ALTISCOPE

Applying Visual Separation Principles to UAV Flocking

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1. Introduction

Numerous companies and researchers have demonstrated the ability of small unmanned aerial vehicles (UAVs) to swarm or flock together. While the largest and most eye-catching displays are intended more for entertainment, Altiscope believes the underlying principles will be a crucial tool for autonomously managing future airspace density and capacity constraints. Formation flight serves many purposes in military and general aviation today. Separately, visual separation techniques available to controllers in today's airspace allow two aircraft that can see one another to fly much closer than prescribed separation minima otherwise would. Altiscope proposes a path toward establishing a set of UAV flocking behaviors based on both formation flight and visual separation that would take advantage of onboard sensor equipment and vehicle-to-vehicle (V2V) communications links. Taking an approach that is rooted in present-day policies and regulations should enable faster adoption of these procedures in an autonomous realm, compared with creating new regulations from scratch.

The terms "swarm" and "flock" have been used interchangeably in most instances. Flocks are frequently associated with groups of birds, many of which carefully coordinate their formations to enable migration and fly more efficiently But "swarm" has a more negative connotation, both because it refers to large groups of insects, and because some media coverage have cited swarms of weaponized drones as an existential near-term threat to peace.[1] Therefore, for the sake of simplifying terminology in the already-acronym-laden UAV space, Altiscope recommends referring to such groupings of UAVs as flocks, regardless of their actual geometric arrangement or mission purpose.

2. Formation Flight in Today's Airspace

There are two primary instances in which formation flying occurs with human-piloted aircraft today. The first is between military aircraft. Flying in formation, with one pilot designated as the flight leader, has tactical and defensive advantages. Doing so enables airborne units to protect one another and provides an effective way to concentrate firepower. Military formation flights, depending on the air navigation service provider (ANSP) and jurisdictional requirements, may be treated as a single aircraft by the air traffic controller, or may be entirely responsible for their own separation within a pre-approved airspace block.

In the first case, this reduces controller workload and improves efficiency, since a controller can issue a single landing clearance or other instruction which then applies to all aircraft in formation. The flight leader is responsible for ensuring that all other aircraft within the formation


Figures 1 and 2. Airbus A350 aircraft in delta formation (left) and modified diamond formation.

follow the controller's instructions. The caveat for the controller is that, in cases where the formation occupies a large amount of airspace (due to the spacing between aircraft and/or the total number of aircraft), the controller may need to provide greater than standard separation between the edges of the formation and any non-participating aircraft. In the extreme, the effect would be to decrease the capacity of the sector through which the formation is traversing.

Formation flight also occurs in a recreational setting. In this context, groups of pilots who know one another may fly in loose formation for fun, or to a fly-in. Most often, these aircraft have similar performance characteristics and are flying VFR, without using air traffic control services during the en-route portion of their flight. This has an operational benefit in settings such as arriving at the annual AirVenture fly-in in Oshkosh, Wisc. If a controller knows that a certain number of similar aircraft are flying together, it is usually less work to schedule and sequence them for arrival to the same runway, since they're already in close proximity.

119 warbirds in formation over London. Each letter comprises 8-11 aircraft flying as an "element." Still from video posted by Instagram user @whatchs.

Current FAA and EASA regulations regarding formation flight are brief. The FAA requires that pilots brief their formation beforehand, but does not mandate the length, structure or details of such a briefing. Additionally, pilots in the United States may not fly for-hire (commercially) in formation.[2] EASA regulations explicitly state some of the responsibilities of the

Figure 3. An Airbus A350 widebody jet (far left), A400M, Eurofighter and H160 helicopter in formation.

flight leader and wingmen in a formation, which is consistent with best practices taught in training for formation flying. [3] Neither body requires a separate rating, endorsement or checkride before participating in a formation flight.

Formations can take several different shapes depending on the needs of the mission. Most formations can be scaled to incorporate large numbers of aircraft by splitting the formation into elements, each of which has three or four aircraft.

Formations need not consist of identical aircraft types, as long as all aircraft in the formation can maintain their relative positions and climb, descend and cruise at the same speeds while in formation.

As a general principle in formation flying today, the flight leader is responsible for the formation, including ensuring that all other aircraft are in the correct positions. Communications within the formation can use hand signals or a dedicated radio frequency separate from any air traffic control frequency in use. Only the flight leader talks to air traffic controllers.

