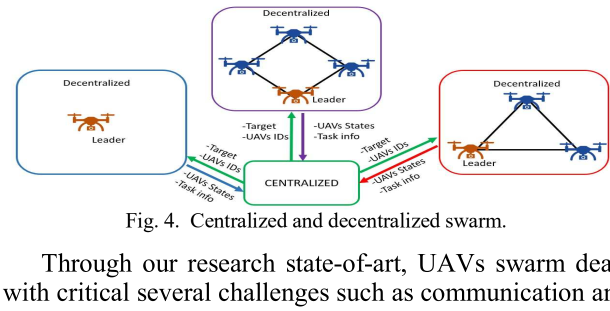

Fig. 4. Centralized and decentralized swarm.

Through our research state-of-art, UAVs swarm deals with critical several challenges such as communication and control schemes, incorporating properties, devising mechanisms, control and connectivity, and implementing functions. Dealing with the communication and control schemes challenges, it is cleared that UAV swarms can use either infrastructure-based-swarm architecture or flying ad-hoc (FANET)-based-architecture, as a type of swarm communication [7]. Where, the communication through infrastructure-based-swarm architecture is based upon the GCS which receives the telemetry data from all the participant UAVs in the swarm and send downlink with all data to each UAV, through critical issues the GCS may communicate individually to one of the UAVs in real-time to send commands through its onboard flight controller. Almost, through the infrastructure-based swarm, the mission is pre-programmed for each UAV and the GCS is used to control and observe the systems. The UAVs operating in such architecture are considered to be semi-autonomous because they still need commands and data from central control to achieve the mission [7]. Whereas, FANET architecture is more elastic and powerful, since each UAV act as an access point or a router by itself, and at least one UAV has the connection with the GCS, through [8, 9] FANET is discussed sufficiently, where the powerful of FANET appeared through the fact, it is a type of network that doesn't rely on existing infrastructure, where the entities inside this network are dynamically connected based on powerful routing protocols, which was discussed before through [10]. Also, through [9], the benefits of FANET appeared when it is equipped with a cloud computing system to gain its facilities and power computing process, which will decrease the overhead and the load through the network itself. Using such a network allows real-time communication between the UAVs as shown in Figure.5, where the direct communication and the routing algorithms are used to solve the problem of the decision making, which appears before through the infrastructure-based-swarm architecture discussed before. Definitely, studying UAVs behaviors through the swarm mission from the point of view that each UAV act as an entity inside this network, with the probability of joining or leaving the swarm, the aim of this part into the research is to highlights UAVs swarming problems under several phenomena, respectively self- organized aggregation, self-organized dispersion, and foraging, all these phenomena are the behavior of the entities (UAVs) inside the swarm (network).

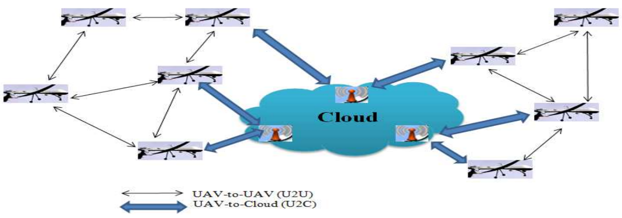

Fig. 5. UAVs Swarm Communication.

A. *Self Organized Aggregation*

To study the self-organized aggregation behavior, Markov dynamical system is used to examine the behavior of the entities (UAVs) inside the swarm system, where it can be classified into three main categories, respectively, individual dynamics, mobility, and collective dynamics [11].

B. *Individual dynamics*

The dynamics of each entity (UAV) υ will be represented by a Markov chain with a variety state χ, where $\chi^{(\upsilon)}$ represent the overall size of space, which is discrete and finite, reflecting the size that the UAV is a part of. Considering both situations of entities (UAVs), first, if the UAV is standalone (static entity), the second situation is UAV with a group of nodes or neighbors (UAVs) with a communication range between them. So, for a finite number of UAVs, the overall size of the space could be given as

$$\chi^{(\upsilon)} = j \in \{0,1,2,\dots,N_o\} \quad (13)$$

Where, j reflect the overall size, which the UAV is a part of, and $\chi^{(\upsilon)} = 0$ reflects the mean of a searching entity. On other hand, the condition for a moving UAV to join the overall size j , can be given the following probability

$$P(\chi^{(\upsilon)} = j \,|\chi^{(\upsilon)} = 0) : \mathbb{Z}_+ \longrightarrow [0,1] \quad (14)$$

