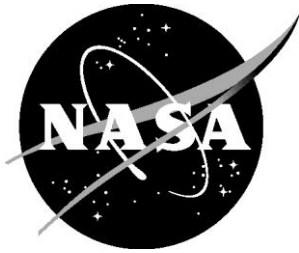


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Adaptive Airborne Separation to Enable UAM Autonomy in Mixed Airspace

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January 2020

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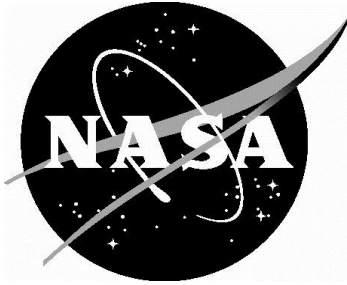
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Abstract

The excitement and promise generated by Urban Air Mobility (UAM) concepts have inspired both new entrants and large aerospace companies throughout the world to invest hundreds 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 have received much less attention, however, and even though NASA's lead is advancing some promising concepts for Unmanned Aircraft Systems (UAS) Traffic Management (UTM), most operations today are limited to line of sight with the vehicle, 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 vehicle-based traffic management in the very low altitude airspace within a metroplex called UTM airspace in which piloted traffic is rare. A management scheme was proposed in that work that takes advantage of the homogeneous nature of the traffic operating in UTM airspace. This paper expands that concept to include a traffic management plan usable at all altitudes desired for electric Vertical Takeoff and Landing urban and short-distance, inter-city transportation. The interactions with piloted aircraft operating under both visual and instrument flight rules are analyzed, and the role of Air Traffic Control services in the postulated mixed traffic environment is covered. Separation values that adapt to each type of traffic encounter are proposed, and the relationship between required airborne surveillance range and closure speed is given. Finally, realistic scenarios are presented illustrating how this concept can reliably handle the density and traffic mix that fully implemented and successful UAM operations would entail.

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1. Introduction

The development of electric and hybrid turbo/electric Vertical Takeoff and Landing (eVTOL) vehicles by both large and small aerospace companies for Urban Air Mobility (UAM) and short inter-city air taxi transportation is proceeding at a feverish pace. New battery technology, that has also created a resurgence of electric cars, is being adapted to drones for operators hoping to perform real transportation missions for packages and even people in metropolitan areas that frequently experience surface gridlock, resulting in long door-to-door transit times. Work on the vehicle side of this vision has progressed rapidly, with experimental first flights carrying people in Airbus' Vahana, Kitty Hawk Cora, Volocopter 2X, and Workhorse Surefly [1][2]. Drones capable of surveillance missions and carrying small packages have also performed proof-of-concept flights. On August 2, 2019, the first drone flight approved by the Federal Aviation Administration (FAA) for Beyond Visual Line of Sight (BVLOS) operations took place as a pipeline inspection outside of Fairbanks, Alaska. Larger eVTOL and hybrid turbo/electric powered vehicles capable of carrying from one to six or more people are being designed and some have been test-flown in a piloted mode, but 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 helicopter services perform a very small part of urban transportation and are expanding very slowly because of their high cost and noise (i.e., public acceptance) considerations.

Traffic management of the new drones has been developing along a separate track. NASA has been instrumental in providing both a forum for government/industry cooperative development and by sponsoring local trials of Unmanned Aircraft Systems (UAS) Traffic Management (UTM) procedures. UTM is defined by increasingly complex Technical Capability Levels (TCL) permitting drone operators to reserve airspace for their missions in controlled airspace using third party applications on their smartphones. These third party UAS Service Suppliers (USS) have received FAA approval to use their software to ensure deconfliction of various drone operations in proximate airspace, thus avoiding the former, lengthy approval process that involved direct application to the FAA for each flight. UTM is not designed to handle large numbers of vehicles. In the recent TCL-4 trials in Reno, NV, five live vehicles and fifteen simulated drones were considered high density.

UTM is also only applicable in the airspace 400 feet Above Ground Level (AGL) and below where small (less than 55 pound) drones operating under Federal Aviation Regulation (FAR) Part 107 rules are used for photography, future small package delivery and hobby use. UAM calls for heavier vehicles carrying one or more human occupants flying at higher altitudes and among much greater numbers of vehicles than are using UTM procedures today. As their numbers grow, it will be increasingly impractical to separate these operations using airspace reservation procedures while still meeting the demand, and there will therefore be an incentive for the vehicles to separate themselves, freeing up significant volumes of airspace they plan to use on their missions.

Separation of UAM vehicles is commonly compared to the existing Air Traffic Control (ATC) system, in place for piloted flights, but that paradigm is fraught with difficulties when applied to UAM. Surveillance and communication are hampered by a myriad of obstacles blocking transmissions, creating multi-path errors and hazards to navigation itself. The projected number of users needing separation service is expected to be well beyond the capacities of Automatic Dependent Surveillance Broadcast (ADS-B) and conventional radar beacon surveillance. The use of flight plans and pre-authorizations for flight is not compatible with the unfettered use of millions of vehicles. The Adaptive Airborne Separation concept proposed in this paper applies principles of Airborne Trajectory Management (ABTM) and Autonomous

Flight Rules (AFR) [3][4][5] to ensure safety in flight and for persons and property on the ground. The concept is designed to accommodate realities of the UAM vision that, in the long term, make it unsuited for either the UTM paradigm or an extension of the existing ATC-based Air Traffic Management (ATM) system.

For UAM to be a major component of urban mobility and to be both economically viable and operationally practical, autonomy must be pursued now for all aspects of drone and air taxi flights. Adaptive Airborne Separation addresses the traffic management aspect of autonomy within a framework of approved rules and procedures.

2. Background

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. Operators of these vehicles and the air taxis propose to use altitudes that place them in airspace that directly interacts with all other flight operations, including airline, General Aviation and military, using both Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). By contrast, small package delivery services using drones flying in and under the Class B metropolitan airspace below 500 feet AGL enjoy a uniquely protected airspace nearly devoid of all other conventional traffic.

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 the same as piloted helicopter flights today. However, adding these aircraft to the mix in Class B and C airspace could easily overwhelm the ability of ATC to manage them. 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. If the number of drones in the Dallas/Fort Worth metroplex were just one percent of the number of cars, there would be 50,000 of them. Putting this many aircraft into the existing ATC system would overwhelm it, making it unmanageable. If growth of eVTOL transportation was attempted by making use of existing ATC 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. Additionally, as long as they are piloted, the numbers of these flights will be small for the same reason that the number of helicopter flights is small: direct operating cost. The cost to pay a pilot and the fact that the pilot accounts for one-half to one-sixth of the payload prohibits profitable mass transportation using this model.

For that reason, an evolution to an alternative form of traffic management was proposed in papers on ABTM [4] and AFR [5]. ABTM is an evolutionary, stepwise concept for automating aircraft trajectory optimization in the presence of hazardous weather, all other traffic and restrictions in the airspace. Originally designed for use in airline aircraft, the first step in the ABTM Roadmap, known as Traffic Aware Strategic Aircrew Requests (TASAR), has already been tested in operational use on one airline and is being pursued for adoption by multiple airlines [6]. Succeeding steps in the ABTM Roadmap introduce data communications to the request/reclearance, adding the speed and time dimension and integration with traffic flow management (TFM) to the optimization logic, automatic approvals of the trajectory change requests and finally, full airborne separation in mixed traffic rules airspace.

That final step in the ABTM Roadmap is enabled by AFR. When operating under AFR, air-to-air surveillance supports the use of approved separation logic in the aircraft that provides flight guidance to either a human pilot or autopilot to ensure safe and legal separation. Current intent information is

continuously provided to ATC for situational awareness. AFR flights give right of way to both IFR and VFR piloted flights, and thus ATC is not adversely impacted with new responsibilities for the safety of any AFR or IFR flight [7].

As described in [3], traffic management of the operations in UTM airspace could be conducted locally using AFR, within the vehicles themselves, by adapting existing technologies and implementing appropriate rules and procedures tailored for their operations. That concept appears in summary in section 4 of this paper. The use of AFR also enables non-interfering UAM flights in the ATM airspace above 500 feet AGL. Sharing the broader airspace above 500 feet with piloted vehicles and centrally managed traffic control services presents a new set of challenges to overcome. For instance, there are multiple classes of both piloted and unpiloted vehicles, and there is the simultaneous use of three sets of flight rules. Traffic encounters may occur between any combination of vehicle and flight rule types and all must be appropriately handled. Those operational interactions are the central focus of Adaptive Airborne Separation, explained in section 5, and notional separation criteria for each type of traffic encounter are presented.

This paper expands upon the UAM concept to address the issues brought forth by high volumes of autonomous aircraft in mixed traffic airspace (ATM 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.

3. UAS Autonomy in the National Airspace System

“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 programed in varying degrees to stabilize the aircraft’s attitude, maneuver and navigate from one place to another and even land and stop on a designated spot. Except for the autoland mode, however, autopilots in airplanes are not certified to be fail safe, but instead, rely on a human pilot 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 independently control and navigate the aircraft under all circumstances.

In the UAS world today, even though a pilot is not in the vehicle, a remote pilot controls its flight and its mission. In previous work [8], the extent of the remote pilot’s involvement was described as “Pilot in the Loop” (PITL), “Pilot on the Loop” (POTL), and “Pilot Operator as Manager” (POM). PITL means the pilot is actively controlling the thrust and aerodynamic surfaces of the vehicle to maintain its attitude and flight path, such as flying a traditional radio-controlled model airplane. In POTL, a pilot controls an autopilot in the vehicle much as a pilot in a modern commercial transport using the autoflight Mode Control Panel and Flight Management System today. In POTL with remote pilots, 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 POM in which there is a flight operations manager, probably not a licensed pilot, who initiates flight operations (even many flights simultaneously) 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 control of the aircraft in the event of onboard failures. These must be handled “autonomously” by the vehicle using internal sensors, logic and safety systems. Thus operational autonomy is the conduct of flight operations by POM.

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 Part 107. The majority of civil UAS flights today use remote pilots (i.e., POTL) 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 Low Altitude Authorization and Notification Capability (LAANC). A drone operator can use an app on a smartphone to request approval to operate within five miles of an airport through one of fourteen third party USS and receive approval within seconds if the requested airspace is available. These POTL flights are auto stabilized and navigated using the Global Positioning System (GPS) to fly to specified locations and maintain commanded heights.

