Aerial robot swarms: a review

Manan Luthra
Ira A. Fulton Schools of Engineering, Arizona State University, Arizona, United States

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ABSTRACT

The purpose of this review is to highlight the current research on aerial robot swarms and their applications. It focuses on the system architecture and follows the current trend in aerial robotics promoting research in this field along with its impact on society. Further, it explores the dynamics as well as the flying mechanisms of a drone and sheds light on the different algorithms being used to control aerial swarms. Due to a lot of research going on in this field, we also discuss the different trends that are active and of keen interest to the researchers, including the swarm pattern formation behavior.

Corresponding Author:

Manan Luthra
Ira A. Fulton Schools of Engineering, Arizona State University
Arizona, United States
Email: manan894@gmail.com

1. INTRODUCTION

Swarm robotics involves studying groups of robots that function together by interacting and cooperating with each other. They solve different problems and perform tasks collectively that are difficult for a single robot to perform. Swarm robotics is inspired by the collective behavior of species observed in nature [1]. One of the key things to understand is that a swarm is not organized by an external system, rather their organization is self-emerging [2]. This is fulfilled by the localized interaction between the swarm robots themselves. Guided by intelligent principles [3], swarm robotics has a wide area of application these days [4]. It is indeed a valuable engineering tool in modern times. They have been contributing to various natural swarm intelligence models by refining and validating the systems [5].

Aerial swarms have gained a lot of recent growth in terms of solving real-life problems [6]. They are different from the ground swarms since they are operated in a three-dimensional space which adds an extra level of complexity [7]. The most important factor by which these swarms are guided is the family of algorithms [8] that allows them to achieve their goal efficiently.

In any application, these autonomous swarm robots are expected to be more capable than individual aerial robots [9]. One of the major challenges in swarm robotics is deploying these aerial vehicles into an unknown environment [10]. For a better understanding of swarm robotics, we identify some ground concepts and review several swarm behaviors and their applications in this paper.

2. CLASSIFICATION OF UNMANNED AERIAL VEHICLES

Unmanned aerial vehicles (UAVs) can be classified according to their weight, size, and different structures. It is important to know the characteristics and considerable advantages of each type. According to the weight and size of the drones, UAVs can be classified into nano, micro, miniature, medium, and large.

This may however vary from industry to industry. The weight range and the flight range of a typical classification are given in Table 1.

Table 1. Drone Classification

Size	Weight range (average)	Flight range (average)
Nano	<200 g	<25 km
Micro	200 g to 2 kg	25 km to 40 km
Miniature (Small)	2 kg to 150 kg	25 km to 40 km
Medium	150 kg to 600 kg	70 km to 300 km
Large	>600 kg	<1,500 km

Further classification could be done on the basis of the type of drone wing and rotors. These could be fixed-wing, fixed-wing hybrid, single-rotor, and multi-rotor. Fixed-wing UAVs utilize the airlift due to the aircraft's forward motion. The shape of its wings allows it to thrust upwards with ease. Fixed-wing UAVs are usually self-propelled. Fixed-wing hybrid UAVs are a combination of both fixed-wing and rotary-wing UAV configurations. A single-rotor drone has one big rotor and a tail for providing stability. The multi-rotor drone uses more than 2 rotors to generate lift. By changing the speed of different rotors, the multi-rotor drone can be used to make it hover, ascend or descend [11].

The swarm of drones can be classified into fully autonomous and semi-autonomous, as shown in Figure 1, which can further be divided into single-layered autonomy and multi-layered autonomy. The parameters which usually decide this division are the altitude, range, and endurance of a particular drone category. Fully autonomous drones operate independently without any human interference, while semi-autonomous drones require some sort of human intervention.

