ADAPTIVE AUTONOMOUS SEPARATION FOR UAM IN MIXED OPERATIONS

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Abstract

The excitement and promise generated by concepts for Urban Air Mobility (UAM) have inspired both new entrants and large aerospace companies throughout the world to invest 100s of millions in research and development of air vehicles, both piloted and unpiloted, to fulfill these dreams. The management and separation of all these new aircraft has received much less attention, however, and even though NASA’s lead is advancing some promising concepts for UAS (Unmanned Aircraft Systems) Traffic Management (UTM), most operations today are limited to line of sight or airspace reservation and geofencing of individual flights. Various schemes have been proposed to control this new traffic, some modeled after conventional air traffic control and some proposing fully automatic management, either from a ground-based entity or carried out on board among the vehicles themselves. Previous work has examined the very low altitude airspace within a metroplex in which piloted traffic is very rare. A management scheme was proposed taking advantage of the homogeneous nature of the traffic. This paper expands the concept to include all altitudes desired for eVTOL (electric Vertical Takeoff and Landing) urban and short, inter-city transportation. The interactions with piloted aircraft operating under both visual and instrument flight rules are analyzed, and the role of ATC provided services in the postulated mixed traffic environment is covered. Design separation values for each type of possible traffic encounter are derived and the relationship between required surveillance range and closure speed is given. Finally, realistic scenarios are presented illustrating how the concept can reliably handle the density and traffic mix that fully implemented and successful UAM operations would entail.

Introduction and Background

The development of electric and hybrid turbo/electric eVTOL vehicles by both large and small aerospace companies for UAM and short inter-city air taxi transportation is proceeding at a feverish pace. Demand projections for these services continue to predict a bonanza for those who might fill the need. This widely shared vision for new transportation services started with the success of battery powered hobby drones that have become very popular for surveillance recently. New battery technology, that has also created a resurgence of electric cars, might permit drones to be scaled up to perform real transportation missions for packages and even people in the metropolitan areas that frequently experience surface gridlock, resulting in long door to door transit times. Work on the vehicle side of this vision has, indeed, produced successes in the form of first flights carrying people by Airbus’ Vahana, Kitty Hawk Cora, Volocopter 2X, and Workhorse Surefly [7]. As expected, drones capable of carrying small packages have also performed proof of concept flights. While larger eVTOL and hybrid turbo/electric powered vehicles capable of carrying from one to four, and in a few cases six or more people, have flown in a piloted mode, the new air taxis still face hurdles of regulation, public acceptance and economic viability before a major implementation will be seen. Helicopters, after all, perform these services all over the world today, but these services are expanding very
slowly because of their high cost and noise (public acceptance) considerations.

The vehicles being designed by Boeing, Airbus and Bell have, in addition to their vertical takeoff and landing capability, the ability to transition to a higher speed, forward flight mode using lifting wings for greater efficiency. This is being done to serve the short to medium haul inter-city transportation market in addition to the UAM role. Certainly, this broadens the market demand for eVTOL transportation, but it also places these operations into airspace that directly interacts with all other flight operations, airline, General Aviation and military, both VFR (Visual Flight Rules) and IFR (Instrument Flight Rules). By contrast, small package delivery services using drones flying in and under the Class B metropolitan airspace below 500 feet enjoy a uniquely protected airspace nearly devoid of all other traffic. As described in a paper on Airborne Traffic Management (ABTM) for UAM [1] delivered at the 2018 AIAA Aviation conference, traffic management of these operations could be conducted locally, within the vehicles themselves, using existing technologies, new rules and procedures tailored for their operations. Sharing the broader airspace above 500 feet with piloted vehicles and centrally managed traffic control services presents a whole set of new challenges to overcome.