Operations of larger unmanned vehicles beyond visual line of sight and in clouds may be approved with an exemption under section 333 of the FAA Modernization and Reform Act of 2012 [9]. 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 IFR flights generally climb to the positive controlled airspace above Flight Level (FL) 180 while within restricted airspace to avoid interaction with VFR flights not in contact with ATC. The number of these large 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 (i.e., POM) will require the waivers for BVLOS and, depending on the mission, flights 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 not accommodate the cost of pilots for every vehicle. Very active teaming activity by the FAA and manufacturers is underway today to create the necessary rules for certification of these vehicles that will provide the requisite safety. Current regulations for certifying airplanes and helicopters are inadequate for the lift and thrust configurations on the new vehicles 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, flight anomaly mitigation, separation from other aircraft, and participation in surface operations management. All of this must be provided with redundancy and other contingent measures for all known and anticipated system failures. This implies a fairly high level of artificial intelligence to recognize, troubleshoot and resolve vehicle system failures, adverse weather encounters and unforeseen traffic situations in flight and at the ground operations sites.

While autonomous flight control of unpiloted vehicles has been experimentally demonstrated [8], 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 Unmanned Air Vehicles (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. Direct controller-to-UAV communications do not yet exist without the remote human pilot intermediary. It could be envisioned in the future world of ATC data communications that controller-to-vehicle automated

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 data, which the UAS 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 in the National Airspace System (NAS), the two concepts must be merged in a fashion that supports the economical operations of eVTOLs while not burdening ATC.

4. UAM/ATC Interoperability Through AFR

In the AFR concept, airborne software monitors the traffic, weather and airspace restrictions to define a conflict-free and optimized trajectory from present position to the destination. How it can do this in a manner that does not interfere with other ATC operations is best explained through a short review of the broader system for centralized, ground-based air traffic control. ATC 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 VFR 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. Landings have priority over takeoffs and the sequence is set by the closest (in time) to the launch and recovery spot. These VFR flights employ a form of autonomy that has existed during the entire century-plus history of powered flight. It is dependent, however, on pilots being present on 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 it is therefore not permitted. One exception to this statement is the military flight formation that is maintained visually by the pilots, often even in clouds, but ATC separates the entire formation 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. To address this issue, electronic surveillance systems and automated Conflict Detection and Resolution (CD&R) systems have been developed and rules employing these systems established to create a capability known as Detect and Avoid (DAA). Standards for DAA [11] were developed and separation values determined in RTCA Special Committee (SC) 228 to enable UAS to remain “well clear” of piloted VFR flights when operating BVLOS. This capability is considered a requirement for the commercial viability of UAM.

While this paper focuses on the *separation* of UAM vehicles from all flights, it is recognized that ATC provides both a separation function and a 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 its current acceptance rate. “Automated Tower” software with a self-organizing feature can do these functions but it does not address enroute separation. Aircraft separation 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 International Civil Aviation Organization’s “Review of the General Concept of Separation” Panel. The author was a founding member of that panel, representing the International Federation of Airline Pilot’s Associations. 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 among stakeholders on an “acceptable level of risk”.

One example of the difficulty of changing historical separation criteria is the reduction from 2000 to 1000 feet vertical separation above FL290. This reduction, Reduced Vertical Separation Minimum, took 32 years to accomplish from the first serious efforts until it was finally implemented, initially in the North Atlantic. UAM stakeholders expect a much faster procedural and regulatory accommodation.

The separation function in any control paradigm 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 extended non-intersecting paths or separated by time at fixed, charted merge or intersection points. Strategic separation generally does not include direct surveillance but depends upon position reporting from the controlled aircraft and on-board navigation to ensure separation from obstacles and other aircraft. Geofencing is a form of strategic separation. “Tactical” separation control presumes near-real-time surveillance. Controllers use a display of aircraft in their sectors, fed by radar and ADS-B, to locate the aircraft and measure their dynamic interactions. When standard separation is predicted to be lost (determined either through mental projection or using conflict prediction software), control instructions are issued to one or more of the pilots to alter their flight trajectories in a manner that resolves the predicted conflict. Controllers then receive acknowledgement by radio and monitor the flight paths 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 automated separation systems within the aircraft themselves. This vehicle-hosted, automated separation process is inherent to AFR operations, as described in detail in [5]. Self-separation under AFR relies on ADS-B In surveillance and CD&R algorithms embedded in flight guidance software. The CD&R algorithms would cover all combinations of vehicle encounters and be approved for use by the certifying authority. The flight guidance output can be displayed to a human pilot or fed directly to the UAV automated flight control system. In the automated case, the control loop times are much smaller and therefore enable much smaller minimum-separation values. The AFR concept for use in an airline environment was extensively tested in multiple fast time and human-in-the-loop (HITL) simulations [7]. A follow-on roadmap for facilitating the implementation of AFR was described in [4] presenting a series of five steps of increasing capability of ABTM, beginning with the TASAR application of in-flight conflict-free trajectory optimization, currently being explored by multiple airlines for adoption. A follow-on series of Next Generation Air Transportation System and aircraft system improvements lead 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. While this roadmap was developed to enable conventional vehicle operations to transition to AFR, alternate roadmaps may be more appropriate for introduction of AFR to new types of vehicles and operations such as UAM, since they are not already steeped in the current ATM system.

Reference [3] applies the AFR concept for traffic self-separation to low altitude UAS flight operations, 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. Reference [3] also introduced a new concept for separating passenger-carrying unpiloted air taxis using a maximum angular velocity between passing vehicles to define a minimum lateral separation distance between the aircraft in conflict to prevent the appearance of a collision hazard. The symbol ω_{sep} 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 most UAM proposals have assumed the involvement of traditional ATC in these separation encounters as a result,

operating either as VFR or IFR. During an initial period in which these aircraft are piloted and their numbers are small, that model might work. The introduction of Data Communications (Data Comm) to the enroute airspace will help simplify the communication between remotely piloted UAVs and controllers. However, the overwhelming volume of traffic envisioned in UAM makes this assumption impractical as a sustainable and scalable solution and impossible once the numbers of eVTOLs begins to surpass traditional aircraft. Uber and others have already indicated they plan to operate above 400 feet AGL, so these flights will not be down in the UTM airspace with the package-carrying drones. For these higher-altitude, mixed operations, this paper proposes AFR as the safest and most expeditious means to integrate UAM vehicles in the airspace.

Air traffic in the airspace at and above 500 feet AGL is already considered by ATC to be “congested” in the urban areas, and delays attributed to congestion are commonplace. Alternate control paradigms are needed to overcome the limitations of human centered ATC. Some such paradigms are being investigated, such as the government/industry consortium in Kansas that recently completed an FAA-approved, BVLOS flight using an Iris Automation, Casia manufactured, computer-visual DAA system [10]. AFR is another example of an alternate control paradigm to overcome the limitations of human-centered ATC.

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: (1) the automated function could be centralized physically 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), or (2) the separation automation (following rules approved by the regulatory authority) could be hosted locally in the vehicles (i.e., distributed among 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 point out the disadvantages of the centralized solution and the advantages of 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 the presence of many tall buildings reflecting and shielding electronic signals. It also requires either very many receiving sites or high-power transmissions from the communicating vehicles. Transmissions for surveillance are safety-of-life critical and cannot be placed in a queue to be delivered in turn. Even the cell networks are severely challenged by this requirement.

Distributing the surveillance and communication tasks to the vehicles themselves ensures that those aircraft in close enough proximity to each other to be in conflict will also have short-range, usually direct-line-of-sight, communications available, even in low altitude, high density operations. 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 [13]. The local, distributed solution permits the use of low power surveillance transmissions, thus preventing lost messages due to frequency saturation.

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 at least a local failure of separation service. Some of the possible failure modes would disrupt the service for all the drones in the whole service area. There are many examples of this having taken place within our current ATC system [14][15]. Conversely, placing the separation capability within the aircraft using redundant equipment guarantees that no single system failure will impact the entire operation. 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 through adherence to aviation standards for AFR eliminates the need for major infrastructure development and acquisition by the government and greatly limits its liability, like VFR. This approach will speed the approval and implementation of eVTOL services in the National Airspace System.

The foregoing arguments are particularly relevant to low altitude (400 feet AGL and below), very dense operations in UTM airspace. UAM flights in the ATM airspace at 500 feet AGL and above must meet the requirements for surveillance and communications of piloted aircraft but their great numbers could quickly overwhelm ATC services. The use of AFR by these aircraft is naturally scalable and prevents the increase in traffic from becoming unmanageable.

5. Notional Design of Adaptive Airborne Separation in Mixed Operations

The rest of this paper assumes the local/distributed separation approach (i.e., AFR) to mixed operations (i.e., autonomous eVTOL and piloted vehicles) in Class B, C, D, E, and G airspace. It is assumed that eVTOLs will not operate above FL 180 and thus not in the Class A airspace, though AFR was originally designed to be fully compatible with Class A operations. Separation encounters will be considered among five classes of vehicles, defined as follows:

1. UAV_{cargo} is a cargo, small package or surveillance eVTOL vehicle with no humans aboard (i.e., UTM using AFR)
2. UAV_{pax} is a passenger carrying autonomous eVTOL (i.e., UAM using AFR)
3. PA_{VFR} is a piloted aircraft operating under VFR
4. PA_{IFR} is a piloted aircraft operating under IFR
5. PA_{AFR} is a piloted aircraft operating under AFR

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

Both classes of UAV, whether carrying humans or not, are presumed to operate under AFR. Whether used by piloted flights or embedded in software controlling autonomous flights, the operating principles of the proposed AFR rules are the same. Using onboard surveillance, CD&R algorithms detect traffic conflicts and resolve them using approved and standardized rules for priority and applied separation distances. Because there are differences in the control loop times for piloted and autonomous flights (due to human reaction time), their design separation values are different. ATC is kept advised of the AFR flight's intent for situational awareness but is not responsible for its safety in any way. Autonomous vehicles using AFR are thus known to ATC but are not subject to ATC for pre-approval of maneuvers. Rather than providing maneuvering flight guidance to the pilot to resolve traffic conflicts, the CD&R output of the onboard automation directly controls the flight path of the UAV. In order to prevent controllers from having to consider the AFR traffic, IFR traffic is given right of way in every AFR-IFR encounter. VFR traffic is avoided using the rules of AFR and the separation distances derived for DAA in RTCA SC 228.