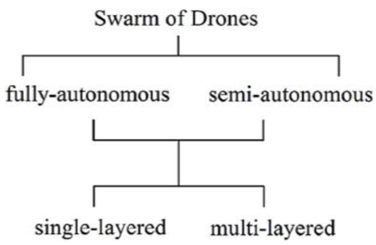

Figure 1. Classification of drone swarms

3. DYNAMICS AND FLYING MECHANICS

The propellers of a drone allow its movement in pitch, roll, and yaw directions as shown in Figure 2. This movement depends on the throttle provided by the different motors. The pitch of the drone does not change when the four rotors move at the same speed. The pitch, roll, and yaw are changed by the continuous feedback from the rotor computed by different algorithms. Figure 3 shows the two most common drone structures with the '+' configuration in Figure 3(a) and the 'x' configuration in Figure 3(b). In both configurations the rotors on the opposite side rotate in the same direction, while the two rotors on the same end rotate in the opposite direction. The 'x' configuration is more stable while the '+' configuration has better maneuvering capabilities. The '+' configuration is well suited for flying in sports, while the x configuration provides a much more stable hover for cinematography and photography.

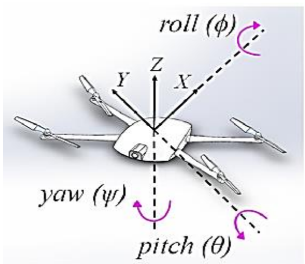

Figure 2. Flying mechanics

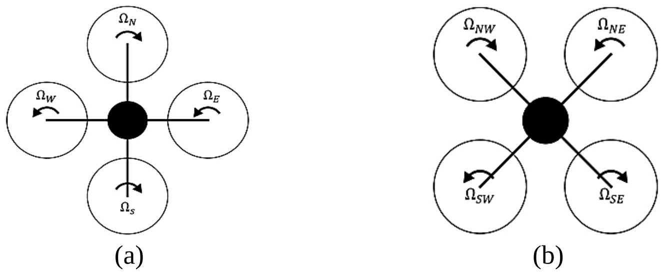

Figure 3. Quadcopter configurations: (a) plus and (b) cross configuration

The mechanical design of a basic drone system consists of four rotors, batteries, sensors, transmitters and receivers, programmable microcontrollers, electronic speed control (ESC), and an inertial measurement unit (IMU). ESC and IMU are the two major sensors for the control of any drone. They allow the drone to be controlled easily and provide stability to it. The IMU consists of a gyroscope and an accelerometer. It helps determine the altitude as well as the angular position of a quadcopter. The gyroscope helps in measuring every axis’s rate of angular rotation while the accelerometer measures the acceleration forces with respect to the earth. A lot of drones use ultrasonic sensors for low-altitude obstacle avoidance. Some of them also employ barometers and magnetometers for high-precision control. Barometers help measure the absolute as well as the relative altitude of the drone. The magnetometer allows the drone to scan and detect metals and further obtain the geo-referenced maps of a particular area.

Light detection and ranging (LiDAR) sensors are used for remote sensing by using scanners while flying. They send pulses of light to the ground which further penetrate the vegetation and then come back to the ground and further back to the sensor. It allows the drone to collect information regarding the topography of a particular area. Other components which are commonly integrated along with a drone are a camera and a global positioning system (GPS).

4. STATE ESTIMATION AND LOCALIZATION

As a robot moves through a three-dimensional environment, it needs to obtain the position and velocity estimates reliably. State estimation deals with the challenge of estimating the state of the vehicle by using onboard sensors and numerous mathematical tools. This usually involves the position, orientation, velocity, and angular velocity of the vehicle. State estimation is helpful in areas where it is hard to obtain GPS signals. This is especially useful while performing a task inside a building where GPS could be very inaccurate. To maneuver the drones accurately without GPS, the drone needs to have a good estimate of its position relative to the indoor structure of the building. The sensors on the robot allow it to obtain relevant information about its surroundings and further allows it to localize itself by estimating its position. Since aerial swarm robotics is expected to operate in environments that might not be structured properly, they must have the onboard capability to maneuver themselves.

4.1. Simultaneous localization and mapping

Simultaneous localization and mapping (SLAM) algorithms are utilized in aerial navigation, mapping, and odometry for virtual reality and augmented reality, and are based on concepts in computational geometry and computer vision [12]. SLAM incorporates multiple types of sensors which gives rise to multiple algorithms. The different algorithm pertains to the different sensors. To compute the SLAM problem, Kalman filters play an important role. They help in providing probability functions for the drone as well as the map parameters. Figure 4 shows the collaborative SLAM system that combines images from multiple aerial robots to generate 3D maps.