Where equation.14 is knowing as $P^{join}(j)$. Also, the condition for UAV to leave the overall size j and end searching can be given by the following probability, and it is known as $P^{leave}(j)$.

$$P(\chi^{(\upsilon)} = 0 \,|\chi^{(\upsilon)} = j) : \mathbb{Z}_+ \longrightarrow [0,1] \quad (15)$$

Thus, from equations 14 and 15, it is cleared that any UAV can change its state, not only by its behavior but also with other entities' behaviors, these behaviors can be simplified through the Figure.6, assuming several autonomous systems and UAVs (entities) are joining and leaving through these systems [11].

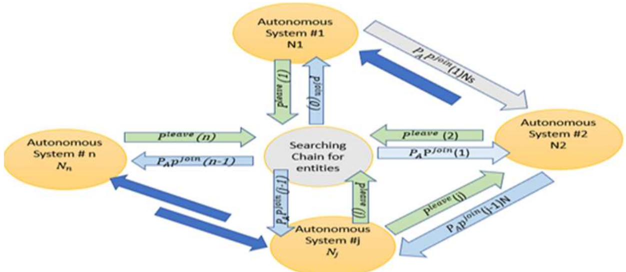

Fig. 6. The dynamic movement of entities between different Autonomous Systems.

C. *Mobility*

Assuming, uniform distribution for UAVs inside the Autonomous System, with constant speed and constant sensing range. So, inside the Autonomous system with (N) UAVs, the probability to encounter one of these UAVs is calculated by NP_c, where P_c can be determined through the following probability relation,

$$P_c \sim \frac{1}{A_{total}} \upsilon_r \omega_d \mathrm{T} \quad (16)$$

Where A_{total} represents the area of the Autonomous system, υ_r is the average speed for the UAV, ω_d represent the UAV communication range, and T is the discretization time of the Autonomous system.

D. *Collective dynamics*

The behavior of one UAV into the Autonomous system can be described by the Markov chain, by describing the UAV at a chosen state inside the Autonomous system to act as a random variable (P), having a value (j) at (k) time interval, to be calculated through equation (17), as follow

$$P_j(\mathrm{KT}+\mathrm{T}) = P_j(\mathrm{K}) + \sum_{j\varepsilon x/j} (P_{\grave{j}j}(\mathrm{KT}+\mathrm{T})P_{\grave{j}}(\mathrm{K}) - P_{j\grave{j}}(\mathrm{KT})P_j(\mathrm{KT})) \quad (17)$$

Where, the conditional probability at time (KT + T) for the Autonomous system in state (j), and at a time (KT), when the Autonomous system state is $(\grave{j})$ given by $(P_{\grave{j}j}(\mathrm{KT}+\mathrm{T}))$. Also, this condition can be determined as a transition probability for the Autonomous system to change state from j to $\acute{j}$, and to determine the numbers of UAVs expected at state j, inside the Autonomous system using equation. (17), it can be calculated as follow

$$N_j(K) = N_o P_j(KT) \quad (18)$$

Where, (N_o) is the total number of UAVs, (T) is the discretization time of the Autonomous System, and (K) is the indexing time steps, and for the simplicity of the calculation (T) will be neglected. From equation (18) into (17), we can calculate the discrete-time rate equation as follow

$$N_j(K+1) = N_j(K) + \sum_\iota (P_{\iota j}(K+1) N_\iota(K) - P_{j\iota}(K) N_j(K)) \quad (19)$$