Both classes of UAVs are unpowered and self-separate following AFR right-of-way rules. They also self-

separate from 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. This means no piloted aircraft or controller has to change rules or procedures when AFR operations are occurring in the airspace. UAV_{cargo} to UAV_{cargo} encounters use the smallest design separation value possible since they will have the tightest control loop parameters for surveillance, separation computation and control. Notionally, the design separation could be as low as 50 feet both laterally and vertically [3]. UAV_{cargo} to UAV_{pax} encounters risk startling and causing anxiety in the UAV_{pax} passengers if the encounter has both high closure speed and small design separation, so the ω_{sep} variable separation is proposed to limit the angular velocity at passing to an acceptable value (e.g. 1 radian per second). The same is true for UAV_{pax} to UAV_{pax} encounters. Either UAV class to PA_{VFR} follows the “remain well clear” practice among VFR aircraft. The DAA Phase 1 Minimum Operational Performance Standards (MOPS) translates that to a 35 second τ (range divided by closure speed) or 4000 feet lateral and 450 feet vertical separation in these encounters [8]. A very rigorous mathematical and analytical process was conducted to establish this engineering equivalent to “well clear” separation in the MOPS [16].

Normally, the calculation of separation values is based on the performance of the surveillance and control systems (i.e., accuracy, latency, control response). But even if the surveillance and aircraft control were to have perfect performance, the controlling parameter for minimum separation distance becomes 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 HITL simulations and flight test.

Table 1. Notional design separation values for encounters between different classes of aircraft.

	UAV _{cargo}	UAV _{pax}	PA _{VFR}	PA _{IFR}	PA _{AFR}
UAV _{cargo}	L 50 feet V 50 feet S 50 feet	ω_{sep} 250 feet 250 feet	4000 feet 450 feet 1/4 mile	3 miles 1000 feet 2 miles	ω_{sep} 500 feet ½ mile
UAV _{pax}		L ω_{sep} V 250 feet S 250 feet	4000 feet 450 feet ¼ mile	3 miles 1000 feet 2 miles	ω_{sep} 500 feet ½ mile
PA _{VFR}			L Well clear V S	Well clear	ω_{sep} 500 feet ½ mile
PA _{IFR}				L 3 miles V 1000 feet S 2 miles	3 miles 1000 feet 2 miles
PA _{AFR}					L ω_{sep} V 500 feet S ½ mile
<p>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 Blue indicates existing separation values Green indicates proposed notional separation values</p>					

The principle of “least disruption” is a key component of applying the AFR concept to 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 that are 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 directly between landing spots (“vertiports”) rather than the UTM design of segregated flyways or the use of dedicated UAM airspace. It also permits controllers to continue to manage their traffic in the Class B, C, D, and E airspace without changing their procedures or having any concern for the thousands of UAM flights taking place around them without interference, since they will all be operating under AFR which requires giving way to all IFR traffic.

Integrating UAM flights into ATM will not require changing the regulatory 200 knot speed limit below 2,500 feet AGL within 4 nautical miles (NM) of a Class C or D airport and beneath the Class B airspace. In all other airspace below 10,000 feet above Mean Sea Level (MSL), the 250-knot limit still applies. These speeds are important, not only for “see and avoid” from piloted aircraft, but also to 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 an ATC clearance in Class B airspace would be covered by the AFR rules providing position and intent to ATC in these and all airspaces. Access by eVTOL to the primary airports in these classes of airspace would be non-interfering to and from vertiport areas located to the sides of the runways, as covered in [3].

Surveillance of other traffic by the eVTOLs can be easily satisfied in the Class B airspace because of the transponder and ADS-B equipment mandate as of January 1, 2020. ADS-B In and low power active Traffic Alert and Collision Avoidance System (TCAS) interrogations from the eVTOLs would provide redundant sources of active surveillance data for both separation and collision avoidance. In Class G and Class E airspace below 10,000 feet MSL, surveillance is complicated by the fact that cooperative surveillance equipment is not required. An active radar system, an electro-optical (EO) 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 three miles visibility in the Class E airspace below 10,000 feet and none of the non-cooperative targets are very fast, existing electronic vision systems should be sufficient for this purpose. In the Class G airspace, only one-mile visibility is required, so late detection using visual means alone might not support the separation values for VFR traffic in Table 1. Technically, transponders and ADS-B equipment are not required for *IFR flight* in Class G and E airspace either, outside the 30-mile veils, but as a practical matter, there are almost no aircraft in the United States (U.S.) that are certified for IFR and that do not carry this equipment. ATC could keep an IFR flight with a transponder or ADS-B failure separated from all other IFR and AFR traffic, because this is such a rare event. This means that onboard radar/EO equipment is not required for UAVs to separate themselves from IFR traffic.

Communication equipment on autonomous eVTOL aircraft must serve three purposes: (1) provide mission-level status and control to the operator; (2) provide state and intent information to ATC; and (3) coordinate maneuvers with other aircraft during collision avoidance. The first of these communications may take many forms and is between the operator and the Federal Communications Commission to establish and approve. In the second, ADS-B provides velocity vector information, but not longer-term intent. Recent development of Data Comm within the FAA’s ATC automation systems use the term “Flight Object” to describe the information coming from an aircraft on its identification, state information, and intent. Providing intent from an autonomous UAV in 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 System Wide Information Management (SWIM) in the interim. For the third, AFR applies “implicit coordination” (i.e., rules of priority and maneuver direction) that does not rely on communications between vehicles for the separation function, but AFR also includes a collision avoidance function that could use the TCAS crosslink communication standards [17].

As presented in [3], all separation performed to the design separation values listed in Table 1 use the principle of implicit coordination in the tactical separation algorithms, which uses state-based trajectory predictions versus explicit trajectory intent. These state-based trajectory predictions are also used in the tactical separation algorithms for AFR. They make it possible to resolve a separation conflict without two-way communication between the aircraft in conflict. Using extensions of existing right-of-way rules and conflict detection accounting for trajectory prediction uncertainty, 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 by the closest point of approach.

If the burdened aircraft does not maneuver, or the maneuver is predicted to be insufficient, the priority aircraft, if it is also operating under AFR, will maneuver to achieve the design separation (i.e. the principle of redundancy in a distributed system). 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 on their current trajectory and the AFR aircraft will maneuver accordingly. The communication link for sending ownship intent information to ATC could also 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 Automatic Dependent Surveillance Rebroadcast (ADS-R). This intent data could be used in the separation logic to filter out some “state derived” conflicts that the intent data shows will not occur, particularly during vertical maneuvering.

6. Applying “Design Separation” to Reduce UAM Surveillance Requirements

Recent tests by NASA of the UTM TCL-4 system have confirmed the difficulty of surveillance and tracking of aircraft in challenging electronic and obstacle rich urban environments, so it is important not to have to provide these functions at greater distances or to include larger numbers of aircraft than necessary for reliably accomplishing the separation function. Even at higher altitudes, ADS-B capacity will quickly be exceeded if used by the huge numbers of envisioned UAM aircraft. What *is* required is to detect and track any aircraft with enough time to predict the miss distance and relative orientation at the closest point of approach (CPA) and, if in conflict, automatically maneuver to achieve the design separation value by the CPA using normal accelerations and only modest margins. The separation philosophy of vehicle-hosted CD&R performed at relatively close range and automated execution without human involvement provides for the greatest possible use of the airspace to achieve safe passage and mission assurance for 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 at the most effective moment to achieve design separation, no sooner or later.

UAM resolution maneuvers will be tempered with vertical accelerations, lateral roll rates, 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 the acceptable range of these resolution maneuver parameters. The vertical and horizontal accelerations, speeds and displacements used in the resolution models must, of course, be within the aircraft's performance capability.

Two notional examples will be used to illustrate the relationships among required surveillance, class of aircraft in the encounter and applied design separation. In the first example, two UAV_{cargo} (i.e., package carrying) drones are in conflict, each weighing less than 55 pounds and flying at 300 feet AGL and 60 knots. Their encounter is head-on at the same altitude such that the calculated miss distance is zero (i.e. a worst-case encounter). 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 vehicle must displace to the right 25 feet by the time they pass. The packages tolerate larger acceleration than humans, and so a rapid 45-degree bank to the right produces 1.4 Gs. The needed horizontal displacement of 50 feet is achieved in just over one second. At the closure speed of 120 knots (203 feet per second), the allotted two seconds to establish a track and declare and resolve a conflict plus one second to accomplish the resolution suggests that the conflict could be detected and resolved when the two vehicles are approximately 650 feet apart at the start and achieve the required 50 foot separation after maneuvering onto their safe headings. This example is intended to illustrate the approximate scales involved in such a worst-case encounter. In practice, additional margins would be applied to account for onboard compliance monitoring and various contingencies.

In a second example, a UAV_{pax} (i.e., passenger-carrying UAM eVTOL) at 4000 feet flying at 150 knots is head-on with an arriving Southwest 737 at the same altitude flying at 250 knots and operating under IFR. Here, IFR separation applies, and since the airliner has right of way, the AFR UAV_{pax} must create 1000-foot vertical separation or three miles of lateral separation using a maneuver that does not alarm the passengers of either aircraft. The disproportionate shape of IFR protected airspace (see Figure 1) strongly favors the use of a vertical resolution when the projected miss distance is zero. This illustration, while not exactly to scale (i.e., the VFR and UAV_{cargo} 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, determine the direction and magnitude of the miss distance at CPA, and compute the resolution maneuver; and

T_R is the time to perform the maneuver and resolve the conflict.

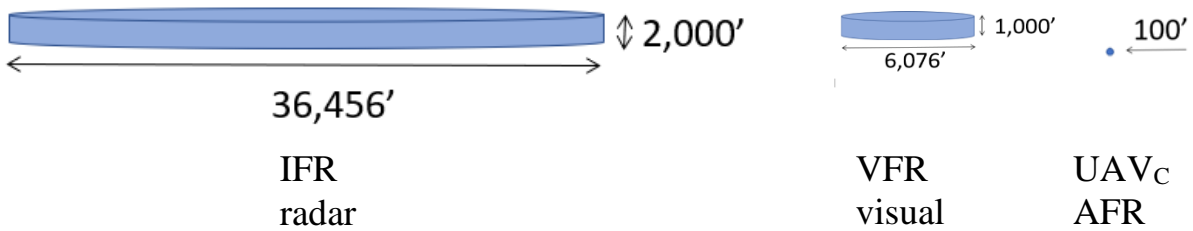


Figure 1. The disproportionate geometry of protected airspace around vehicles generally favor vertical resolutions for UAM encounters with VFR and IFR aircraft.

