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Unmanned Aerial Vehicles Swarm Flocking Architectures: An Overview

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***Abstract*-The eruption of unmanned aerial vehicles (UAVs) use has disrupted the aviation industry. More recently, swarming in UAVs has been gaining popularity and has attracted a huge interest from researchers and industry players due to their potential application in various fields. A UAV swarm, which is a collection of many UAVs has the capability of autonomous navigation and operation hence suitable for diverse applications. The capabilities inherent in a single UAV are expounded by having many such vehicles performing similar or differentiated tasks while flying together. The potential of UAV swarms is yet to be fully explored as many researches are still concerned with the theoretic specifics of these complex multi-agent systems. The purpose of this article is to provide an overview of the swarm flocking architectures used in UAVs and their origin. Also some applications and challenges of swarming in UAVs is presented.**

Keywords— unmanned aerial vehicle, swarming, formations, leadership, flocking

I. INTRODUCTION

Unmanned aerial vehicle (UAV) also known as an aerial drone is a powered aerial vehicle that does not carry a human operator, flies autonomously or piloted remotely, and can carry a payload. Even though a drone can be built for any size, most designers tend to keep them small hence better energy efficiency and a low cost. The recent advance in technology has drastically reduced the cost of miniature electronics by making them powerful even in their small sizes. Most notable are microprocessors, cameras, global positioning systems (GPS), inertial measurement units (IMUs), batteries, and motion capture systems which are essential parts in a UAV.

This advancement has revolutionized the conception of UAVs as researchers, small companies and hobbyists can own UAVs which in the recent years was a reserve for military and global conglomerate companies. This move has led to an increase in the capabilities and applications of UAVs in areas where many would not have envisaged. For instance in agriculture, transportation and delivery, network stations, entertainment and performances among others. A group of UAVs flying together in a collective motion as Fig. 1 shows have been used recently to imitate a flock of birds. This behaviour is commonly referred to as flocking or swarming, an emergent behaviour.

Emergent behaviours are behaviours that do not depend on an individual, but rather on their relationship with other individuals. They are implicit and no overt plans run them. Swarming is a particular emergent behaviour of simple autonomous individuals. However, swarming is not merely about the numbers, but rather on the interactions between individuals in a group. In [1], swarming was viewed in two ways: the group interaction amongst individuals and the swarming tactics. Of importance is the collective simplistic autonomous individuals with reactive behaviours relying on local sensing amongst themselves to interact such that a global behaviour emerges from these interactions.

Swarming have gained a lot of attention in the context of collective robots [2], [3], [4]. The reactive behaviours within individuals leading to collective behaviour was observed in the fruit fly where the researchers found that the flying motions were driven by fly-to-fly interactions and that the flies used their legs and wings to touch each other and establish some personal space [5]. Synchronization of movement especially wing flapping during swarming is an adaptation to a rhythm generated by a group leader in a swarm.

Fig. 1: Drone swarm. Adapted from [6]

Swarming of UAVs mimic the observed real natural occurrences of collective motion in a large number of self-propelled individuals, moving en masse towards a target. This phenomenon is seen in flocking of birds with coordinated wing strokes [7], [8], social synchronization in ant colonies and beehives [9] and coordinated fin movements in fish schools [8]. This natural organization and synchronization of individual behaviours pre-empts the concept of leadership and communication during motion.

In this article, we give a survey of the main applications of aerial vehicle swarms in section II, a discussion of swarm flocking architectures where hierarchy, leadership and dominance as it applies to swarming is given in section III. Section IV highlights the potential challenges and threats affecting swarming in UAVs. Finally, in section V we discuss a structure and the underlying issues of a generic architecture for successful swarming in UAVs.

II. AERIAL VEHICLE SWARM APPLICATIONS

We present a few selected applications of drone swarms in various fields.