3. Visual (Own) Separation Between Pilots

While formation flights are intentionally created and may fly together as a group for hours on end, they usually do so under visual flight rules, where there is no prescribed separation minima. By contrast, there are normal air traffic control situations that occur in which two aircraft may pass closer than the usual separation requirements. These encounters are managed using either controller-provided or pilot-provided separation.

The former is exclusively available to tower controllers, who can look out of their windows, observe two aircraft and ensure that they adhere to any instructions to keep them safely apart.

This principle allows for simultaneous parallel runway departures without needing a 1-mile or 3-mile stagger. In United States Class B airspace, in which all aircraft must be properly separated, it also allows controllers to monitor two VFR flights passing one another with less than 500 feet vertical or 1.5 miles horizontal separation.

Pilot-provided visual separation, also known as "own separation" in ICAO documentation, is one of many tools available to air traffic controllers to make more efficient use of their airspace in certain circumstances. Rather than adhering to strict IFR lateral or vertical separation minima, pilots flying under properly applied visual separation may operate much closer to one another. Most commonly, this is used in situations like:

- Very closely spaced parallel approaches in visual meteorological conditions (VMC)
- One aircraft climbing or descending through another aircraft's level
- One aircraft passing behind another aircraft

ICAO PANS ATM §5.9 limits the use of pilot-provided visual separation to daytime VMC operations in Class D or E airspace below 10,000 feet MSL.[4] However, individual countries may tailor their rules of visual separation. Thus, in the United States, controllers may solicit pilot-provided visual separation in any airspace class (except Class G) below FL180.[5] Additionally, pilot-provided visual separation allows controllers to waive wake turbulence separation requirements (except for aircraft behind an Airbus A380 or Antonov-225).

ICAO sets several other requirements for the controller to exchange relevant traffic information between the aircraft using visual separation, and to consider aircraft performance characteristics before using it. Most countries, in their specific air traffic control rules, also require the controller to ensure that another form of approved separation exists before and after the use of visual separation. In other words, visual separation is not intended to be used for the entire length of a flight, but rather to address a specific encounter between two aircraft.

In most cases when properly applied, pilot-provided visual separation should not require either flight crew to perform much maneuvering or speed adjustment beyond what they would normally be doing during that particular route segment or phase of flight. For example, it could involve a benign scenario of one aircraft crossing 2 miles in front of another (thereby violating the standard terminal lateral separation minima of 3 miles). Or it could involve two aircraft passing opposite-direction to one another, but offset by less than the required mileage. Local procedure design, terrain or airspace restrictions may make such an operation preferable to vectoring or step climbs/descents.

But quality assurance reviews in many countries often target improper use of visual separation as a causal factor leading up to validated losses of separation. The controller may have exchanged traffic correctly, but the operation placed both aircraft in very close proximity to one another, or resulted in an Airprox (NMAC) encounter or traffic collision avoidance system resolution advisory (TCAS RA). In other instances, ambiguous traffic calls have resulted in the pilots spotting a third aircraft that was already safely separated, but never actually seeing the aircraft in conflict. And, especially in cases when a faster aircraft is told to "follow" a slower aircraft, the resulting overtake or compression may have required an abrupt vector or a missed approach to resolve.

In spite of those pitfalls, the visual separation framework appears almost directly transferable to a UTM environment, with a few key assumptions or changes. In particular, suitable onboard sensors (which could be a combination of cameras and surveillance receivers) must be able to positively identify the correct vehicle. Varying jurisdictional restrictions on airspace classes may need to be smoothed out as well.

4. Architecture for UAV Flocks

Researchers have already demonstrated the ability of small UAVs to autonomously flock.[6][7] That research showed the ability of up to 10 GPS-equipped UAVs in a flock to maintain spacing between each other while all following a lead vehicle's routing, even given latency and multipath GPS errors. More recently, another group of researchers demonstrated the viability of a centralized system to maintain a UAV flock using image comparison from downward-facing cameras on each vehicle to maintain relative positions within the flock, without any need for GPS.[8]

Along similar lines, the Chinese UAV manufacturer Ehang synchronized more than 1,300 vehicles in a night-time light show, arranging the vehicles to spell out political slogans and icons.[9] The technology giant Intel achieved a similar feat with about 1,200 UAVs during the opening ceremony of the Pyeongchang Winter Olympics.[10]