In the current example, the UAV can comfortably climb or descend at 1000 feet per minute so the time to resolve is just over 60 seconds. The time to detect and compute is the same two seconds as the first example, for a total of 62 seconds. At the closing speed of 400 knots, the needed surveillance range in this example is 675 feet per second times 62 seconds, or 41,850 ft (6.9 NM), plus three miles to accomplish the altitude change before encountering the cylindrical protected airspace, or roughly 10 miles total. It should be noted that the separation system surveillance radio frequency can be protected and its computational capacity not exceeded by using a variable surveillance range that is a function of the maximum relative velocities that may be encountered in the airspace, thus limiting the number of aircraft trajectories that must be tracked and modeled at any given time. The 200-knot speed limit exists at the lowest altitude followed by the 250-knot limit below 10,000 feet MSL to unlimited speed above 10,000 feet MSL. Traffic densities also decrease with increasing altitude, so that when the longer-range surveillance is required, the lower traffic density still limits the number of aircraft that must be simultaneously tracked, and their trajectories modeled.

Three aspects that characterize the UAM adaptive separation solution are: (1) variable surveillance range and tailored design separation values to match the traffic environment, (2) the ownship and traffic aircraft class (e.g. cargo vs. passenger, unpiloted vs. piloted), and (3) 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 class 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 target aircraft differ from what was modeled by a chosen value in the direction that decreases separation. For example, if the logic called for the traffic aircraft to maneuver and pass a certain distance behind ownship, and the surveillance shows that the modeled maneuver is not being followed and design separation will not be achieved by the traffic aircraft, ownship collision avoidance takes over. At this point, three things change. The resolution logic attempts to increase the predicted separation at the CPA in whatever dimension can achieve this first. The second change is that the speed and acceleration imposed by the avoidance 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.

One other change to collision avoidance enabled by the nature of eVTOLs is that the longitudinal dimension (speed up or slow down) is considered in the resolution calculation. This could be analogous to a full braking stop in a car.

7. 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 pilots and 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 state-based prediction 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 flexibility of operations for all airspace users. This flexibility ensures the ability of all operators to optimize their flights to maximize battery reserves, minimize missed arrival slots and diversions, and ensure safety of passengers and the public below.

It is suggested that further research be conducted to the application of AFR to UAM vehicles using onboard separation automation 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 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 piloted 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 piloted 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.

Addendum: Analysis of Foundational Prerequisites

Reference [3] presented a concept of operations for UAM with a concentration on the traffic management aspect of those operations. The focus of the concept was on flights below 500 feet AGL in which piloted flights are rare except in the short segments right after takeoff and just before landing. Recent documents describing these operations call this UTM airspace. The current publication addresses the traffic management aspects of autonomous UAS flights in the airspace above 500 feet AGL shared with many piloted aircraft operating under either VFR or IFR. It proposes the application of ABTM (i.e., Airborne Trajectory Management) and AFR (i.e., Autonomous Flight Rules) to UAM operations in both UTM and ATM airspace. ABTM was originally proposed for conventional piloted aircraft, progressing through a series of increasingly capable steps in cockpit automation from traffic-aware trajectory optimization to self-separation in an environment of mixed flight rules traffic [4]. AFR was proposed as a mechanism to clearly define the manner in which self-separation operations could be integrated in ATM airspace without disrupting either IFR or VFR procedures being used in that same airspace [5]. This addendum addresses their foundational prerequisites, many of which are not unique to ABTM/AFR but would be required by any UAM operating concept.

These operational concepts rely on several foundational prerequisites for their success. Unless these prerequisites are ready for implementation near the start of UAM services on a large scale with adequate reliability and at reasonable cost, these concepts for UAM are unlikely to be realized. This addendum lists and describes 12 foundational prerequisites for applying ABTM to UAM. The analysis includes high-level requirements for use in UAM, assesses their current state of development and Technical Readiness Level (TRL), suggests additional development where necessary, and postulates how the UAM concept would be limited without these capabilities being in place. Most of these prerequisites are not unique to ABTM and AFR, but rather would apply to any concept for UAM traffic management. Table A1 lists the 12 prerequisites analyzed for ABTM as applied to UAM.

Table A1. List of foundational prerequisites analyzed for ABTM as applied to UAM.

Foundational Prerequisites	Needed for UAM w/ ABTM	Needed for Any UAM	Estimated TRL	NASA Research Needed
Global Navigation Satellite System (GNSS)	x	x	9	Low
ADS-B	x	x	9,6	Med
On-board Radar and Visual Surveillance Systems	x	x	5-6	Low
Common Separation Algorithms	x		4	High
Fully Autonomous Vehicles	x	x	2	High
Automated Weather Sensors	x	x	9	Low
High Number of Takeoff and Landing areas	x	x	9	Low
Use of Tau in Collision Avoidance	x	x	3-4	Med
Speed as a Collision Avoidance Mode	x	x	4	High
Scalability to High Traffic Density	x	x	5	High
Dynamic Obstruction Database	x	x	8	Low
Resilient Performance in All Foreseeable Failure Modes	x	x	3	High

A. GNSS: Global Navigation Satellite System

The UAM concepts in reference [3] and the current publication presume that GPS will be the primary navigation source for the air vehicles. As a source for civilian applications, GPS now has two civil frequencies for navigation to make jamming and spoofing more difficult. Other GNSS constellations are reaching operational readiness, offering even more redundancy for civil users. Galileo, GLONASS and Beidou navigation satellites are now operational and manufacturers are producing receivers that can access and use multiple constellations of satellites. Both local and wide area augmentation are operational in the U.S., providing the integrity and accuracy for high reliability, precision navigation tasks. For these reasons, GNSS should provide the necessary coverage, reliability and accuracy for nearly all UAM navigation tasks. Landing and departing from pinpoint spot locations throughout the metro area requiring sub-meter accuracy will likely require electronic visual confirmation using Electro-Optical/ Infrared (EO/IR) sensing during the final few feet of descent. Also, when operating inside buildings, under rooves and perhaps near street level with high rise buildings on all sides, GNSS signals may be compromised or occasionally non-existent. However, extensive experience of motorists and pedestrians on the streets and sidewalks of all major cities has proven this is not a serious limitation, and GPS is generally available for all but indoor use. The U.S. government is now actively pursuing a GPS backup for Precision Navigation and Timing (PNT). In indoor environments, visual and primary radar navigation, augmented with map database information appropriate to the area of operation may be required, and has been demonstrated experimentally. But for the envisioned kinds of UAM flights that do not include flying indoors, the GNSS constellations are adequate and mature.

The vulnerabilities of GPS that received so much attention a decade ago when it was the sole operational navigation constellation and contained a single civil frequency have largely been, or are being, overcome through redundancy and technical upgrades on the newer satellites and GNSS receivers. As commercial aviation has become more dependent on GNSS for its needs, these vulnerabilities have been systematically addressed and many electronic navigation aids have been declared unnecessary and decommissioned as a result, because of the availability and widespread aviation use of GNSS. Most airline and many General Aviation (GA) aircraft have inertial reference systems for attitude and heading reference and these can provide a period of “coasting” navigation capability, even after a failure of GPS signals. For UAM vehicles, as for piloted aircraft, the Wide Area Augmentation Service (WAAS) in the U.S. assures system integrity. As a result, GPS navigation is approved by the FAA for all flight environments, for both VFR and IFR operations. The TRL for GNSS is estimated at 9. No further development of this system is required for its use in UAM.

B. ADS-B: Automatic Dependent Surveillance Broadcast

All flights within the airspace now requiring ATC transponders will be required to have operating ADS-B Out equipment after January 1, 2020. That includes Class A, B and C airspace and the Class E airspace above 10,000 feet MSL. For UAM, the Class B and C airspace will be extensively used, thus requiring the approved ADS-B equipment under current rules. ADS-B is a defined surveillance system standardized by the RTCA and specified in their two publications, DO-260 B and DO-282B for use of the 1090 MHz transponder and the 978 MHz Universal Access Transceiver, respectively. The airborne transponder avionics equipment itself is approved under TSO-166b and TSO-154c. These systems are widely used in current operations.

The ABTM for UAM concept includes a differentiation between UAS operations below 500 feet AGL and those at and above that altitude. Even though Class B and C airspace extends upward from the surface

inside the inner area and cooperative surveillance is required out to 30 NM for the major airports listed in FAR Part 91 appendix D, the concept assumes an exemption for UAS flights below 500 feet in Class B and C from the requirement for ADS-B and, in Class B, from requiring an ATC clearance. Separation of UAVs from piloted aircraft is proposed to be accomplished by geofencing the takeoff and landing corridors at airports within Class B airspace and providing right of way to all piloted aircraft. It is expected that the tens of thousands of small UAS (mainly package delivery) operating within 400 feet of the surface in a single metropolitan area will far exceed the capacity of the ADS-B frequencies, rendering the 1090 MHz frequency unusable even for ATC and TCAS use. For that reason, “ADS-B like” surveillance is proposed in ABTM for these very low altitude, very high-density operations. FAA announced their intention to require the broadcast of identity and position by all UAS in a Notice of Proposed Rulemaking expected out in October 2019. However, no means for accomplishing this was given in the announcement. EmbraerX has proposed in their “Flight Plan 2030” that merely reducing the power of standard ADS-B may not be enough to satisfy the requirement and they suggest using another frequency in the aeronautical band. Some in Europe, Korea and Japan have been experimenting with the 4G LTE networks for surveillance because it is ubiquitous in urban environments and should enable high-density operations. The 3rd Generation Partnership Project tested 4G LTE for this purpose and found that it works well near the ground, but its performance degrades with altitude because of direct line interference and handover problems between cell towers. There are fixes proposed for the issues, but they are not yet implemented [18].