Virtually all the passenger carrying eVTOL manufacturers plan to begin operations with a human pilot on board, even though the vehicles are being designed for eventual autonomous flight. These human pilots can see and avoid other VFR traffic and interact with ATC (Air Traffic Control) the same as piloted helicopter flights today, but adding these to the helicopter corridors could easily overwhelm the ability of ATC to manage them. The numbers of these flights will be small for the same reason that the number of helicopter flights is small, cost. The cost to pay a pilot and the fact that the pilot accounts for one fourth to one sixth of the payload prohibits mass transportation using this model. If these flights are to make an impact on transportation as a whole, there must be a great many of them, probably two orders of magnitude greater than the number of conventional aircraft flying today. Putting this many aircraft into the existing air traffic control system would swamp it, and it would be unmanageable. If growth of eVTOL transportation was attempted making use of existing services, delays would mount as the traffic grew to the point where the service would first suffer, then become untenable as an alternative to surface transport. For that reason, an evolution to an alternative form of traffic management was proposed by a team at NASA and previously described in papers on Airborne Trajectory Management (ABTM) [2] and Autonomous Flight Rules (AFR) [3]. This paper expands upon the UAM concept to address the issues brought forth by high volumes of autonomous aircraft in mixed traffic airspace and shows how the ABTM and AFR paradigms could enable the realization of safe, high density autonomous operations alongside conventionally piloted and centrally controlled flights.

**Autonomous Flight in the NAS**

The word, “autonomy” has many connotations depending on the context and the scope of its application. When applied to flight, it is frequently equated with automation or automatic flight, as performed by an autopilot or “autoflight” system. Autopilots are capable of controlling aircraft in all phases of flight and may be programmed in varying degrees to keep the aircraft in stable flight, maneuver and navigate from one place to another and even land and stop on a designated runway. Except for the autoland mode, however, autopilots are not certified to be fail safe, but rely on a human pilot being able to take over and continue the flight safely in the event of failure or encountering unforeseen events. These aircraft are thus not autonomous in their ability to control and navigate the aircraft under all
circumstances. In the UAS world, even though a pilot is not in the vehicle, a remote pilot controls its flight and its mission. In previous work performed for NASA [4], the extent of the remote pilot’s involvement was described as “Pilot in the Loop”, “Pilot on the Loop” and “Pilot Operator as Manager” (PITL, POTL and POM). “In the loop” means the pilot is actively controlling the thrust and the aerodynamic surfaces of the vehicle to maintain its attitude and flight path. This is like flying a traditional radio-controlled model airplane. A pilot on the loop controls the autopilot in the same way as a pilot in an airplane using the Mode Control Panel and Flight Management System today. The degree of involvement is the same in programming and executing the flight trajectory through the autoflight system. The remote pilot “is engaged” and can take over in the event of failure either through direct use of the flight controls or by executing other means for safe termination of the flight. True autonomous flight control emerges in the third (POM) phase in which there is a “manager”, probably not a licensed pilot, who initiates flight operations that are programmed to accomplish the entire mission. The manager may subsequently alter or terminate a mission early but does not control the autoflight system in the manner of today’s piloted aircraft. Also, he is not capable of “taking over” in the event of onboard failures. These are handled autonomously by the vehicle using internal sensors, logic and safety systems.

Building upon the experience of 100 years of radio control hobbyists, the FAA recently created an initial set of rules for flying small drones that are contained in FAR (Federal Air Regulations) Part 107. The majority of civil UAV flights today use remote pilots for their control and employ vehicles weighing less than 55 pounds that are thus subject to the rules of FAR Part 107. These rules require the operator, or a visual observer, to keep the drone being controlled in sight and avoid presenting a collision hazard to other aircraft or endangering the life or property of another. Other specific limitations include no flight at night, over people, more than 400 feet above the ground or within five miles of an airport without ATC approval. Waivers to these limitations may be requested, reviewed and approved by the FAA on an individual basis. Of these limitations, the most onerous is the prohibition of flight near airports, since that is where most people live and would like to fly. Because of this, the FAA has established automated approval procedures called LAANC, for Low Altitude Authorization and Notification Capability. A drone operator can use an app to request an instant approval to operate within five miles of an airport through one of fourteen third party services over the internet and receive approval within seconds if the requested airspace is available. These flights are also mostly using POTL, meaning the flights are auto-stabilized and navigated using GPS (Global Positioning System) to fly to specified locations and maintain commanded heights.