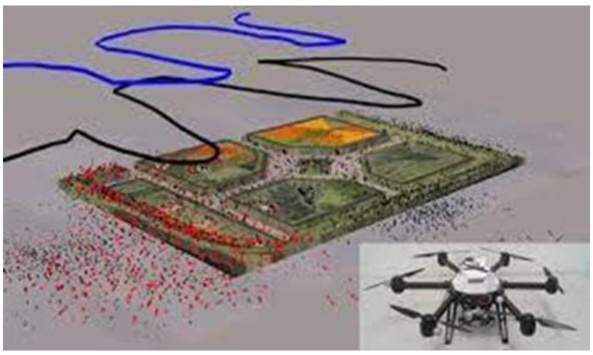

Figure 4. Collaborative SLAM system in action

Another technique used in robotics and autonomous systems is visual semantic simultaneous localization and mapping (VSSLAM). As shown in Figure 5, its approach combines the visual information obtained from the cameras and the semantic information (object detection and classification) to allow the drones to map and understand their surroundings. VSSLAM provides a more comprehensive and accurate understanding of the drone’s surroundings as compared to the traditional SLAM techniques.

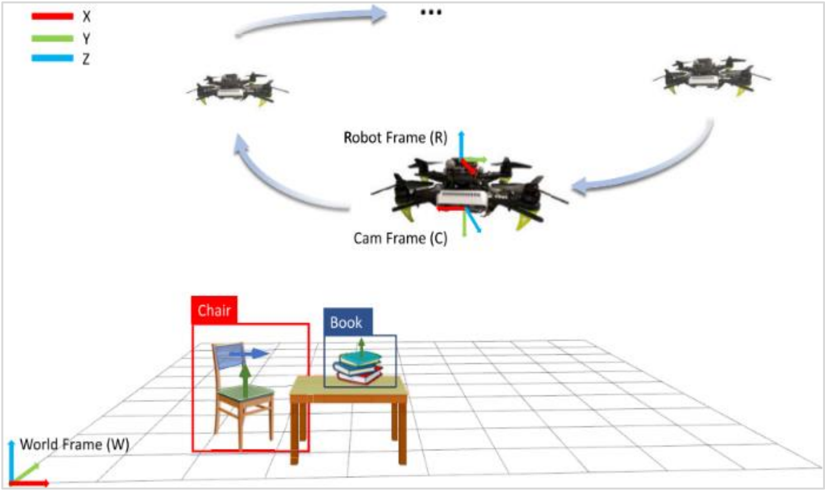

Figure 5. Visual semantic SLAM approach

5. APPLICATIONS
5.1. Security and surveillance

Aerial robotics swarms allow real-time surveillance because of their robustness and reliability. They have the potential to subdivide a task into smaller individual tasks and accomplish it faster. Their use in the military has been very prominent in the recent past. Due to their versatility, they have been employed in military surveillance missions monitoring and surveillance. This overtakes the requirement of large manpower to perform the same tasks. In addition to this, they have been used in surveillance in agriculture [13], since they can cover a larger area of land, as shown in Figure 6. They can monitor a larger area without much manual supervision and provide data that is otherwise difficult and time-consuming to obtain.