The purpose of drone-to-drone, and drone-to-ground surveillance is for separation and traffic control, of course, but an examination of FAR 91.225 that sets forth the accuracy and integrity requirements for ADS-B position and velocity source information shows that these values are quite high, sufficient for standard IFR separation and DAA, but not precise enough to support the small separations described in [3]. The use of WAAS-augmented GNSS is certainly capable of the necessary accuracy and integrity, but the specifications for equipment used on these drones to separate themselves from each other need to be drawn up with this in mind, as merely complying with 91.225 will not suffice. To support separation values as low as 25 feet (7.6 meters) a Required Navigation Performance (RNP) of about 2 meters would be required. An “ADS-B like” service must be demonstrated to provide this precision, and the rules created to reflect that requirement. The technical readiness assessment for ADS-B is divided between those operations 500 feet AGL and above in “mixed airspace” and the high-density drone operations within 400 feet of the surface. The former is estimated to have a TRL of 9, and the latter, a 6. Prototype ADS-B-like service has been demonstrated in operational environments with varying degrees of success, but the final configuration and standards for hardware and software systems must still be determined and implemented. This process will likely take three to five years. Without this in place, high volume, low altitude UAM operations will not be possible.

C. On -Board Radar and Visual Systems

Assuming the FAA requirement for broadcasting identification and position from all UAS becomes law in the future, an “ADS-B Like” service is sure to emerge. That system will provide the primary surveillance means to ensure drone-to-drone separation using ABTM but, of course, obstacles will not participate, and at very close range between vehicles, visual angular location and radar ranging will provide better positioning and far less latency than ADS-B. Since drones were invented to provide visual imaging services, the sensors being used on them today often have the necessary accuracy and integrity to provide this function; but again, there are not yet standards and specifications for these to ensure the desired level of safety when these sensors are used for separation and collision avoidance.

The functions described in [3] that must be supported by primary radar and visual systems include DAA

service for encounters with piloted VFR aircraft not equipped with ADS-B Out, intentional operations down to 50-foot separation between autonomous vehicles, scanning for obstacles, people, pets and vehicles before landing or taking off from private vertiports located in both commercial and residential neighborhoods, avoiding obstacles, both stationary and in motion that are not charted in any obstacle database, and for collision avoidance from any such obstacles and any other non-cooperative airborne vehicles or vehicles on the surface.

Drone cameras are often gyro stabilized and have very high resolution to support their surveillance function of things and events taking place on the ground. But they almost never have totally spherical coverage, meaning that they can't constantly surveil objects at any azimuth and elevation from the ownship vehicle. Most airborne primary radar systems are also limited in their field of view. One such device that was designed without this limitation is called "Unicorn"TM, consisting of top and bottom arrays of radar "horns" to detect passive targets with complete coverage around the aircraft. It is possible to use such a spherical coverage radar to detect the passive target, accurately measure its range and steer the camera to its location for better classification, identification and to more accurately track its angular relative position. This combined data can then be used by the autonomous vehicle's separation and collision avoidance algorithms to determine and execute the proper response to the target's presence.

A combined radar/optical sensor should be able to place objects in the field of view to sub-meter accuracy in near real time at close range. Developments in the autonomous automobile world have made this capability a reality with some companies also using Lidar to map the environment, but these technologies would need to be adapted to the needs of UAM vehicle operations through continued developmental activity. Autonomous cars can get by with a shorter visual horizon than UAS and they will spend less time in fog (i.e., clouds) restricting visibility. The radar and the visual system will need enough range to support the collision avoidance software and may need infrared sensing when operating at night, or in haze and cloud conditions.

Besides spherical coverage, the range and angular measurement requirements for radar/optical surveillance augmentation are related to the maneuvering and minimum design values for separation and collision avoidance. Using simple Tau (i.e., range divided by range rate) set equal to the time to achieve the design separation when maneuvering from a predicted collision, the range requirement for any probable closure speed is easily calculated. The maximum closure for VFR below 10,000 feet would be 500 knots in a head on, and 400 knots below Class B airspace. Using a worst case 15 second Tau, the required detection range is about 1.4 nautical miles. That is considerably more than required for autonomous cars so the radar and visual technologies developed for the cars would have to be tested at greater ranges for their effectiveness. Because of this adaptation risk, the TRL for radar/optical sensors for UAM is estimated between 5 and 6. This required research and testing is likely to take place within existing drone industry partners, without requiring government funding. If it is not ready for operational use in time, the effect will be that larger design separation values will have to be used. Since the number of UAM vehicles will only grow over time, that limitation will not soon be serious, and should be overcome with the needed surveillance capability once the density gets so high that the smaller separations are needed.

D. Common Separation Algorithms

Autonomous UAM vehicles will encounter piloted aircraft, both VFR and IFR, and unpiloted aircraft with or without human cargo on board and must stay safely and legally separated from all of them. The operational concept in the main body of this publication calls for the separation applied in each instance to adapt to the specific type of operation of the target vehicle. For example, standard IFR separation provided

by the on-board separation system will be maintained from piloted IFR flights. DAA rules found in DO-365 will be used to separate UAM vehicles from piloted VFR flights, and “Omega separation”, described in [3] will be applied to unpiloted flights with human occupants. Separation between unoccupied drone flights will adapt the DAA model to use the smallest supportable design separation values determined through analysis, simulation and flight test, targeting around 50 feet, horizontal and/or vertical, to achieve the highest airspace capacity and operator flexibility.

Both Omega separation and the minimum design separation are yet undefined in RTCA standards, but the maneuvers used to establish and maintain separation must be compatible among all autonomous UAS to prevent independent, incompatible maneuvers from creating a loss of design separation. Currently, low-altitude small UAS (sUAS) operations are separated by airspace reservation of the entire intended operating area to intentionally prevent traffic encounters using strategic separation. This is accomplished using the service of one of the USS. The near instant approval of operations in the NAS using one of these third-party service providers, such as AirMap, works very well with the low number of drone operations now extant. This method is not scalable, however, and it does not apply to drone operations above 400 feet AGL (outside of UTM airspace). Autonomous air-to-air tactical separation will be needed to accommodate higher altitude flights encountering other drones and piloted flights, as well as orders of magnitude increases in drone traffic. Some work is taking place in the NASA UTM TCL-4 trials to enable multiple drones in the same airspace, but the process is still strategic. No standards yet exist for tactical separation algorithms now being used experimentally for collision avoidance, or as used in the NASA Autonomous Operations Planner (AOP) research prototype automation system for airborne separation [19]. It is proposed that such standards be developed and agreed through the RTCA and Eurocae processes. The drone industry, through its strong cooperation with NASA, could support this activity if it moves fast enough to keep up with other UAM developments and the public’s desire for drone services. If this activity is not undertaken, then the existing DAA standards would likely be imposed by FAA on all drone-to-drone encounters, resulting in a drastic reduction in potential airspace capacity.

Autonomous separation maneuvers and right-of-way rules, at a high level, should be based upon the FAA standard rules presented in FAR 91.113 and enhanced to allow algorithmic determination of right of way based on the exact geometry of the encounter where the rules now use the term “or nearly so.” Thus, “converging encounters” would have the convergence angle specified to differentiate them from “head-on” and “overtaking” encounters. Similarly, converging in the vertical or a combined horizontal/vertical sense would have precise algorithmic resolutions determined by the encounter geometry, as would non-linear encounters. Another difference from the piloted right-of-way rules could allow passing over, under or in front of the target aircraft while maintaining design separation among autonomous drones. Those prohibitions in the regulation were included to prevent the appearance of hazard to human pilots operating in visual conditions and would not be applicable to autonomous UAS. The priority to landings over takeoff and surface operations should be retained from the Part 91 rules, but priority to the lower aircraft on approach should be replaced by the closer to estimated time of arrival (ETA) at the landing spot.

NASA’s work on self-separation using AFR and the creation of the AOP software tool to provide separation guidance has provided a strong base of knowledge from which to continue this line of research. The AOP work concentrated more heavily on longer-term trajectory-based separation appropriate for transport aircraft, so the separation algorithms would need to be optimized for the UAM application. There would also need to be multiple separation modes available to accommodate the adaptive separation values in ABTM. Because of the extensive fast-time and piloted simulations run using the AOP, balanced against the need to adapt this method to the UAM autonomous vehicles, the TRL for this item is estimated at 4. This is clearly an area in which NASA can provide a valuable research contribution that is not likely to be

accomplished soon by outside industry. If this work is not undertaken, the drone industry will be restricted from growth for a long time using small improvements to the strategic separation, provided by airspace reservations via third party, now being employed.

E. Fully Autonomous Vehicles

Other concepts for UAM in the literature describe a progression of eVTOL air taxi services beginning with human pilots on board, transitioning to remote human pilots and finally to autonomous vehicles as the safety case is built. Whether the pilot is on board or remote, the piloted phases of this economic model resemble existing air taxi operations using piloted airplanes and helicopters. It is a service so expensive that it is only used by a few people with special needs that justify the high cost. There is no reason to believe that piloted eVTOLs carrying only a few passengers would have different economics. Therefore, UAM will never put a dent in relieving surface congestion until the vehicles become truly autonomous. The few passengers that can afford this service will avoid the ground congestion, but the congestion will remain. That is why the autonomous model for UAM is proposed in references [3] and this publication.

To realize the goal of UAM, autonomy must be pursued from the start. The dangers of fielding an unproven, fully autonomous UAS are well understood, of course, and now hotly debated in the autonomous automobile industry. A serious fatal accident involving an autonomous vehicle could trigger a backlash that grounds the industry for a very long time. A more reasonable progression from basic to advanced services in the air taxi model would begin with unoccupied package delivery services using vehicles small and light enough to use automatic parachute recovery for all unmitigated contingencies. As vehicle design improvements and on-board artificial intelligence improved to the point where most contingencies are resolved without a complete mission abort, larger, higher weight vehicles could be added to the mix. Once enough flight data is accumulated to prove the safety of autonomous operations at a level required for passenger flight services, they would begin, backed by a then extensive period of experience in resolving anomalous conditions involving vehicle failures, adverse weather, unforeseen traffic situations and conditions on the ground operational sites.

Another weakness of other UAM concepts of operation is the extensive communications infrastructure required for command and control (C2), and for surveillance. If the vehicles are not autonomous, any loss of the C2 link is potentially catastrophic. Surveillance needed for vehicle separation and traffic management using ground sensors would be extremely difficult to establish given the low altitudes used by these flights and the presence of obstructions and multipath in the operating environment. By contrast, autonomous vehicles using ADS-B and “ADS-B-Like” equipment could reliably perform self-separation at close range with low power, thus mitigating the potential for frequency saturation from great numbers of vehicles in very close proximity. They would also do it with a far smaller radio spectrum requirement.