Operations of larger unmanned vehicles beyond visual line of sight and in clouds are often approved with an exemption under section 333 of Public Law 112-95. Part 107 rules are not applicable to these flights. IFR high altitude missions are flown by a remote pilot in a sophisticated Ground Control Station controlling the vehicle primarily in the POTL mode and interacting with ATC as though he were in the vehicle. These flights generally climb to the positive controlled airspace above FL180 while within restricted airspace to avoid interaction with VFR flights not in contact with ATC. The number of these UAS flights is small enough not to place undue burden on the ATC system. While these flights are generally controlled in the POTL mode, they may be flown in the PITL mode if desired or under certain failure conditions.

Autonomous flights of UAS vehicles in which the operator plans and originates the flight but otherwise only monitors its progress (POM) require the waivers for flight beyond visual line of sight (BVLOS) and, depending on the mission, flight at night and over people. This
mode of operation is ultimately sought by all manufacturers of eVTOLs for UAM as the economics of the operation will demand it. Feverish activity is underway today teaming the FAA and manufacturers to create the necessary rules for certification of these vehicles to provide the requisite safety. Current regulations for certifying airplanes and helicopters are inadequate for the new vehicle lift and thrust configurations and for some of their intended operations, including autonomous flight. The level of automation inherent in these vehicles goes well beyond current autopilots to include the entire flight spectrum from liftoff to touchdown, trajectory optimization, hazard avoidance and flight anomaly mitigation, separation from other aircraft and participation in surface operation management. All of this must be provided with redundancy and other contingent measures for all known and anticipated system failures.

While autonomous flight control of unpiloted vehicles has been experimentally demonstrated, it is not expected to be commonplace for several years. Autonomous flight in the air traffic system presents an entirely different set of issues, however. Even the most advanced UAVs flying IFR beyond line of sight at virtually any altitude still require the remote pilot to be in continuous contact with the ATC facility having jurisdiction over the airspace in which that flight is operating. UAS to controller communications do not yet exist without the remote human pilot intermediary. It could be envisioned in the future datacom world that vehicle automation to controller communication would be possible, but then the air traffic controller would become the de facto remote pilot with its attendant responsibilities and liability. The controller would also be limited by not knowing the mission other than the flight plan intent, which the manager might want to alter from time to time. Also, the controller would not have the efficiency motivation of the operator when determining and altering intent during flight. Therefore, while autonomous flight has been demonstrated experimentally and VFR offers a form of ATC autonomy, the two concepts must be merged in a fashion that supports the economic operations of eVTOLs while not burdening ATC.

**Autonomy in Air Traffic Control**

Air Traffic Control services, as they exist in the world today, are a complex mix of hardware, automation systems and procedures enabling human controllers to maintain safe separation among most of the aircraft in their defined sectors of airspace. The term *most of the aircraft* is used because in Class G and most Class E airspace, VFR flights are permitted to operate without participating in any air traffic services and often without the knowledge of ATC. The pilots of such flights are responsible for their own separation using “see and be seen” principles, standard right of way rules, and at non-towered airports, standard flight patterns and direct pilot to pilot communications on the Common Traffic Advisory Frequency (CTAF). These VFR flights employ a form of autonomy that has existed during the entire 115 years of powered flight. It is dependent, however, on pilots being present in the aircraft and vigilant for other nearby traffic. In Instrument Meteorological Conditions, (IMC) this form of separation cannot work because of the lack of visibility and is not permitted. One exception to this is the military flight formation that is maintained visually by the pilots, often even in clouds, but the entire formation is separated by ATC as a single entity from other aircraft. In the world of high volume, dense UAS traffic, other systems must perform this separation function independent of ATC and do it more reliably than is possible using human vision.