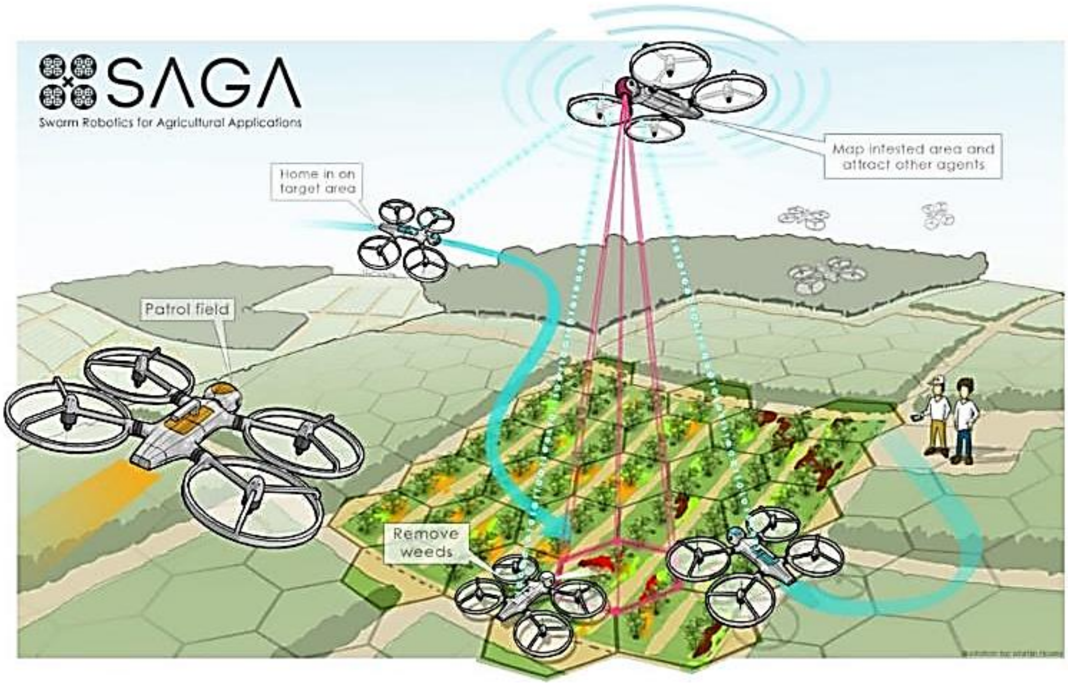

Figure 6. Drone swarms in agriculture

5.2. Entertainment

With the ongoing revolution in the entertainment industry, robotic aerial swarms have been playing a huge role in supporting it. One of the most attractive drone applications in this industry is the outdoor and indoor drone light shows. Equipped with light-emitting diode (LED) lights, aerial robotic swarms use SLAM algorithms to form different patterns in the sky creating an attractive light show, as in Figure 7. This is usually accompanied by music which makes it more interesting and entertaining. Other swarm aerial applications in the entertainment industry include aerial image projection and drone-launched fireworks. Industries are revolutionizing this field by equipping drones with unique lasers that allow them to project 3D animations in the night sky. Swarm aerial robotics could also be used for image acquisition for cinematography.

5.3. Transportation

Another application of aerial swarm robotics is in the area of cooperative transportation. Aerial swarms can provide increased efficiency while transporting a load from a specified location to another. Due to their flexibility in taking off and landing vertically, they are gaining a lot of attention in various commercial sectors. Their controlled performance and cooperation allow them to meet delivery requirements in warehouses and cargo sectors. With the increased adoption of drones, various challenges are to be addressed during the transportation of goods. These could be resolved by using mathematical modeling approaches as well as nature-inspired approaches [14]. Figure 8 shows multiple drones combining their lifting capacity to lift a heavy object. By working together, these drones can distribute the load evenly, reducing the risk of damage to the object.

Figure 7. Intel aerial swarm show

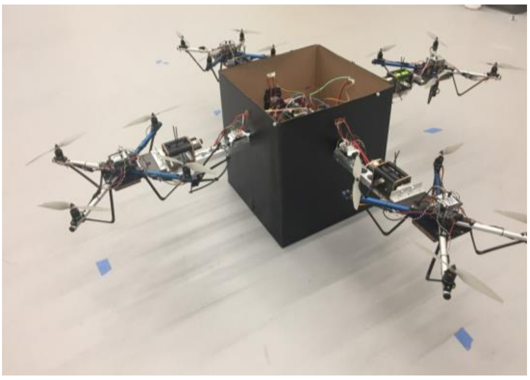

Figure 8. Collaborate swarm lifting object

5.4. Disaster response

In an event of a disaster, drone swarms can be of leverage for the search and rescue team. They can also be used to provide food, water, and other resources for any trapped survivors until additional help arrives. In case of a fire, aerial robotic swarms utilize infrared and thermal technologies to search for missing people while giving live feedback to the rescue team. These drones could also be used as first responders in a medical situation, as shown in Figure 9, and provide relevant information to the personnel about the environment as well as the harmed survivors. This would allow the medic team and other trained personnel to assess the situation even before arriving at the location, and quickly act accordingly [15].