Air taxi services requiring the equivalent of Airline Operational Control for flight planning, dispatch, flight-following and contingency management have been proposed, but this concept also suffers from the need for multiple personnel and expensive facilities and communications systems to function. The surface taxi models Uber and Lyft are successful because all the vehicle dispatch, routing, scheduling and payment is accomplished over the internet through the app. Fully autonomous air taxi vehicles should use similar automated support services, perhaps growing out of the USS community. At the pick-up site, the vehicle would have a prominent sign on the door, “stand back” until the vehicle was ready, then the door would open and a “board now” sign would illuminate. Inside the vehicle, the destination previously entered on the customer’s phone would appear on a display with a “confirm” request, and any seats with weight in them would be sensed to ensure the seat belt was fastened before the vehicle departed.

Full autonomy is rare in the UAS world today, but the government is encouraging its development and testing. Both the 2018 National Defense Strategy and the 2019 National Defense Appropriations Act mandate that the Services develop, test, and implement autonomous and artificial intelligence (AI) systems. The Air Force sponsored testing of John's Hopkins University's "Testing of Autonomy in Complex Environments" (TACE) they call "middleware" that monitors commands sent to a UAV autopilot to ensure their safety, then sends the aircraft state information back to the AI. In March of 2019 they were able to demonstrate the TACE system's ability to re-direct an aircraft to a safety area as it approached a virtual border, and the ability to track a simulated vehicle on the ground without human commands. The TACE uses open systems architecture, allowing the testing of third-party AI algorithms [20].

The Flirtey Company, working with the University of Nevada in Reno, demonstrated the first "fully autonomous, FAA-approved urban drone delivery in the US" in March 2019. In an uninhabited residential setting in Hawthorne, Nevada, a six-rotor drone flew a predetermined path and lowered a package containing food, water and a first aid kit right on target in the urban setting [21]. While claiming a "first" for autonomy, it is still a long way from doing the flight planning, the weather analysis and coping with any and all contingencies that might arise, all autonomously, on board as described in the ABTM for UAM concept.

Many companies working alone, in teams and teaming with NASA, FAA and the military are pushing hard to advance the state of the art for drone autonomy, but there is still a long way to go to achieve the UAM autonomous vision. Creating this autonomy through functional AI software and hardware is a strong area for NASA to provide research, guidance and leadership over the next seven to ten years. This item, in the list of foundational prerequisites, has the lowest estimated TRL of 2. There is time to do this development before regular use of autonomous air taxis exists. If it is not done, UAM will never progress beyond a niche service to a true economic and transportation revolution.

F. Automated Weather Sensors

Because of their low speed and low disk loading, eVTOL aircraft are particularly impacted by turbulent air conditions. Along with strong winds and precipitation, turbulence along the flight path is the most difficult challenge to cope with. A high degree of control authority is required to counteract the effects of turbulence and maintain a stable attitude and flight trajectory, something in which all aircraft, both piloted and unpiloted, are limited. It is, therefore, very important for the autonomous vehicles to have access to current wind information from which turbulence probability can be calculated. Direct sensing of turbulence severity, such as the eddy dissipation rate (EDR), would be valuable if measured at the scale appropriate for the UAV in question.

Automated weather sensing systems are a mature technology and in widespread use at airports both large and small across the country. The FAA's automated weather program started with the Automated Weather Observing System (AWOS) that provided the required parameters to pilots using an airport via synthetic voice recording, to free up airport control frequencies and ATC personnel from this task. More recent installations are Automated Surface Observing System (ASOS) and Automated Weather Sensing System (AWSS). They are both the same system, but the latter was re-named in a follow-on acquisition and installation program. These systems are being installed on a nation-wide basis in a joint effort by the National Weather Service, FAA, and Department of Defense. The voice broadcasts of weather information may be received out to 25 miles and up to 10,000 feet. ASOS and AWSS also include a data output of the sensed weather information distributed on national communication networks that can be used by automation systems on the surface and by software resident in aircraft. The list below gives the sensed parameters

available from these systems:

- Cloud Height
- Visibility
- Precipitation
- Freezing Rain
- Pressure
- Temperature and Dew Point
- Wind direction and Speed
- Rainfall Accumulation
- Automatic Lightning Detection and Reporting System (ALDARS)

The needs of autonomous UAVs for the weather data to do flight planning and operational decision making are somewhat different from the needs of piloted aircraft. There is no need for the voice broadcast and several of the existing weather parameters are not necessary either. As they will operate autonomously in both IMC and VMC, cloud height and visibility are not necessary. A visibility of a few meters is enough to confirm the safety of the landing area and this is far below the threshold of current visibility sensors. Eliminating the cloud height and visibility sensors, the rainfall accumulation, the ALDARS and the voice broadcast portion of the AWSS would provide significant savings in the cost of these installations. This is important because even in the larger metropolitan areas, there are only a few such stations currently installed for the needs of piloted aircraft. For UAM there will be a need for the remaining weather parameters plus turbulence to be reported on a much finer grid throughout the area. For example, if they were placed in a 1 nautical mile grid within the DFW 30-mile veil, there would be over 2800 of them. Clearly there is a need to define a much lower cost AWSS for UAM that would be self-sustaining (probably solar powered) and very low maintenance. The spinning anemometer could be replaced with solid state wind sensors, for example. In high rise downtown areas, both rooftop and ground level sensors may be needed because of the venturi effect of closely spaced tall structures amplifying the prevailing wind near the surface.

The weather parameters that are most important to UAM operations are first the wind (and its turbulence derivative); then temperature, dew point and atmospheric pressure (to calculate density altitude); and then precipitation, including when it is freezing rain or drizzle. UAM vehicles are not likely to tolerate any structural icing. These sensors could be mounted atop single poles about 20 feet high and equipped to communicate via the cell networks to the user community. Most could be located on public land or existing utility poles to save on real estate costs. Since turbulence intensity is so important in UAM, the appropriate EDR must be calculated or measured, perhaps using orthogonal hot wire anemometers and a short period algorithm to analyze the three-dimensional wind variations. Each UAV type would be certified for the maximum wind gust it could tolerate and the maximum turbulence intensity that it could safely navigate in the airspace, based on its performance and control authority. Comparing the weather conditions on the intended trajectory to the aircraft limits would inform the go, no-go decision software. Once in flight, the conditions ahead would determine the “continue” or “divert/abort” decision at regular intervals. The dense array of sensors would make it possible to detect an advancing gust front that would ground UAM operations before it was ever experienced at the vehicles themselves. There would need to be some sensors placed outside the normal UAM operating area to protect the edge operations.

This is another example of a mature technology requiring adaptation to meet the needs of the UAM operators. Miniaturization of the sensors to minimize size and power requirements, inclusion of just those weather parameters needed for UAM and the data communication medium appropriate to this function need to be determined and agreed in the community. NASA leadership is required here also, and even though

the underlying technology is at TRL 9, this adaptation and the standardization of it will require several years of focused effort, either in the UAS community or through RTCA. Failure to employ a dense array of weather sensors will not invalidate ABTM for UAM, but it will delay its growth.

G. High Number of Takeoff and Landing Areas

The ABTM for UAM concept calls for a very high number of takeoff and landing areas throughout the metropolitan operating area. While some UAM concept descriptions have proposed dozens of such sites, the ABTM concept calls for thousands of sites. This is a direct result of the business case for UAM. UAM will never be more than a research project unless the operations are economically viable and the services provided live up to the promise of the vision, i.e., to provide faster transport of goods and people from origin to destination than is possible today using ground transportation, for a comparable cost. If UAM were merely to insert another mode of transport into the middle of the journey, still requiring a transfer to, say, an Uber ground taxi, the advantage is lost. Thus, concepts requiring people and goods to gather at a few distribution centers to be flown to a few locations scattered throughout the city where another transfer takes place to get the customer or the package to the final destination do not save the time or the cost required for this type of UAM to be viable. Instead, package deliveries by drone must be to the address of the recipient and if it is not possible to land there, then the package must be lowered from the vehicle to the ground on a tether. Passenger carrying autonomous air taxis must be able to pick up and drop off from at least as many locations as there are stops on a city bus route so that the passengers can reasonably expect to reach their final destinations on foot. UAM must be a replacement for ground transportation, not a new intermediate mode in the journey.

Another reason for the high number of sites is to abrogate the need for TFM of drone traffic, as now exists for airline traffic at the very few air carrier airports in the country. Taking a delay in a drone delivery, no matter where or how it is taken, also destroys the business case for the service. By flying between a myriad of origin and destination points desired by the customer, there will be very little competition for use of these sites, and thus no need for TFM delays. This is directly analogous to GA flights among the thousands of small airports around the country that never are so busy that TFM is needed to manage a capacity/demand mismatch.

That being the case, there is still a question of whether it is technically and operationally feasible to designate enough takeoff and landing sites to make the whole concept work. An examination of this question is split into two parts, one for the package delivery services and the other for air taxi or passenger services. Taking package delivery first, there is an initial assumption that the FAR Part 107 vehicle weight limitation of 55 pounds will be applied to these operations. It is unlikely that the payload of these drones will exceed 50 percent of the total vehicle weight, so packages that weigh more than 28 pounds are not considered in the discussion that follows.

Package carriers, such as UPS, Fedex, Amazon and the U.S. Postal Service all have multiple distribution centers around the metropolitan area that gather, sort and distribute the goods around the city from the long-haul ground or airline transportation that brought them from the sender. The UAM service is intended to replace the ground vehicles that currently accomplish the intra-city distribution that follows. The box carrier distribution centers will need to have many launch and recovery platforms to be used by their drones, as envisioned in the beehive patent issued to Amazon in 2017. On the other end, every person and business in the city to whom a package is sent has a street address that is shown on the package. If the address is a detached home, the package can be lowered to the street side or the back side of the home, as designated by the addressee. If it is a building without a yard, such as an apartment building, a small business or a

corporate high rise, the building owner must designate a delivery spot and mark it appropriately, visually and electronically. This could be on the roof of some buildings or somewhere around the perimeter on the ground, such as a fenced off area in the parking lot for the building. Package pickup can take place from the same locations. The only ground infrastructure required for these sites would be a visual marker such as shown in Figure A1, also containing a patch transponder, like the ones stuck to a car's windshield to be read at high speed on toll roads. The visual marker would be to permit precise navigation by the drone during the last few feet for pickup and delivery and to confirm the spot is not occupied for safety at the time of use. The transponder would confirm the address of the customer and could indicate accomplishment of pickup or delivery.