While this paper focuses on autonomous separation, it is recognized that ATC provides both a separation function and a Traffic Flow Management (TFM) function. The latter is used to prevent traffic density from
becoming unmanageable by a human controller and to deliver a stream of aircraft to a runway at a prescribed rate. This is a function mostly applied to airline aircraft using busy metropolitan airports and is not the focus of this paper. Separation itself is a complex subject that has received a great deal of attention over the years. For example, separation was studied in depth for decades by the ICAO (International Civil Aviation Organization) RGCSP (Review of the General Concept of Separation Panel) and the author was a founding member of that panel, representing the International Federation of Airline Pilot’s Associations (IFALPA). Rational determination of separation minima in environments both with and without surveillance was sought. The process was very heavy on data gathering, calculating mathematical and statistical risk probabilities and attempting to reach an agreement on an “acceptable level of risk”. One example of the difficulty of changing historical separation criteria is the reduction from 2000 to 1000 foot vertical separation above FL290. This reduction, called RVSM for Reduced Vertical Separation Minimum, took 32 years to accomplish from the first serious efforts until it was finally implemented in the North Atlantic.

The separation function as performed by ATC is a four-step control process that can be described as 1) Measurement, 2) Prediction, 3) Control and 4) Feedback. Separation is said to be strategic if it is based on flights navigating along non-intersecting paths or time separation at fixed merge points. Strategic separation generally does not include direct surveillance but depends upon position reporting from the controlled aircraft. Tactical control presumes near real time surveillance. Controllers use a radar and ADS-B (Automatic Dependent Surveillance - Broadcast) fed display of aircraft in their sectors to locate the aircraft and measure their dynamic interactions. When standard separation is predicted to be lost (determined either mentally or using conflict prediction software), they issue control instructions to one or more of the pilots to alter their flight trajectories in a manner that resolves the predicted conflict. They then receive acknowledgement by radio and monitor the situation to ensure that the commanded action is taking place as planned.

The separation process is performed this way by human controllers in air traffic control facilities throughout the world. However, it is possible to perform the same function automatically using surveillance and automation systems within the aircraft themselves. This automated separation process is described in a NASA Technical Paper (TP) on AFR [3]. Self-separation under AFR relies on ADS-B IN surveillance and Conflict Detection and Resolution (CD&R) algorithms embedded in flight guidance software. The concept was validated by NASA in several fast time and piloted simulations [5]. A follow-on roadmap for facilitating the implementation of AFR was described in a paper on ABTM [2] presenting a series of five steps of increasing capability bridging from the use of an in-flight trajectory optimization algorithm in the TASAR (Traffic Aware Strategic Aircraft Routing) concept’s use of TAP (Traffic Aware Planner) software, through a series of NextGen (Next Generation Air Traffic Control System) and aircraft system improvements, ultimately to AFR, at which time participating aircraft could optimize their flight trajectories while separating themselves from all other traffic in the airspace, both VFR and IFR. The AFR concept for traffic separation was applied to UAM flight operations in reference [1], where it was shown how urban UAVs could separate themselves while flying within 400 feet of the surface where most piloted aircraft do not operate. In reference [1], a new concept for separating passenger carrying drones was introduced using a maximum angular velocity parameter to define minimum lateral separation between a pair of aircraft in conflict, to prevent the appearance of a collision hazard. The symbol wosep is used in this paper to indicate the use of
angular velocity to derive the adaptive, minimum design separation value.

Self-separation in the airspace above 400 feet involves interactions with piloted aircraft and many have proposed or assumed the involvement of traditional ATC in these separation encounters as a result. However, the sheer volume of traffic envisioned in UAM makes this assumption impractical at best, and impossible once the numbers of eVTOLs begins to surpass traditional aircraft. Once it is accepted that separation among UAM aircraft must be automated, two choices emerge regarding separation of UAM aircraft from conventional piloted aircraft in mixed operations airspace, one that the automation be centralized physically and with the placement of authority and responsibility within a body such as the FAA or a third party provider approved by the FAA to provide this function, and the other in which the separation automation is distributed among all the vehicles and responsibility for separation is placed with the operators of each of the vehicles. This choice can be said to be between a global versus a local separation solution. The following arguments favor the local, distributed solution.