Figure 9. Aerial swarm as first responders

6. CURRENT TRENDS IN AERIAL ROBOTICS

6.1. System miniaturization

With the evolution of aerial robotics, there have been a lot of technological advancements which allow industries to design aerial robots that are the size of a fingertip. Surprisingly, these designs are fairly optimum and have a lot of future scopes. A lot of research is currently going on in this field which would allow engineers to develop swarm formations of thousands of miniaturized drones to complete a task efficiently [16].

6.2. Aerial mapping

Aerial mapping allows us to obtain 3D surveys, photogrammetry, and topographic surveys from the airframe as shown in Figure 10. This also includes mapping unknown environments using swarms of aerial robots. This requires performing data and algorithm interfacing. It also requires enabling the robot's real-time operation and path-planning functionalities [17].

6.3. Autonomous motion planning

Since aerial robots work in a highly dynamic environment, they require a high level of autonomy. It is also highly required for an aerial robotic swarm to have flexible decision-making capacities. This is a major challenge for miniaturized robots since they are small in size and have lower computational power. Autonomous motion planning allows robotic swarms to complete the desired task in an unknown environment without colliding with obstacles as shown in Figure 11 [18].

Figure 10. Vegetation mapping

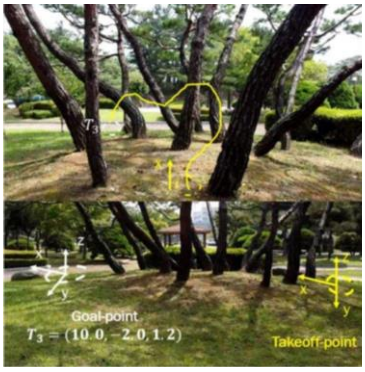

Figure 11. Test environment for drone automation

6.4. GPS denied navigation

There are a lot of situations where aerial robotic swarms have to operate in closed environments or in areas where GPS is usually degraded. To navigate drones without using GPS, researchers today are studying different ways to use vision to navigate drones. This is usually done by integrating the sensor inputs with the IMU. The most common techniques used to perform GPS-denied navigations are visual odometry and simultaneous localization and mapping (SLAM) [19], [20].

Da-Jiang Innovations (DJI) drones use the Attitude mode which is also called ATTI. This is a flight mode that does not utilize GPS or other visual positioning systems. When things go wrong or the drone is unable to receive a good GPS signal, it switches automatically from autonomous flight to ATTI mode in which the pilot has to take control of the drone and maneuver it manually.

7. PATTERN FORMATION BEHAVIORS OF SWARM

During a disaster, exploring unknown territories can be pretty challenging, especially in an uncontrolled environment. However, with the help of swarm intelligence, swarm robots might be suitable for such conditions. Swarm intelligence relates to insects such as ants, which work on solving a problem based on the collective intelligence of the group. A similar behavioral pattern can also be seen in bees. Usually, multi-robot systems can be found with centralized control, in which case, if there is a single bot failure, the whole system might be disabled. Swarm intelligence utilizing different pattern behaviors can be used to overcome such limitations [21]. Pattern formation of swarms is a very challenging task and is important to focus on since it can drastically increase the efficiency of the swarm system.

Arnold *et al.* [22] proposed numerous algorithms and control methods for enhancing survivor detection with the help of UAV swarms. They used the concept of behavior-based artificial intelligence. Behavior-based artificial intelligence is used where the system lacks centralized control. It combines the separate behaviors of the individual units in the system to result in an overall intelligent systemic behavior. They determined three sets of methods based on their effectiveness: standard method; spiral method; scatter method.