Altiscope's architecture for UAS traffic management systems assumes that, once fully implemented, the vast majority of vehicles will operate in a "managed" environment. UTM service will issue instructions to resolve conflicts, reroute vehicles around bad weather or airspace restrictions, and deploy capacity management strategies to ensure safe airspace density. Vehicle self-separation therefore, would be limited to areas outside of UTM service coverage, since in routine operations, one or more UTM services should have already accomplished those tasks. Onboard detect-and-avoid (DAA) equipment would be a last-resort redundancy system to avoid an imminent collision, similar to the role of TCAS today.

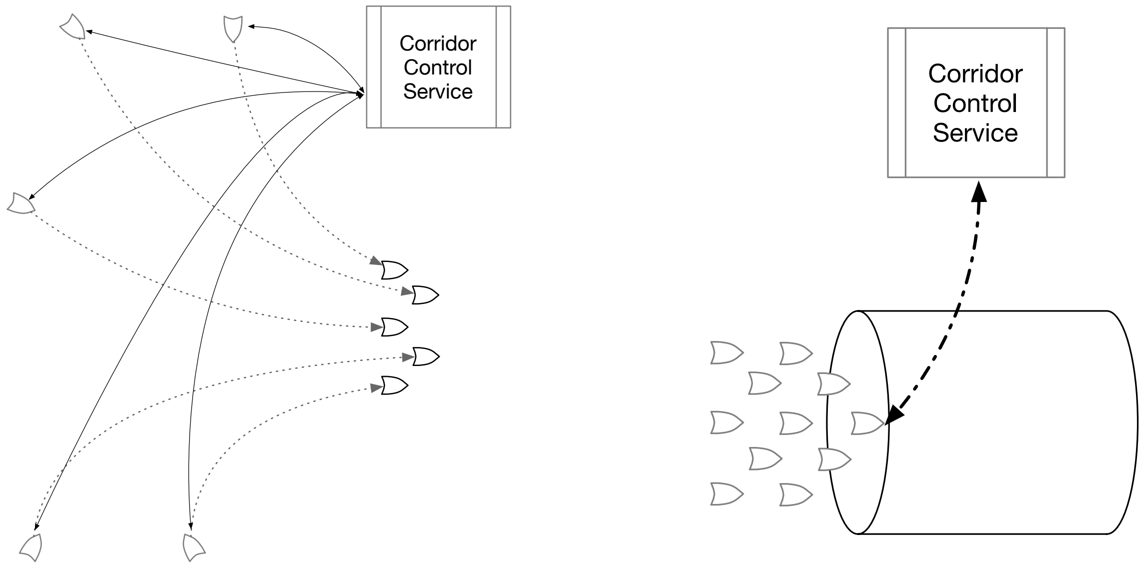

Figure 4. At left, the corridor control service communicates with each vehicle to assemble the flock, including traffic information about the other vehicles that will join the flock. The corridor control service also designates one vehicle as the "lead aircraft" of the flock. At right, once the flock has assembled, the corridor control service sends instructions only to the lead aircraft, which then relays necessary commands to other vehicles in the flock. The lead aircraft monitors vehicle positions within the flock.

It is an open question whether a UTM service would pass all instructions to a flock through a single lead vehicle (similar to how today's air traffic controllers handle formation flight), or whether a UTM service would continue to send instructions to each vehicle, playing some role in the flock's internal organization. For the sake of illustration simplicity, the scenarios in this section assume the former. In such a setting, all participating vehicles would need to meet the same communications and performance requirements, though exact hardware equipage may vary.

Airspace capacity will be a function of the required separation for all UAVs in a given volume. Therefore, the ability to have vehicles "flock" along similar route segments has the potential to greatly increase airspace capacity, especially if all vehicles within a flock are able to maintain spacing between each other that is a fraction of any other separation requirement.

Depending on the airspace needs and vehicle abilities, a flock may be created by a UTM service managing an area of particularly congested airspace as one way to effectively lower airspace density. We assume that, just as in today's air traffic system, a UTM service would treat a flock as a single vehicle, maintaining separation around that flock from other non-flocking vehicles, but not actively controlling spacing within the flock. In other instances, though, a single operator or group of operators may initiate the flock. For example, one company might use a flock of vehicles to inspect a bridge or to arrange all of their package delivery vehicles departing a warehouse headed in the same direction.