A. Security and Monitoring

Drones initially were created for military purposes and they were expensive. However, due to the advances in the related technologies including cameras, sensors, powerful processors and other off-the shelf solutions, drones have become easily accessible to the general masses. Moreover, with installation of cameras possessing motion and thermal imaging capabilities have made aerial surveillance and monitoring a lot easier. This has led to a shift from the traditional methods involving foot patrols and static position CCTV cameras to live video feeds with high resolution. This is aided by the fact that a single drone can cover a relatively large area within a short duration. For a much larger area, a swarm of drones can be used whereby the area is divided into sections and each drone carries out monitoring in specific section(s). The greatest advantage is that drones can be deployed in potentially dangerous and hazardous environment where human intervention is not possible for example during volcanic eruptions, floods and disaster monitoring and in war areas.

Primarily, drones were created to carry and deploy weapons [10], [11]. With the use of GPS and infer-red markers, drones have the ability to deploy weapons and hit targets with pin-point accuracy [12]. This has been a game changer especially in counter-terrorism efforts [13], as a drone can penetrate enemy lines and performs reconnaissance military operations without the risk of human loss [14].

B. Entertainment and performances

In recent years drones have been used in entertainment performances in different countries. The Intel group pioneered the first drone swarm of five hundred drones[1] in 2016; entered the world record books for the most number of drones flying simultaneously. Since that first performance by Intel group, several other companies have performed such fetes for different occasions. Despite having fewer numbers, during Hungary's Independence Day celebrations[2] in 2018, 38 autonomous drones performed a magnificent 3D animation of a deer walking, then seamlessly transitioned into the Hungarian cross and later into the king's crown. Other such animations and magnificent shows have been carried out in different parts of the world.

More recently being the spectacular show during the opening ceremony of the Tokyo 2021 Olympics[3] games where 1,824 drones fitted with LEDs formed sets of 3D geometric shapes representing different themes. Notably is that at the end of the show, each drone docked in the exact position it took off from. Amazing, isn't it? In the future, we expect aerial choreographed animations similar to amusement park events and interactive shows such as those proposed in [15].

C. Flying networks

Drones can be equipped with cellular communication modules in such a manner that each drone acts like a flying base station providing a network coverage [16], [17], [18]. These networks are referred to as flying ad-hoc networks (FANETs) [19]. No routers or access points is needed for an ad-hoc network and they do not rely on an existing infrastructure to establish the network. They provide an inbuilt redundancy such that an entire swarm is not dependent upon an existing network infrastructure to communicate. Reference [18] suggested that FANETs could be used as clusters of deployable base stations to assist ground base stations due to on-demand extension of network connectivity. Similar configurations have been proposed in [16], [20]. A 3D deployment of a drone-base station was investigated in [16] which sought to improve congestion, flexibility and dynamism inside a network cell therefore enhance the quality of service and maximize the number of users served. In [20], a justification of the business model for mobile base stations was made. It was argued that the fixed wing UAV is suitable for high endurance operations, while a multirotor is suited for high flexible operations, hence combining the two modes would assist network planners and operators to exploit the capabilities of both simultaneously.

Can the flying base stations replace ultra-dense cells? This was explored in [17]. It was argued that in specific scenarios it was profitable to have such a network. Among them was the non-static users requiring temporary network access, where their network requirements vary with time. For instance, a group of people moving in a crowd as spectators heading to or leaving a sports stadium. It was economical to use a flying base station in such a scenario as opposed to setting up a temporary base station. In the long run, it is anticipated that due to the ever increasing amount of network devices, there will be a big demand and stress on infrastructure and connectivity especially for the non-static users, and the use of flying base stations would be ideal.

D. Other Applications

Drones has been used to carry physical payloads. In Rwanda[4], a team of hospitals have a delivery service using drones for small supplies like blood, medications and patient laboratory reports. Other ingenious examples of drone transportation are given in [21]. The biggest task and future directions in this area is that of collaborative transportation. This is where a group of drones transport a large load which a single drone cannot carry on their own. Therefore, the load is transported collaboratively within a group. Research in this area provides an interesting perspective of aerial load transportation. The issues stem from navigation and the type of loads; rigid or flexible [22]. Reference [23] presents a method using cameras for navigation while [24] presents a control architecture for positioning and trajectory tracking while maintaining a stable swarm formation.