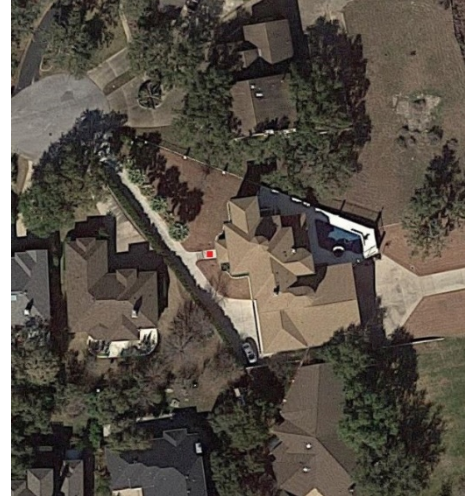


Figure A1. Residential drone drop off location.

UAM air taxis, by contrast, will weigh several thousand pounds, generate more noise and pose greater risks to other nearby activities than the small package drones. The Uber project has called for a fifty-foot square area to be reserved for takeoff and landing of these vehicles. Similar markings and electronic identification could be used to designate these areas, but the inability to lower and raise the customers from a hovering drone, as may be done with packages, prohibits the operation of these vehicles from every address in the city. Accordingly, an automated survey of the metropolitan area could be performed using location identification software with an application such as Google Earth to identify for analysis those places that could be used for air taxi operations in every neighborhood. The middles of cul-de-sacs, corners of parks and parking lots, a portion of the real estate in strip malls and at some private homes with large lots, the air taxi square could be designated and fenced. In the city center, most vertiports will be on the top levels of parking garages, on rooftops and on piers in the rivers and lakes. In some areas, a portion of surface parking lots could also be used. Figure A2 illustrates how many such locations are feasible in varied DFW neighborhoods. The goal would be to find a potential spot in every block. People and businesses desiring air taxi service could be instrumental in finding and seeking approval for sites near them. These sites would not provide drone services like charging and maintenance / inspection / cleaning or even passenger services of any kind. The latter would be handled in the same manner as the existing ride services. These spots would, however, make point-to-point transportation feasible without transfer to another mode of transport.

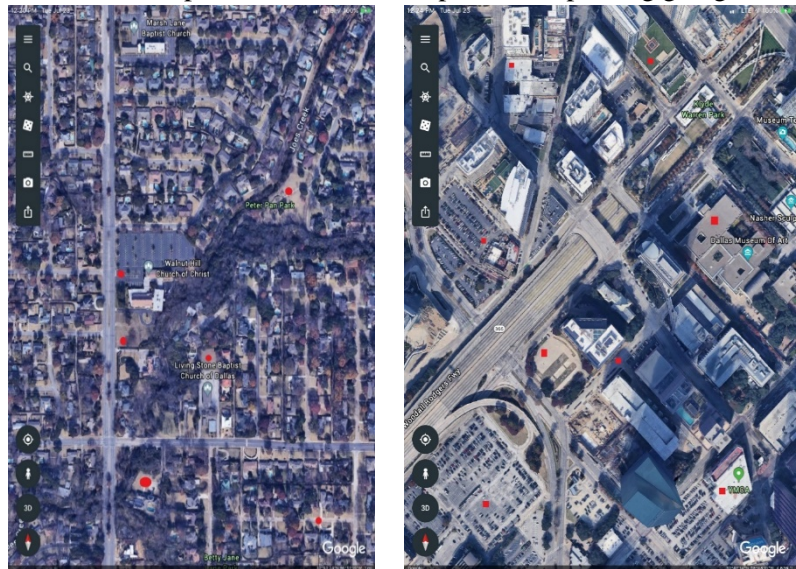


Figure A2. Potential vertiport sites in residential Addison, TX and downtown Dallas, TX.

This item contains more logistic and legal hurdles than technology challenges. Some successful highly publicized deliveries and people movements could produce a groundswell of demand leading to the public asking that points of operation be approved at their homes and businesses. The costs for designating spots with addresses, painting small markings and installing tiny transponders are truly minimal. Conversely, a bad experience could create a public outcry demanding an end to these flights. This item has a TRL of 9 but is a public relations challenge that is only just beginning. The industry must confront this as soon as they realize that without it, the whole UAM economic model collapses. It is not just an ABTM issue.

H. Use of Tau in Collision Avoidance

The ABTM concept for UAM calls for the surveillance and trajectory modeling data to be applied in the self-separation algorithms, as well as in the collision avoidance logic that is activated if the surveillance shows the separation logic is not being adhered to by one or both aircraft in conflict. Tau, the slant range to a target divided by range rate (i.e., closure speed), is a basic, instantaneous approximation of time to CPA and thus important to separation logic. Modified Tau, used in TCAS logic, separates the horizontal and vertical components of aircraft closure such that Tau mod is the estimate of time to the horizontal CPA. It is used in conjunction with a value of DMOD, the horizontal distance that will trigger a TCAS alert even with very slow, or no, closure. The vertical closure, modeled from successive Mode C altitude reports, also checks for a projected value less than the appropriate minimum in the alerting logic. Simultaneous triggering values in the horizontal and vertical will trigger a Resolution Advisory. The reference to the use of Tau in the separation logic section of [3] was intended only at the highest level of the logic to trigger additional modeling of the target's future trajectory and to assist in prioritizing the threats from the rest of the track files. The paragraph erroneously implied that the legacy TCAS logic played a major role in the ABTM collision avoidance logic.

In the low altitude UTM airspace, level flight will be rare as the vehicles are following the terrain and obstacles in the vertical. It is probable that a spherical coordinate system fixed within ownship would be used in analyzing the target aircraft trajectories for conflict. Simple Tau might be more useful as a basic filter in this system than separating it into the horizontal and vertical components. In reference [22], the author presents a concept called "Tau-Tau" that works better than simple Tau in filtering conflicts in which the encounter geometry will result in a miss by calculating the trajectory that would create a collision and using the difference between the measured and collision trajectories to find the Tau-Tau value. That process eliminates a lot of the nuisance alarms issued by both basic and modified Tau logic.

ABTM logic relies heavily on using the velocity vector and its first derivative (for detecting target aircraft maneuvering) to model the future trajectory and predict the miss distance and direction that is used in declaring a conflict and determining an appropriate avoidance maneuver. This was desired, but not possible, when TCAS was being developed. It was not possible because the only angular measurement to the target at the time was from the TCAS directional antenna. That was adequate to show the target aircraft on a display for situational awareness but not sufficiently accurate to predict the miss distance, or even to determine on which side of ownship the passing would take place. Modeling in the vertical using successive values of the Mode C altitude report was far more accurate and supported the use of the vertical avoidance maneuver, which is still the only dimension used in TCAS today. It is expected that the position and velocity vector, included in the ADS-B report, supplemented by EO/IR for angular measurement and primary radar for range, can permit accurate miss distance calculations. This will eliminate most nuisance alarms and permit much smaller design separation values.

It is estimated that the TRL for the separation and collision avoidance logic proposed for ABTM is not

very mature, probably a 3 or 4. Unfortunately, the concept using ABTM for UAM is very dependent on this logic being developed. The UTM work currently in progress is still mostly “airspace reservation-based” even when the reserved airspace is dynamically adjusted as the drones perform their missions. True air-to-air self-separation is mentioned as a desired capability in some reports, but no specifics are given. If this development is taking place, it is likely within private companies. Because of the interoperability requirement, this development should be sponsored by the government (probably NASA) and the results of their research be used to create standards in the RTCA. This activity is crucial to ABTM for UAM.

I. Speed as a Collision Avoidance Mode

It was intended in the present concept to point out the difference between TCAS collision avoidance and the ABTM for UAM collision avoidance proposed here for eVTOL aircraft. TCAS has a single dimension in space used for conflict resolution, the vertical dimension. It was designed to be used on conventional piloted aircraft, primarily air carrier aircraft, that have limited maneuvering capability in each of the three dimensions. Lateral maneuvers are limited by roll rate and permissible bank angle. Also, when TCAS was developed, projecting the lateral miss distance through surveillance was not nearly as accurate as the projected vertical miss distance. That is a function of the encoded altitude being broadcast for height tracking versus the angular precision of received responses through the TCAS directional antenna for the lateral tracking. Vertical tracking was far more precise, thus requiring a smaller displacement from the original trajectory to assure a miss. Because of the poor accuracy of the projected lateral miss distance, lateral resolution maneuvers, originally to be included in TCAS III, were never implemented.

Longitudinal trajectory changes (i.e., speed up or slow down) are very limited on transport aircraft, particularly at high altitude. Even when the allowable speed range is larger at low altitude, the acceleration and deceleration rates are quite small, so this dimension was never considered in TCAS. eVTOL aircraft, however, are capable of speeds from zero to their maximum at all of their more limited range of altitudes. A combination of ADS-B and ADS-B-Like tracking supplemented with electro-optical and radar tracking at short range is capable of supporting trajectory modeling that is precise in all three dimensions. This means that the projected miss distance at the closest point of approach will be known in all dimensions and the collision avoidance logic will first use the dimension that needs the smallest increase to produce a miss, followed by the others if maneuvering by the traffic aircraft negates the effectiveness of the first collision avoidance maneuver. It is true that hovering for most UAM vehicles uses more power than forward flight and the use of hovering in the concept document was meant to show the availability of all maneuver dimensions for UAM collision avoidance, not that hovering would ever be extensively used for that purpose.

The technology associated with UAM collision avoidance is still immature and has been previously covered in the sections on Common Separation Algorithms and Use of Tau in Collision Avoidance. Thus, the same estimated TRL of 4 is appropriate for this item. Similarly, this is an area where NASA research capability is of utmost importance, as the logic must be standardized and applied across all users. Hovering, however, is not a necessary prerequisite for ABTM use in UAM.

J. Scalability to High Traffic Density

Most UAM concepts put forth to date take a traditional developmental approach to both vehicle control and to drone traffic management. The manufacturers of the eVTOL vehicles say that they will initially be piloted by humans but are being designed to fly autonomously. The proposals for traffic management

include corridors throughout the Class B airspace reserved for drone use and centrally managed reservations for the use of airspace and vertiport facilities. This paradigm directly mimics what is done for piloted aircraft. It does not properly account for the envisioned numbers of drones and densities of drone traffic necessary for UAM to become a major player in the relief of surface congestion within a metropolitan area.