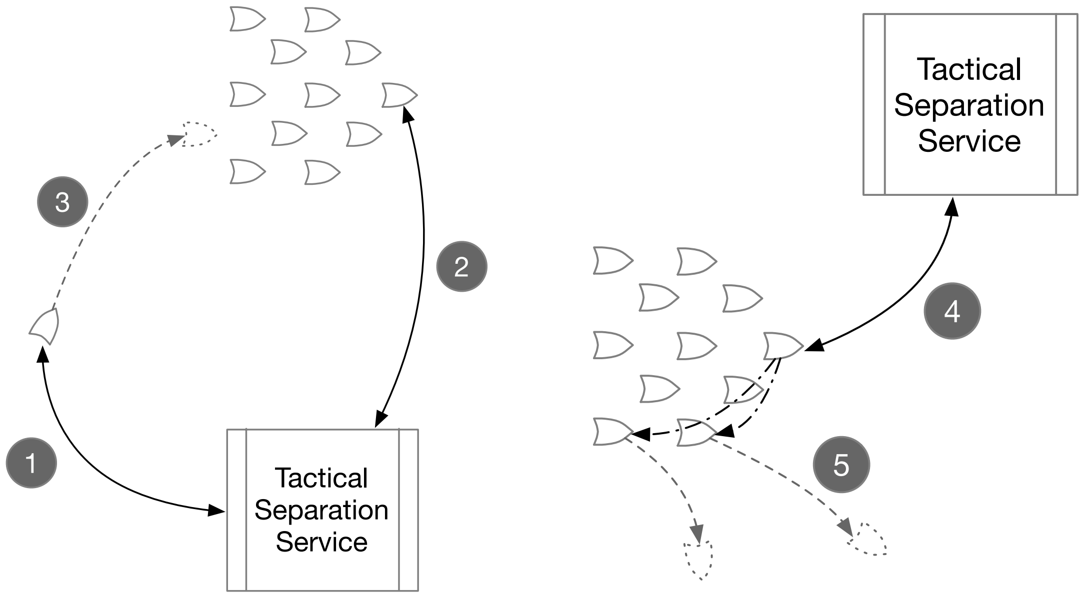

Figure 5. (1) The tactical separation service is tracking an existing flock and identifies a single vehicle that could benefit from joining that flock. (2) The service communicates information about the joining vehicle to the flock's lead aircraft. (3) The separation service gives the vehicle routing instructions to join the flock. (4) When vehicles need to leave the flock, the lead aircraft advises the separation service. (5) The aircraft leave the flock following breakaway instructions received from the lead aircraft and shared with the separation service.

Flocks may also be the most effective way to manage high-volume flights through defined UAV corridors, rather than metering each vehicle's discrete entry or exit time. A corridor control service may recognize an upcoming period of congestion that would exceed its maximum capacity. With access in advance to information about each vehicle's performance and route plans, it could proactively create a flock, sending instructions to each vehicle about its position in the flock and rallying point outside of the corridor to create the flock.

Flock shape and spacing between vehicles will be a function of the performance capabilities of each vehicle and any 4-D airspace constraints. A corridor may have specific lateral and vertical bounds in which a flock may be required to fit, or a capacity management service may require that an entire flock traverse over a waypoint within a given amount of time.

Assuming that UAVs would benefit from the same reduction in induced drag that flocking birds experience, then variations on delta or echelon formations would be most advantageous. Further study of downwash and rotor wake patterns is required to establish whether than principle would be effective in reducing aerodynamic drag. As Figure 5 illustrates, multiple delta formation elements slot easily behind one another, creating a fairly dense mass of vehicles. The predictability of the pattern should aid onboard sensors in positively identifying adjacent vehicles, since other vehicles would be arrayed in 45-degree increments around one's own vehicle.

Fixed-wing aircraft formations, particularly in military settings, fly very close together. We aim to achieve similar scales of spacing within UAV flocks, particularly when all aircraft are of a similar type or have similar performance envelopes. In that case, the offset spacing between two vehicles would ideally be as little as half the average width or wingspan of those vehicles. Tail-to-nose (or back-to-front) spacing would be that same distance to ensure as symmetric of a distribution of the flock as possible.