In agriculture, drones have been used in crop monitoring, pesticide spraying, irrigation and irrigation equipment

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[1] https://www.guinnessworldrecords.com

[2] https://collmot.com/our-shows/st-stephens-day-2018

[3] https://olympics.com/ioc/

[4] https://www.itu.int/hub/~/how-medical-delivery-drones-are-improving-lives-in-rwanda/

monitoring, GIS mapping, cattle herding and scouting [25], [26]. With the right equipment(s) and accessories attached to a drone, precision farming becomes a reality. In [27], it is shown that drones can monitor fields more often and accurately than satellites and with many such drones, the benefits can be immense even for large and extensive fields.

III. UAV SWARM FLOCKING ARCHITECTURES

There are two main types of flocking architectures that can be modelled for swarming UAVs. The first is the leader-follower formation, where hierarchy exists [28]. Fig. 2 shows birds flying in such a formation. The second is the leaderless architecture. As the name suggest, there is no explicit leader(s) in the flock hence, no centralized coordination and motion. Fig. 3 shows a leaderless flock of birds. This flocking architecture is based on consensus among members in the flock. Here, we give a literature review of these two architectures. Many literature often describe flocking in UAVs using Reynold's rules of separation, alignment and cohesion [29], [30].

Fig. 2: Birds following a leader. Adapted from [31]

Fig. 3: A leaderless flock. Adapted from [32]

A. Leadership and Hierarchical flocking

Flocking as a collective behaviour of homogeneous individuals, social relations such as leadership and dominance [4], [33], [34] usually apply. For this purpose, leadership refers to a member's influence over a groups' decision and dominance may refer to the preferential treatment of an individual member's information set or decision above that of others. Leadership might infer dominance but not vice versa. An adaptive leader as presented in [35] was time dependent and hierarchical such that the neighbours of the leader would change their motion according to the leader's perception of the environment. The flock structural control would reorganize under certain circumstances. A star based model was used where the neighbours were made aware of the leader's circumstances and hence each would reduce their overall local collective weightings (control and communication) so as to be dominated and controlled by the informed leader. Leadership maybe absolute in two instances; in a strict leader follower formation [30], [36], [37] and through dominance [31], [34]. In [34], social dominance was investigated vis-à-vis leadership roles for a group of pigeons. It was found that there was a direct link between dominant members and leadership, and presence of a more egalitarian decision system where dominance was absent.

A hierarchical flocking architecture was presented in [33], where the system was modelled as a leader-follower formation. An egalitarian and a hierarchical decision system between members of the flock was presented. For the egalitarian system, each member in the flock had the same contribution to decisions and communication while in the hierarchical system, different members had varied weighted contributions. A contribution matrix and a dominance matrix were designed to define the strength of contribution from each member and the direction of the flow of communication between a pair of members respectively. If we denote C_{ij} as the contribution matrix and D_{ij} as the dominance matrix then, with subscript $i, j \in N$ representing members in a flock, the two decision systems could be summarized as follows:

(i) For an egalitarian system, every member would have the same contribution value, a constant while for a hierarchical decision system, C_{ij} would follow some predefined probability distribution.

(ii) For a pair in an egalitarian system, communication is bi-directional and thus $D_{ij} = D_{ji} = 1$ whereas in a hierarchical system $D_{ij} = 1$ and $D_{ji} = 0$ due to dominance of j by i.

Studies carried out including the quantitative motion of flocks in [34], could not establish the conditions which hierarchical flocking can be optimal. However, in [38] flocking was categorized into two; cluster flocking where the goal was to optimize the control law, and line flocking where the goal was to minimize energy used by each member in a flock. It was established that in cluster flocking, mandatory presence of a leader for collective motion during flocking was not a necessity. In line flocking, the natural phenomena found in large birds such as geese, is based on the advantage of the formation shape. Presence of a leader in this category was mandatory. The members in the flock experience different levels of drag and up wash depending on their position on the line or the V-shape [39]. This flocking architecture can be applied in robotics, however the formation configuration requires offline planning such that each member has a unique position that contributes collectively to the overall cohesiveness of the flock.