E. Self Organized Dispersion

The self-organized dispersion can be understood numeral the opposite form of the self-organized aggregation, the problem can be simplified as how to perform a uniform spreading of UAVs swarms through different Autonomous systems [12]. In addition, using gradient descent algorithm, where this algorithm is used to calculate the minimum of a multivariable function $F(X)$, defined in N-dimensional Euclidean space, and through our research, it is an Autonomous System for the UAVs. This algorithm is characterized as, iterative, first order, defining the initial state for the UAV (X^o), inorder to move for a minimum value of $F(X)$, this movement is controlled by the mean of the equation given in (20), as follow

$$X^{K+1} = X^K - \alpha \nabla F(X^K) \quad (20)$$

Where X^K and X^{K+1} respectively are the present and the future location for the UAV location into the swarm. While, (α) is the learning rate algorithm's, this rate is characterized by a positive scale value, and it is responsible for the step size of the algorithm, and through giving the gradient for the multivariable function $F(X)$, it is calculated in N-dimensional vector as shown in equation (21),

$$\nabla F(X) = \left[\frac{\delta F(X)}{\delta X_1}, \ldots, \frac{\delta F(X)}{\delta X_N}\right]^T \quad (21)$$

Through our research work, the UAV movement is in three-dimension space, without neglecting the power strength of the communication signals received from other UAVs. This problem can be defined using three-dimensional gradient descent implementation, where the function (F) is taken under consideration to minimize the received signal strength (RSS), without neglecting that (RSS) between two UAVs is inversely proportional to the distance between them, this leads us to highlight that through minimizing the (RSS), an increase between the UAVs distance will be indicated, resulting in targeted dispersion [12]. Thus, through a three-dimensional cartesian plane of motion with coordinates $\chi, y, and\ z$, and by neglecting the pitch, yaw, and roll for the UAV, the general gradient descent equation can be simplified as in (22),

$$\left.\begin{aligned} \chi^{\kappa+1} &= \chi^\kappa - \alpha \cdot \frac{\delta F}{\delta \chi^\kappa} \\ y^{\kappa+1} &= y^\kappa - \alpha \cdot \frac{\delta F}{\delta y^\kappa} \\ z^{\kappa+1} &= z^\kappa - \alpha \cdot \frac{\delta F}{\delta z^\kappa} \end{aligned}\right\} \quad (22)$$

Through the mission application, the mission designer usually sets a termination criterion, where the dispersion is completed. Thus, UAV starting at an initial location (χ^o, y^o, z^o) will move through its first waypoints (first iteration) to the new location (χ^1, y^1, z^1), and keep repeating the same waypoints process until the termination criterion is satisfied.

F. Foraging

Assuming a swarm of UAVs $\mathbf{N_o}$, flying into the same Autonomous system and beneath these UAVs $\mathbf{M_o}$ missions scattered through the area of mission for these UAVs as fire, monitoring, and reconnaissance as shown in Figure.(7).

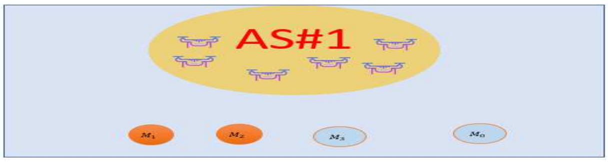

Fig. 7. UAVs Swarm mission.

So, at $t = 0$, we can clarify the effect of interference for the searching UAVs as follow;

$$\frac{d\,N_s(t)}{d\,t} = -\alpha_u N_s(t)[N_s(t) + N_o] + \alpha_u N_s(t - \tau)[N_s(t - \tau) + N_o] \quad (23)$$

Where it is cleared that the number of searching UAVs decreases when two UAVs detect each other and beginning bypass maneuvers, also it is increased when the UAV that started avoiding this behavior leaves at time $(t - \tau)$. In addition, the number of uncollected missions or tasks decreases in time because UAVs begin to encounter missions and this can be shown clearly through equation (24) as follow;

$$\frac{d\,M(t)}{d\,t} = -\alpha_M N_s(t) M(t) \quad (24)$$

Where, $\alpha = \frac{\alpha_M}{\alpha_u}$, $t \longrightarrow \alpha_u N_o t$, $\tau \longrightarrow \alpha_u N_o \tau$, in which α_u represents the rate detecting another UAV, α_M is the rate of detecting a mission, $N_s(t)$ is the number of UAVs in the search state at a time (t), N_o represent the total number for the UAVs, and finally $M(t)$ is the number of uncollected missions or tasks at a time (t) [13].