Figure 12 depicts the standard, spiral, and scatter methods from left to right. UAVs are depicted by the blue dots, destination targets by the grey areas, and the red triangle shows the concentration of disaster survivors. In the standard pattern, all aerial robots follow the same pattern throughout. In the spiral method, the drone locates a survivor, moves outward in a spiral pattern, and then returns back to the standard method. In the scatter method, every drone moves to a different location simultaneously to find a survivor.

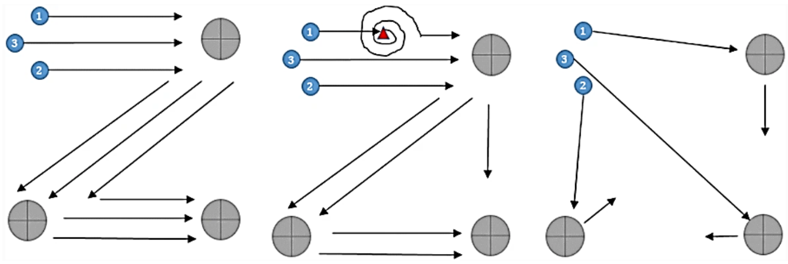

Figure 12. Standard, spiral, and scatter methods

One of the important results that the paper shows is that during and after a disaster, the survivors are likely to gather around together. This is where the spiral method helps since there are chances to discover more survivors after spiraling outwards from the location of the first few people found. The approach of the experiment is pretty well suited for different types of disasters, mainly earthquakes and tsunamis. Such situations might include the presence of hostile situations. Due to limitations in the range of swarm communication, and battery life, the pattern behaviors are optimized over an area of 2 km square.

Othman [23] proposed theories and algorithms in swarm robotics pattern formation, and also discussed the two major paradigms for pattern formation of robot swarms viz, biomimetics and physicomimetics. Biomimetics involves systems mimicking the behavior of biological systems. Reynolds [24] was one of the first researchers to model the flocking characteristics of fishes and birds, thus investigating behavioral control animation. The basic flocking model has three steering behaviors- separation, alignment, and cohesion.

Physicomimetics [25], on the other hand, involves gaining ideas from physical systems such as fluid flow analysis. Here, the main focus of the research is on the behavior of the robots similar to that of solids, liquids, and gas. In swarm robotics, there is a variety of distributed sensing tasks to create a virtual radar, hence there is a need to maintain the lattice geometry of the system. The crystalline behavior of solids is an excellent formation example in this case.

The algorithms for multi-robot patterns usually include three categories–bio-inspired algorithms, potential field-based algorithms, and leader/neighbor following algorithms [26]. This paper focuses on bio-inspired algorithms-algorithms inspired by biological systems [27]. It proposes a gene regulatory network (GRN) [28] based self-organization algorithm for swarm robot pattern formation. The fundamental idea of this approach is to regard each robot as a cell while modeling both the cell-to-cell signaling process in multicellular organisms and the interactions between robots and their local environments through reaction-diffusion mechanisms.

One of the case studies in the paper involves performing some simulations in a two-dimensional environment by a swarm of robots. The upper-right corner robots in Figure 13 are intended to form the capital letter "B." The non-uniform rational B-spline (NURBS) model [29], which is incorporated into each robot's dynamics, serves as a representation of this shape.

Starting with t=0, the robots are randomly distributed, while creating a local coordinate system (LCS). When a reference robot is selected, the target shape 'B' is built up. A similar experiment was conducted 35 times using the global coordinate system (GCS) method and the experimental results showed that the convergence time of the robots was less in the case of the LCS.

Pattern formation is relatively easy if global communication or centralized control is used, but for distributed decision making it is a considerable challenge, especially while operating in unknown terrains [30]. Self-organization of a robot swarm into a particular swarm is a huge challenge and has been studied by numerous groups in the past [31], [32]. Some challenges [33] to pattern formation in swarm robotics include the establishment of pattern–identification of robots forming patterns, positioning of robots in the pattern, maintenance of pattern, reconfiguration, and role assignment.