As stated above, any separation system requires some form of surveillance, communications, and control. Centralized surveillance relies on communication being maintained with all vehicles at all times from the central location. This can be extremely difficult in an urban environment due to presence of many tall buildings shielding electronic signals. Distributing the surveillance and communications to the vehicles themselves ensures that those aircraft in close enough proximity to be in conflict will also have short range, usually direct line of sight, communications available. The use of ADS-B IN, or any active surveillance system risks frequency saturation if the transmissions are at high enough power to be received at a remote centralized location. The local solution permits the use of low power surveillance transmissions. An additional argument comes from the failure analysis. In a centralized control system, any single point of failure in the communications, surveillance or automation equipment performing the CD&R function will cause a failure of separation service and some of the possible failure modes would disrupt the service for the whole service area. There are many examples of this having taken place within our current ATC system [7] [8]. Conversely, placing the separation capability within the aircraft using redundant equipment guarantees no failure will impact the entire operation and even in an individual conflict, either aircraft in the conflict pair can ensure a safe outcome in the presence of a failure on the other. Finally, individual responsibility for safety eliminates the need for major infrastructure development and acquisition by the government and greatly limits its liability. This approach will speed the approval and implementation of eVTOL services in the NAS.

Notional Design Requirements

The rest of this paper assumes the distributed separation approach to eVTOL operations in mixed, autonomous and piloted vehicle airspace in Class B, C, D, E, and G operations. It is assumed that eVTOLs will not operate above FL 180 and thus not in the Class A airspace. Separation encounters among five classes of vehicles are considered as follows:

1. **UAV<sub>C</sub>** is a cargo, small package or surveillance eVTOL vehicle with no humans aboard
2. **UAV<sub>P</sub>** is a passenger carrying autonomous eVTOL
3. **AC<sub>V</sub>** is a piloted aircraft operating under Visual Flight Rules (VFR)
4. **AC<sub>I</sub>** is a piloted aircraft operating under Instrument Flight Rules (IFR)
5. **AC<sub>A</sub>** is a piloted aircraft operating under Autonomous Flight Rules (AFR)

Each class of aircraft will be considered with respect to the separation values and rules applied
with every other class since all may be encountered in the subject airspace.

Both classes of UAV, whether carrying humans or not, are presumed to operate using Autonomous Flight Rules. Whether used by pilots of manned flights or embedded in software controlling autonomous flights, the operating principles of the proposed new flight rules called AFR are the same. Using on board surveillance, CD&R algorithms detect traffic conflicts and resolve them using standard rules for priority and applied separation distances. The objective of AFR is to provide the maximum freedom of action in managing the flight’s trajectory so ATC is kept advised of the AFR flight’s intent but is not responsible for its safety in any way. In order to prevent controllers from having to consider the AFR traffic, IFR traffic is given right of way in every AFR/IFR encounter. Autonomous vehicles using AFR are thus known to ATC but not subject to ATC control. Using autonomous separation, rather than providing flight guidance to the pilot to resolve traffic conflicts, the CD&R output directly controls the flight path of the UAV.

Both classes of UAVs are unpiloted and provide self-separation among themselves following standard right of way rules. They also provide separation between themselves and every other class of aircraft giving those aircraft right of way in all situations. The design separation values do vary, however, adapting to the specific class of aircraft they encounter as shown in Table 1. UAV_C to UAV_P encounters use the smallest design separation value possible given that they will have the tightest control loop parameters for surveillance, computation and control. Notionally, the design separation could be as low as 50 feet both laterally and vertically [1]. UAV_C to UAV_P encounters run the risk of startling and causing anxiety in the UAV_P passengers if the encounter has both high closure speed and small design separation, so the \( \omega_{\text{sep}} \) variable separation algorithm is used to limit the angular velocity at passing to an acceptable value (e.g. 1 radian/second). The same is true for

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**Note:** Wake separation criteria would increase these values when applicable.
L = Design lateral separation
V = Design vertical separation
S = Design longitudinal or slow closure separation
UAV\(_F\) to UAV\(_P\) encounters. Either UAV to AC\(_V\) recognizes the current practice among VFR aircraft of “remaining well clear” and translates that to UAS MOPS (Minimum Operational Performance Specifications) values of 35 seconds \(\tau\) or 4000 feet lateral, and 450 feet vertical in these encounters [6]. A very rigorous mathematical and analytical process was conducted to establish an engineering equivalent to “well Clear” VFR separation for use in the MOPS [9]. But if the surveillance and aircraft control are “perfect”, the controlling parameter for separation is the perception of hazard by the passengers during aircraft passage. Table 1 presents notional values for all combinations of aircraft encounters that should be validated through Human in the Loop simulations and flight test.