With a decentralized approach to managing the flock (that is, the designated "flock leader" receives UTM commands, coordinating with other vehicles within the flock), it's possible for complex flocks to operate effectively. Another nearby vehicle going in a similar direction could receive information about the passing flock and join it to take advantage of a premium scheduled slot time for a corridor it plans to use. Once exiting the corridor or dense airspace region, some vehicles might leave the flock for their destination, enabling the flock to optimize its arrangement.

5. Enabling Flocks with Visual Separation

The crucial element of formation flight today is that the pilots of each aircraft can see and communicate with each other. The previous section discussed, at a high level, use cases that rely on both V2V communications within a flock, and vehicle-to-UTM links to coordinate overall flock movement. A combination of V2V links and onboard sensors that are sensitive enough to properly identify other vehicles at a variety of distances and angles relative to a UAV in the middle of the flock will be necessary to meet something similar to today's visual separation requirements.

For the most part, including in military settings, formation flights are VFR (MARSA, or Military Assumes Responsibility for Separation of Aircraft, relieves the air traffic controller from IFR separation duties). Our proposed architecture brings the elements of formation flight into the realm of managed flight within a UTM, which has many parallels to IFR flight today.

Making this a reality requires taking the concepts of visual separation and stretching them to very new uses. Many vehicles, including off-the-shelf small UAVs available today, include a variety of obstacle detection sensors and onboard software algorithms to successfully navigate around objects in their path. Cameras and infrared sensors on some vehicles today can already detect objects like a person's hand, a tree or a power pole from 100 feet away. Given that aircraft in formation flight today are often much closer to one another than that, we may be closer than we think to the sensor system performance that will be required for flocking vehicles.

These same sensors, with changes to the algorithmic software processing, could be used to identify companion vehicles within a flock and relay commands to the vehicle's electronic speed controller to maintain the same relative position from each adjacent vehicle in the flock. Coupled with a robust V2V link so that each vehicle can verify the aircraft around them in a flock, these technologies, including future detect and avoid (DAA) equipment, may be the enabling functionality for autonomous visual separation.

Just as applying pilot-provided visual separation today requires use of prescribed phraseology on the part of both the pilot and the controller, we fully expect that initiation and breakup of flocks will require specific encoded messages between vehicles and UTM services so that all participants are aware of one another's intentions. This is critical for the UTM's other tactical separation responsibilities, since it must know which vehicles are in a flock (and therefore can be considered a single flight, just like aircraft formations today) and which require separation from the flock.

6. Next Steps for Flocking Research

Validating the concepts explored in this paper will require extensive simulation testing. The results of those future studies will help to define the performance standards required for flocking behavior. Starting with small flock sizes and simple arrangements, what process does a UTM service use to assemble the flock? This must include consideration of path planning that gets vehicles into the desired arrangement without conflicting with one another. Many pilots who fly formation today begin at offset altitudes (though less than IFR vertical separation minima), especially when joining in a slot position between two other aircraft. This enables a gentle climb or descent (dictated by cockpit visibility of the other aircraft) when aligning into the final position. Thus, we expect UTM services would take advantage of similar principles to safely assemble a flock.

Once assembled, what is the optimal spacing between vehicles? How much should the spacing vary depending on the type of vehicles in a flock or their range of performance characteristics? Answering these questions will require a suite of studies specifying a variety of target separation distances and vehicle performance assumptions, then collecting data on how closely vehicles conform to those target distances.

From an architecture and communications standpoint, what is the best way for a UTM service to communicate with vehicles already in a flock? Given that we expect these operations would occur using an as-yet-unspecified digital protocol, there may not be any computational or network penalty for the UTM to communicate with each vehicle in a flock. On the other hand, doing so most likely would mean the UTM would have responsibility for managing internal flock behavior (e.g. moving vehicle positions in anticipation of breaking up the flock). This is a more centralized approach than allowing the vehicles within the flock to decide on their optimum arrangement during flight.

Additionally, we will need to conduct further studies along the lines of TR-004 (Metrics to characterize dense airspace traffic) to determine whether flocks are an effective tool for managing airspace congestion. Do they only work in certain types of congestion, or within certain ranges of density? These results can help inform policy about when and where to encourage flocks.

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