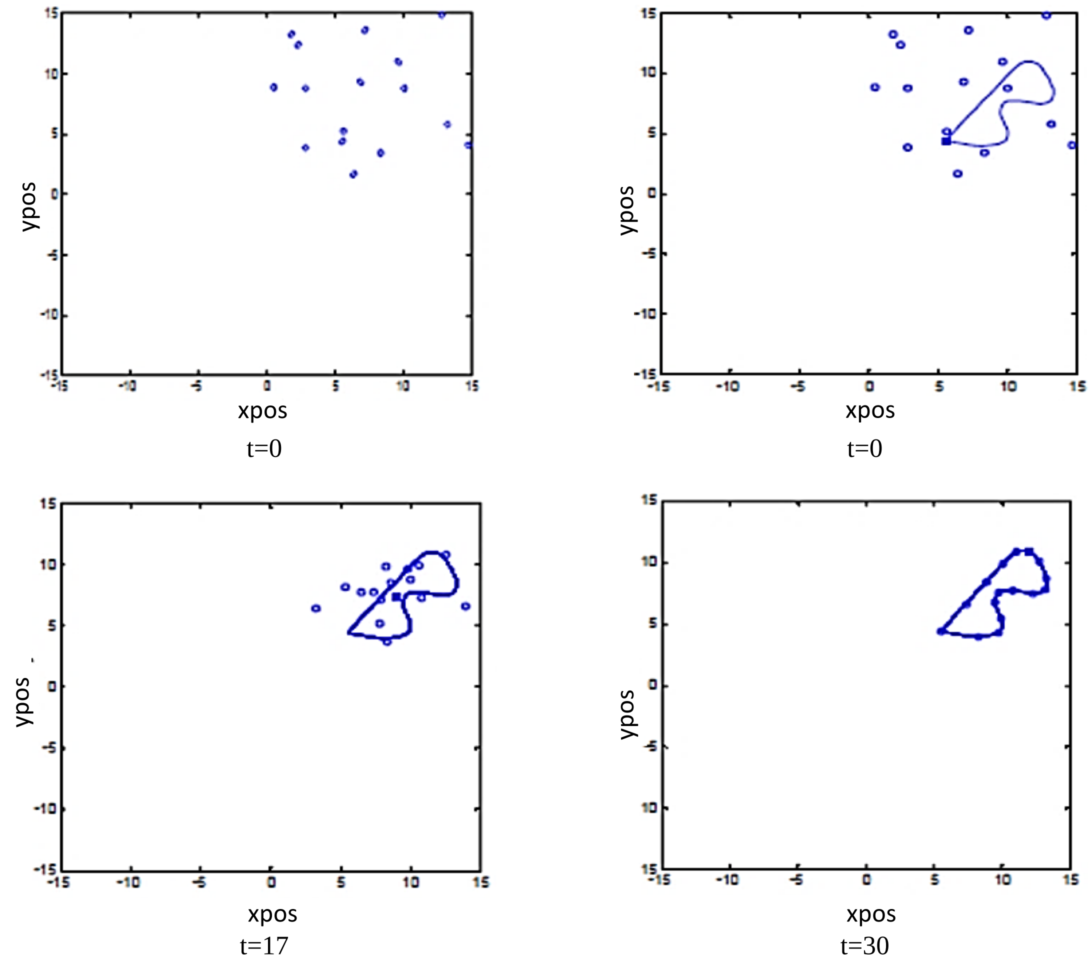

Figure 13. Two-dimensional swarm simulation

8. CONCLUSION

In this paper, we discussed the advancements in the field of aerial robotics. It begins with the introduction to UAVs and robotic swarms and then proceeds towards the dynamic and flying mechanisms of the same. We saw the capability of aerial robotic swarms to perform a single task collaboratively and efficiently. Various applications of robotic swarms were highlighted in this paper. It is fascinating to know the amount of research currently occurring in autonomous swarm planning and GPS-denied navigation.

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BIOGRAPHIES OF AUTHORS

Manan Luthra received his Bachelor of Technology in electrical and electronics engineering from Amity University, India in 2020, and is currently pursuing his Master of Science in robotics and autonomous systems from Arizona State University, USA. His research and interests include aerial robotics, embedded systems, programming for IoT, and CAD designing. He can be contacted at manan894@gmail.com.