The principle of “least disruption” is a key component of this concept for UAM air traffic management. In the context of separation from conventional piloted traffic, this means that the new eVTOL operations will provide the same separation values with piloted aircraft used in the piloted aircraft’s respective flight rules so that those rules do not have to be changed to accommodate AFR. Least disruption for the eVTOL operators favors unrestricted choice in selecting the flight trajectory in exchange for giving right of way to IFR flights in all encounters. This permits optimized flight between “skyports” rather than some form of segregated flyways or any use of dedicated airspace. It also permits controllers to continue to manage their traffic in the Class B, C, D, and E airspace without change to their procedures or any regard for the thousands of UAM flights taking place around them without interference.

Also, UAM flights will not require change to the regulatory 200 knot speed limit below 2,500 feet AGL within 4NM of a Class C or D airport and beneath the Class B airspace. In all other airspace below 10,000 feet MSL, the 250 knot limit still applies. These speeds are important as they help define the required airborne surveillance range for the eVTOLs as will be shown below. The rules that require being in communication with ATC in Class C and D airspace and on a clearance when in Class B airspace would be covered by the AFR rules providing position and intent to ATC in these, and all airspaces. Access to the primary airports in these classes of airspace would be non-interfering to and from the side of the runways, as covered in Ref [1].

Surveillance for the eVTOLs can be easily satisfied in the Class B airspace because of the required transponder and ADS-B (as of January 1, 2020) equipment. ADS-B IN and low power active TCAS (Traffic Alert and Collision Avoidance System) interrogations on the eVTOLs would provide redundant sources of surveillance data for both separation and collision avoidance. In Class G and Class E airspace below 10,000 feet, surveillance is complicated by the fact that cooperative surveillance equipment is not required. Either an active radar system, an electro-optical sensor or both are needed to provide surveillance data to the UAVs to detect and avoid non-cooperating VFR traffic legally flying in this airspace. Since VFR requires 3 miles visibility in the Class E airspace and none of the non-cooperative targets are very fast, vision systems should be sufficient for this purpose. In the Class G airspace, only 1 mile visibility is required, so late detection using visual means alone might not support the separation values for VFR traffic in Table 1 when in Class G. Technically, transponders and ADS-B equipment are not required for IFR flight in Class G and E airspace either, but as a practical matter, there are almost no aircraft in the US certified for IFR that do not carry this equipment. ATC could keep an IFR flight with a transponder failure separated from all other IFR and AFR traffic, because this is such a rare event.

Communication equipment on autonomous eVTOL aircraft must serve three purposes; 1. providing mission status and top level “control” to the operator; 2. providing state and intent information (the Flight Object) to
ATC; and 3. coordinating with other aircraft during collision avoidance. The first of these communications may take many forms and is between the operator and the FCC (Federal Communications Commission) to establish and approve. Providing the Flight Object to ATC should be accomplished using established Data Comm protocols once the FAA’s equipment is operational but may be done using airborne SWIM (System Wide Information Management) in the interim. For the coordination cross link, up to now, only self-separation using design separation values and implicit coordination has been discussed, but AFR also includes a collision avoidance function that would use the TCAS crosslink standards.