V. RESULTS AND DISCUSSION

The idea of this architecture is to allow the autonomous navigation of the swarm through different environments, for which it is necessary to establish a set of optimal routes to ensure that the drones reach their objectives in a safe and coordinated manner. To this end, trajectory planning algorithms have been developed whose computation time does not increase as the number of vehicles used increases, thus demonstrating the scalability of the architecture. In addition, as shown in Fig. 8, the computation time remains within acceptable values when increasing the number of vehicles involved in the swarm, so that in a time of less than 1 second, the algorithm is able to establish a set of optimal routes in 3D for the swarm to navigate safely and autonomously through the environment.

Regarding establishment of a configurable architecture when undertaking a mission, the possibility of each of the vehicles going to different locations of interest, or that the group of agents that form the swarm going to the same location in a specific configuration, has been implemented and tested. Currently, the architecture developed contemplates the possibility of reaching a location in three specific formations, as shown in Fig. 8, and which can be seen as a line, square or arrow. Currently, the implementation developed, allows the swarm to navigate in an autonomous and coordinated way through the environment, and reach a destination location in the specific formation desired by the user as shown in Fig. 9. Also, the possibility of including other types of training that may be of interest is also part of future developments.

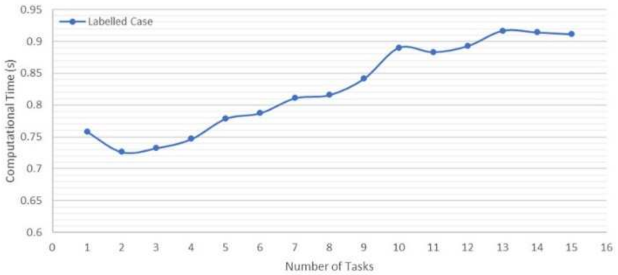

Fig. 8. Computational time vs. Number of Tasks-Drone [14].

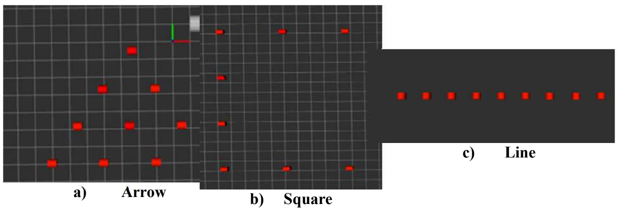

Fig. 9. Swarm Formations [14].

Finally, in reference to this point, it must be said that it has been tested in simulation, and that all the formations are parameterized, as shown in Figure 10, to be able to change the distance between drones, the distance between rows, the size of the formation, etc.

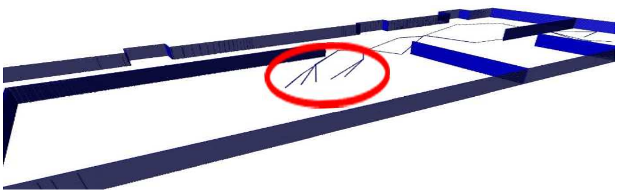

Fig. 10. Route Planning to arrive to an objective with line formation [14].

Regarding the distribution of the swarm, as mentioned above, a central architecture has been established, in which a single node oversees communications with the different drones, and through which information can be sent from one drone to another.

VI. CONCLUSION

Through FASTER project tasks, most of them will be devoted to performing a complete implementation of all software architecture tested and validated in simulation on a real swarm of UAVs. Although the idea is to establish a swarm of real aerial platforms with a structure like the one used in simulation, the complexity of the process is still high because it is necessary to install and configure all the aerial systems, together with the configuration of the central node. In addition, it should be remembered that the proposed software architecture is made up of a set of layers, each of which is aimed at providing the swarm with the necessary technology to solve problems derived from coordinated and autonomous navigation within the same environment. Each of the layers includes a set of methods that increase the robustness of the architecture, through the development of redundant implementations based on different technologies, and, in addition, allow the establishment of different control loops, at a high level, for the safe development of autonomous navigation of the UAV swarm.

DATA AVALABILITY

All the data is available through Drone Hopper Data Center 1, FASTER PROJECT SITE, and the H2020 Faster Project Community

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