An agent based model relying on Reynolds rules was constructed in [37] for collective behaviour during flocking. It was observed that local communication between individuals was extremely important during flocking such that if a low communication radius was used, a correlated motion would ensue. However, collisions would still occur with other non-neighbouring individuals. It was suggested that a much greater radius than that perceived of individual interactions should be used for a collective correlated flocking motion.

In [40], an obstacle avoidance algorithm was used for a flock of fixed wing UAVs to eliminate the possibility where some individuals in the flock would enter into a local minima after encountering an obstacle. The Olfati-Saber's [41] algorithm was applied on a dynamic system modelled using integrators to represent a Euclidean space comprising of position, velocity and control. An interaction distance was set similar to that in [37] in such a manner that the minimum distance between two neighbouring individuals could not be less than the interaction distance. With such sufficient interaction distance between members, there was collective obstacle avoidance maneuvers with no collisions.

B. Leaderless flocking

Collective decisions made by a flock of animals to move together to a target site or to evade a predator involve complex interactions [42]. How is this information transferred to such a large group? How are the not informed individuals distinguished from the informed? And how can a collective decision be made when the informed individuals differ? The process in which such collective decisions are made is not clear-cut, however we can assure that some form of self-organized consensus exists. Self-organization was investigated in [43] and it was found that starlings, interact with their neighbours in the so-called "topological range". This means, apart from the absolute distance between each other, starlings interact with about 6–7 other neighbours [44].

The effect of animal density on a leaderless formation was investigated in [45] where it was observed that an aligned collective motion would emerge from rapid transitions to an orderly movement without the loss of group cohesion. In a research carried under EU FP6 NEST [44], it was argued that the effect of animal density, was quantitatively different in most flocks since some flocking models assume a spatial interaction range between individuals. It was theorized that birds become aware of changes far from them, and they anticipate how they would have to adjust their flight when the change reaches them. They don't think about it, they just react following specific rules that keep them from crashing into each other [5], [29]. Through camera tracking, [5] shows that an asymptotic distance between fruit flies exists as the swarm density increases.

A leaderless formation control problem was presented in [46] for the collective motion of a swarm of robots. Input-output linearization was used to steer the swarm to follow a desired trajectory based on shape parameters. A control law was designed such that the individual robots could transition from any shape while tracking a desired target. A distributed control was used in [47] for a 3D leaderless flocking problem to command small UAVs to fly with constant velocities and achieve group cohesion. Consensus algorithms for decision making coupled with graph theoretic principles were used to design the interactions between the UAVs. Similar formulations using density based method [48], behavioural based approach [49], time varying formation problem [50] and consensus based formation control [51] have since been used in robots and UAVs.

A self-organizing collision avoidance approach was discussed in [52]. The model formulation was simplistic since it used a leader follower algorithm for collision avoidance in a line formation architecture in such a way that the decision of each robot was relied on by one immediate neighbour. And such a decision would be propagated through the swarm.

C. Layers of Control in a Swarm

For successful implementation of any swarm flocking architecture, we highlight the major control layers that should be considered during the control design.

a) Intra-swarm control

This is the low level control of individuals in the flock for a safe flight. At this level, very specific requirements must be satisfied. Among them are the interaction distance, velocity constraints, maneuvering abilities, trajectory tracking capability, hierarchy, obstacle avoidance mechanisms and the intra-swarm communications.

b) Tracking control

The objective of tracking control is to achieve a predefined coordinated motion or a collective motion towards a target. The former involves prior planning of the path or trajectories as was in [33] where a virtual target based on a preset path was tracked by a leader and the followers tracked the leader. In the latter, only the target destination is known and each member must independently traverse the distance to get to the target while still maintaining group cohesion [41].

IV. POTENTIAL CHALLENGES

A number of challenges and potential threats arise in UAV swarms. Most of the challenges exist because of the inherent constraints attributable to physical components. Threats can be analyzed from potential external interference with the operation and/or trajectory of a vehicle.