As presented in Ref [1], all separation performed to the design separation values listed in Table 1 use the principle of implicit coordination in the tactical separation algorithms. Inferred intent is also used in the tactical separation algorithms for AFR. These make it possible to resolve a separation conflict without communications between the aircraft in conflict. Using existing right of way rules and “state-based trajectory prediction“, the aircraft burdened to resolve a conflict can do so with high confidence in the success of the outcome, namely, that design separation will be achieved at the closest point of approach (CPA). If the burdened aircraft does not maneuver or the maneuver is predicted to be insufficient, the unburdened aircraft, if it is also operating under AFR, will also maneuver to achieve the design separation. If design separation is still not being achieved or if the conflict is with a VFR or IFR aircraft, a loss of design separation will activate the collision avoidance logic in the AFR aircraft, and any TCAS-equipped VFR or IFR aircraft, using the existing coordination crosslink on the 1090 MHz frequency to ensure compatible resolution maneuvers. If the VFR or IFR aircraft are not equipped with TCAS, the logic assumes they will continue what they are doing and maneuver the AFR accordingly. The communication link for sending ownship intent information to ATC could be used to receive intent information on IFR aircraft that are being tracked by the airborne surveillance, if this service was provided by FAA, similar to ADS-R (Automatic Dependent Surveillance – Rebroadcast). This intent data could be used in the separation logic to filter out some conflicts that the intent shows will not occur, particularly during vertical maneuvering.

Relationship Between Required Surveillance and Design Separation Value

Surveillance and tracking of aircraft are challenging electronically and computationally so it is important not to have to provide these functions at greater distances or include larger numbers of aircraft than necessary for the separation function. What is required is to detect and track any aircraft with enough time to predict the miss distance and direction at the closest point of approach and, if in conflict, be able to maneuver to achieve the design separation value by that time (CPA) using a “standard” resolution maneuver. This “just in time” separation philosophy provides for the greatest possible use of the airspace by all aircraft classes. It works because the AFR aircraft have the entire separation and collision avoidance control loops in the automation and no time need be allotted for human recognition and action. In other words, the resolution maneuver will begin when it becomes necessary to achieve design separation. The standard resolution maneuvers include vertical accelerations, lateral roll rates and bank angles and longitudinal accelerations that do not unduly alarm passengers during conflict resolution. TCAS, which only resolves vertically, is limited to a $\frac{1}{4}$ G acceleration when modeling the resolution and provides a good starting point for research into resolution maneuver acceptability. The vertical and horizontal speeds used in the resolution models must also be within the aircraft’s performance capability.
Two examples will be used to illustrate the relationships among required surveillance, class of aircraft and applied design separation. In the first, two package carrying drones, each weighing less than 55 pounds and flying low at 60 knots, are in conflict. In the worst case scenario, they are pointed directly at each other at the same altitude such that the calculated miss distance is zero. The closure speed is 120 knots, and the right of way rules require that each alter course to the right. The design separation in this case is 50 feet so each must displace to the right 25 feet by the time they pass. The packages tolerate larger acceleration than humans, and so a nearly instantaneous 45 degree bank to the right produces 1.4 Gs to the right. The needed displacement can thus be achieved in just over one second. At the closure speed of 120 knots (203 feet per second), the presumed two seconds to establish a track and compute that a conflict exists plus one second resolution suggests that the conflict could be detected and resolved when the two vehicles are approximately 650 feet apart at the start and achieve at least 50 feet apart after maneuvering onto their safe headings.

In a second example, a UAV_P at 4000 feet flying 150 knots finds itself head on with an arriving Southwest 737 at the same altitude flying at 250 knots. Here, IFR separation applies and since the airliner has right of way, the UAV_P must create 1000 foot vertical or three miles of lateral separation using a maneuver that does not alarm the passengers. The disproportionate shape of IFR protected airspace (see Figure 1) strongly favors the use of a vertical resolution when starting from the center of the protected space. This illustration, while not exactly to scale (the VFR and UAV_C protected airspaces are slightly larger than scale), is intended to convey understanding of the impact of applying our traditional separation values for IFR and VFR operations. Thus, in this example, it is only necessary to move 1000 feet vertically rather than more than 18,000 feet horizontally. Using the same relationship as above, the needed surveillance range in this encounter is:

\[ R_S = V_R(T_D + T_R) \]

where \( R_S \) is the needed surveillance range;

\( V_R \) is the relative velocity;

\( T_D \) is the time to detect that a conflict exists, calculate the time to CPA and the direction and magnitude of the miss distance at CPA and model the resolution; and

\( T_R \) is the time to maneuver and resolve the conflict.

In the current example, the UAV can climb or descend at 1000 fpm comfortably so the time to resolve is just over 60 seconds. The time to detect is the same 2 seconds for a total of 62 seconds. At the closing speed of 400 knots, the needed surveillance range in this example is 675 fps times 62 sec equals 41,850 ft or 6.9 NM. It should be noted that the CD&R surveillance and computation system on these autonomous vehicles can be simplified by using a variable surveillance range that roughly corresponds to the maximum relative velocities that will be encountered in the airspace, thus limiting the number of aircraft that must be tracked at any given time. The 200 knot speed limit exists at the lowest altitude followed by the 250 knot limit below 10,000 feet to unlimited speed above 10. Traffic densities also decrease with

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Figure 1. The Shapes of Protected Airspace
increasing altitude, so that when the longer range surveillance is required, the lower traffic density still limits the number of aircraft that must be tracked.

Three aspects that characterize the eVTOL autonomous separation solution are variable surveillance range and tailored design separation values to match the traffic environment, the specific aircraft type, and the operating rules being used by the traffic aircraft in the conflict. Since the navigation system knows the altitude and the class of airspace being traversed, it is possible to know the maximum speed of any traffic that will be encountered in the airspace. That maximum speed, coupled with the speed of ownship, determines the necessary surveillance range as illustrated above. This limits the number of aircraft that must be tracked by ownship surveillance. Knowing the type and the operating rules (VFR, IFR or AFR) of the other aircraft determines the design separation value that must be used in the resolution of any detected conflict. The calculated miss distance used in conjunction with the protected airspace appropriate to the conflict determines both the resolution maneuver that will be used and the time to begin that maneuver.

Collision avoidance logic takes over whenever the unfolding trajectories during the conflict resolution differ from what was modeled by a chosen value in the unconservative direction. At this point, three things change. The resolution logic attempts to increase the calculated separation at the CPA without regard to the protected airspace volume or direction of the maneuver. The second change is that the speed and acceleration imposed by the maneuver is increased and the direction is determined by remaining performance capability (what direction will produce the greatest miss distance). The third change is the addition of explicit coordination with the traffic aircraft if it is equipped with TCAS or is operating under AFR. This coordination ensures that any maneuver by the traffic aircraft will be compatible with that of ownship. There is no change proposed to the surveillance means aboard the aircraft, but the update rate should be increased to the maximum capability to improve the trajectory modeling, and the range reduced to more clearly focus on the impending collision situation.

Conclusion

Autonomous Flight Rules are well suited to managing very large volumes of dense traffic where mixed VFR, IFR and AFR traffic are operating simultaneously. As described here for UAM use in autonomous eVTOL aircraft, the separation logic will directly control the flight guidance system, removing any delay normally associated with human response times present in the conventional air traffic control loop. Even with the rather large separation standards used among IFR flights, this method was shown to permit adherence to these standards within the parameters of the tactical separation algorithms. AFR, by using the principles of inferred intent and implicit coordination, is capable of tactically resolving any conflict that may occur in the mixed airspace. No special lanes, routes or segregated airspace of any kind need be established, thus providing the maximum freedom of operation for all airspace users. This freedom ensures the ability of all operators to optimize their flights in all flight regimes for maximum efficiency or some other individual objective.

It is suggested that further research be conducted to build upon the work by NASA’s Langley facility on tactical airborne separation algorithms following the principles outlined in this paper. The values chosen for design separation in each circumstance should be experimentally verified for their operational acceptability, and the maneuvering capability of specific eVTOL types in development should be used to validate the separation algorithms themselves. Some of this work can be performed
in simulation and some parts will need to be done on manned experimental flights to evaluate the subjective acceptability of the chosen values for design separation, maximum angular velocity, and separation maneuvering rates. The development of combined solid-state airborne radar and electro-optical sensing for visual surveillance of non-cooperative targets must be accelerated to enable routine use of the Class G and E airspace by autonomous vehicles without impacting the VFR flights that currently dominate this airspace. The use of experimental manned flights in light aircraft during VMC can facilitate the research and development of both the necessary surveillance systems and validate the AFR tactical separation logic at the same time. That will assist in achieving the low cost, weight and power requirements necessary for this concept to be economically viable on eVTOLs.

References