A common challenge in UAVs is the battery problem. Flight time is an important variable in UAVs i.e. how much time can a battery support a UAV flying under normal conditions. For a swarm of UAVs, this becomes a fundamental constraint for the whole system [53]. If it is desired to have the capability of longer flight times, then the battery problem should be addressed at the design level. Other possibilities available include the use of solar cells and combustion engines.

Fault detection and tolerance. Sensors, actuators and motors are prone to malfunction and fail without prior warning. Therefore, a devolved fault detection method should be present, absence of which there would exist a risk that the erroneous operation of one may encumber the entire swarm. To what extent will failure of a single vehicle incapacitate an entire swarm? [54]. Reference [55] provides an analysis of fault diagnosis and anomaly detection methods for sensors and actuators in UAVs that can be used in detecting and isolating faulty vehicles.

External interference such as flock hijacking and task manipulation offer a serious security risk. Loss of control of these UAV systems to adversaries can be a potential threat to national security, especially in instances where the UAV systems are carrying a lethal payload [56].

Communication in drone swarms exist between members in the swarm or between swarm members and a base station. These communication networks are susceptible to interference for example due spoofing, denial of service, jamming, network congestion, interception of information and eavesdropping [56], [57]. Moreover, use the mobile ad hoc network, MANETs to exchange data between neighbouring UAVs is subject to attacks such that one 'impersonated' drone can send false signals [58], to other drones in the swarm.

These challenges and threats present the potential downside faced in the design, use, deployment and operability of UAV swarms in critical mission and applications. However, some of these challenges are dependent on the application domain of the UAV swarms.

V. AN OUTLOOK OF A GENERIC UAV SWARM ARCHITECTURE

It is paramount that aerial swarm systems require further realistic development for them to be deployable at a large scale. Due to the nature of interactions between members of a flock, agent based designs in modelling and representation would be a perfect fit. Such that, instead of controlling the entire flock, the behaviour of each UAV is specified using a few rules for interactions with its neighbours. Fig. 4 shows such rules. Several individuals can be modelled in a similar manner with similar or different capabilities assigned to each; leadership, dominance, communication capabilities. A number of techniques are suitable, quite notable is game theory [59], [60], [61] which has been gaining a lot of popularity.

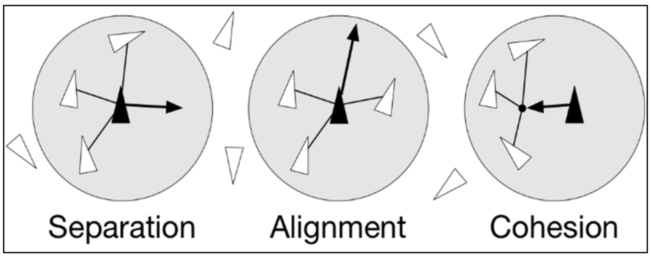

Fig. 4: Interaction rules in agent based modelling

Mission planning and trajectory tracking follows after the low level modelling. Trajectory tracking at the swarm level is a complex problem since it involves many individuals. This can be computationally intensive especially if collision avoidance and individual trajectory planning is desired.

To simplify such a system, a layered architecture can be utilized in which trajectory tracking and mission planning are decoupled. The trajectory tracking layer would be responsible for inter-swarm collision avoidance, communication flow, swarm formation maneuvers and velocity coherence while mission planning would define the target destinations, swarm formations, cohesion and task fulfillment. Each individual should be made aware of their targets from the mission planner, and coordinate with each other to fulfill the mission objectives.

VI. CONCLUSION

This paper has presented a brief summary of flocking architectures as pertains to aerial unmanned vehicle swarm systems and the related researches in the area. The main flocking architectures, current and potential applications, challenges and threats of UAV swarms have been discussed. A generic swarm architecture highlighting the main components has been discussed in brief. As research in this area is geared towards a future of fully autonomous self-organizing systems, it is important to appreciate the principles of swarming in UAVs and its genesis.

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