The ABTM concept for UAM calls for orders of magnitude increases in the numbers of vehicles used for intra-city transport and traffic densities unheard of in conventional air traffic management. Each of the ATM functions of separation, airspace management and vertiport management will need to be performed without human involvement in the control loop, as too many decisions per second will have to be made in the performance of these functions. In NASA's early work on UTM, four TCLs were described with increasing capabilities for handling UAS operations at each level. BVLOS with geofencing is introduced, then a semi-urban setting, then at TRL-4, true multi-vehicle control in a more challenging urban setting. TRL-4 tests were just completed in Reno, NV, and in Corpus Christi, TX. Even here, however, human managers use data to make strategic decisions about initiating, continuing and terminating UAS flights to ensure that only authenticated UAS are in the airspace. "Multi-vehicle" in these tests meant tens of vehicles, not thousands.

The USS provide strategic and tactical reservations, prioritization of flights and contingency management to prevent unsafe multiple operations in the same volume of airspace. But as stated in the Airmap R&D 2019 report on NASA UTM TCL 4 trials, "While the results of the NASA-UTM project successfully demonstrated the power of UTM to address safety and conflict resolution concerns for drone operations in shared airspace, the trials did not address more advanced separation capabilities, including separation minima, detect-and-avoid technologies, air- or ground-based collision avoidance, intent-based avoidance procedures, and tactical deconfliction at different phases of a drone operation. Future projects should evaluate these capabilities in order to build upon the NASA-UTM TCL4 trials" [23].

ABTM for UAM calls for a more advanced form of traffic separation and collision avoidance that addresses the need stated by Airmap. Air-to-air surveillance supports self-separation, and inter-aircraft coordination ensures compatible maneuvers during collision avoidance. These techniques are used exclusively outside the geofenced no-fly areas reserved for piloted aircraft takeoffs and landings. This is completely tactical separation as opposed to nearly completely strategic separation of each drone's operating area, in use today under UTM. Strategic separation works well in limited areas with small numbers of simultaneously airborne drone traffic that characterizes today's drone operations. It will not work when the vehicle numbers are increased ten or one hundred-fold as envisioned for UAM. Tactical separation is necessary to enable far greater capacity at far less cost than strategic separation. Air-to-air collision avoidance is mentioned in some UTM concept papers, but always within the framework of a centralized airspace management and control system. What is meant by the latter is less clear and usually not explained. If it is meant to be automatic without human decision making required, it may be conceptually feasible, but it would still be more vulnerable to failure and more expensive in terms of infrastructure and spectrum use than the ABTM approach to autonomy.

The use of drones in the US has begun on a very small scale and UTM already exists. There are between ten and fourteen USS providing rapid authorization using LAANC for drone flights within controlled airspace, while also offering other operational and planning services. Clearly, for UTM to evolve into a system like ABTM there must be a consensus among the leaders in the UAS industry and the regulators on the direction that evolution should take. UTM, as defined by the FAA in its concept document, only exists within 400 feet of the surface. The concept behind ABTM can take UTM from what it currently does to a system of systems that accommodates all classes of airspace users in all Classes of airspace. It can do it in

a manner that preserves the freedom to fly, accommodates orders of magnitude increases in traffic and, above all, contains a viable economic model throughout the growth of the UAM aviation segment. Current UTM is operating at about TRL 8, only because of very low traffic densities, but the ABTM model is still at TRL 5. NASA has the background knowledge and simulation experience to bring ABTM to a technology capability level where it can be used to allow the natural growth of UAS missions and operations without imposing the constraints that are artifacts of the human centered ATM system.

K. Dynamic Obstruction Database

Autonomous UAM flights will spend a lot of time flying in very low altitude airspace where piloted aircraft are very rare. Obstructions abound in this airspace, however, and must be known to the flight planning and execution function of the autonomous drones in order not to collide with them in flight. Most obstructions are in fixed positions and are mapped in various databases, making it possible to fly missions free from hitting obstructions simply by comparing the intended flight path to the appropriate obstruction data base. New obstructions are being built all the time and some, like cranes and amusement rides, move around and are temporary in nature. These appear in NOTAMS when they are near regular airports but not when they don't impact the airspace navigated by piloted aircraft. Thus, there is a need for a dynamic database of all obstructions throughout the UAM operating area.

In the ABTM operating concept, drones will only be below 50 feet AGL for takeoff and landing, and this will be a vertical ascent and descent maneuver at a known vertiport location. Obstructions less than 50 feet AGL will not be a potential hazard to these operations and therefore, will not need to be included in the dynamic obstacle database. The Electronic Terrain and Obstacle Data (eTOD) is a digital representation of terrain and obstacles provided by States as datasets to satisfy user requirements for many airborne and ground applications such as ground proximity warning systems, terrain alert and warning systems, and the Minimum Safe Altitude Warning provided by ATC. eTOD could also be used to satisfy the needs of UAM. According to SKYbrary [24], a terrain dataset such as eTOD is a digital representation of the elevation of the terrain at a number of discrete points. Major features of a terrain database include geometric distribution/position of discrete points, horizontal/vertical datum and specific units of measurement. In the context of eTOD, terrain is defined as, "The surface of the Earth containing naturally occurring features such as mountains, hills, ridges, valleys, bodies of water, permanent ice and snow, and excluding obstacles."

An obstacle database is a digital representation of the obstacles which includes the horizontal and vertical extent of man-made and natural significant features, whether fixed or mobile, temporary or permanent. Environmental Science Research Institute compiled a toolset for use by States in complying with ICAO rules requiring them to provide an electronic terrain and obstacle database. That toolset is being used by several companies to help States around the world meet their requirement to protect air operations near their airports. Extending this technique to cover entire metropolitan areas is both technically and financially feasible. It is just required that it be done in locations and for the purpose of protecting UAM flights. For those reasons, this item has an estimated TRL of 8, since it is already operationally used to protect aviation but must be extended to fulfill the specific needs of UAM. It is not a capability unique to the ABTM concept, but there is a dependence on its fulfillment for all UAM concepts.

L. Resilient Performance in All Foreseeable Failure Modes

UAM, provided by autonomous vehicles that will be operated by numerous private companies and individuals, contains a great many hazards that must be mitigated to provide the operational safety expected

by the public, and that will be necessary, both in the beginning and on a continuing basis, for UAM to be viable. Comparisons to the accident record of automobile traffic or general aviation flights are not valid because the public has become hardened to these somewhat frequent tragedies through familiarity. UAM introduces a completely new paradigm that the public must learn to trust over years of safe operations. One accident killing people on the ground during the introduction of these services would likely result in suspension of operations, perhaps permanently. Analogies include the Hindenburg disaster and the New York Helicopter Airways crash on top of the Pan Am building in New York.

The failure hazards faced by UAM operations can be placed into two broad categories, those failures that occur on the vehicles themselves and those that occur in the external environment that impact the safety of UAM flights. Nearly all failures can be anticipated through methodical safety analysis and their mitigations planned for in the design of the vehicles and their support systems. The hazard mitigations must be extremely robust as the target level of safety for UAM will likely be an order of magnitude better than the existing record of piloted aviation. The requirement for greater safety is simply a matter of the far greater numbers of people and property underneath the bulk of these flights.

The systems internal to the vehicles are mechanical, electrical and electronic (i.e., avionics). They are to be addressed through certification of the aircraft themselves. Mechanical systems include the fixed structure and all the moving parts – motors, rotors, propellers, tilting wings and moving control surfaces, buttons, batteries and wiring, seats, knobs and handles. In eVTOLs, the electrical system is the heart of the vehicle, responsible for everything to function, from propulsion, lift and flight control to powering all the avionics upon which the entire operation depends. Power distribution, modulation and conditioning must perform flawlessly in all operating environments. Battery temperature must remain stable during the maximum charge and discharge loads. Certification must account for all anticipated loads and failure modes of the components making up the total electrical system, including safe recovery of the vehicle in the event of total electrical shutdown.

The electronics in a UAM vehicle include the navigation sensors (GNSS, radar and optical) and processors; surveillance systems (ADS-B, radar and optical) and the separation and collision avoidance processors they feed; communications systems to send and receive weather data and those that are a part of surveillance and operational control, are all critical to the successful operation of autonomous UAM vehicles. Failures in any of these avionics systems must be accounted for in certification so that none is catastrophic, singly or in combination.

The external environment includes weather phenomena, the radio frequency and electromagnetic environment and the traffic and obstructions present within the navigable airspace. Hazardous weather is not a system failure, but the network to inform the vehicles of such conditions can fail in whole or in part. It is important for a UAV to know that the flight path ahead does not contain winds or turbulence beyond the performance capability or control authority available in the vehicle. Similarly, heavy precipitation or freezing rain or drizzle must be sensed, and its location conveyed to all traffic in the vicinity. Redundant and multiple communication networks must be available to receive the weather and surveillance information, so that single point failures do not bring an end to the flight. Inter-vehicle communications for collision avoidance and vertiport traffic management should also be redundant and use multiple frequencies. The same should apply to communication of geofencing applications to prevent conflicts at airports with piloted flights. Such failures in the support infrastructure are not part of the vehicle certification but their failure to deliver can be just as hazardous to the UAM operations. It is important that RTCA be tasked to create a Minimum Aviation System Performance Standards (MASPS) for UAM support systems in order to meet this requirement.

It is apparent that there will still be numerous failures for which redundant systems or carefully designed and manufactured components cannot mitigate. As most eVTOL designs in development will not be able to glide or autorotate to a safe location in an urban environment, a “smart” ballistic parachute recovery system that can glide to a safe touchdown point will likely be required on most UAM aircraft. The requirements for such a system were submitted to the NASA Langley Technology Transfer Program, in an entry called, “Guided Gliding Parachute Drone Recovery” but it is estimated at TRL 2 and requires substantial R&D to bring it to a ready state for UAS industry adoption. The hardware will likely be available from industry, but the smart guidance should be a NASA development. This is required for all UAM, not just ABTM.

Over the last two decades, NASA has sponsored many studies of aviation hazards and their possible mitigations. The research required to address the risks associated with UAM operations should take advantage of this trove of previous work to speed the process. In this context, the safety work is very closely tied to the AI developments that must take place to enable autonomous UAM flights. While currently estimated at TRL 3, NASA is ideally suited to lead this effort and speed its progress.

Addendum Conclusion

The list of foundational prerequisites to enable the ABTM for UAM concept to come to fruition have been identified by NASA researchers David Thippavong and David Wing and by the author himself. This list has been reviewed and analyzed to show how each technology is used in the ABTM concept, and the TRL of each has been estimated based upon its reported state of development and use in the UAS and piloted aviation industry today. A summary table of these findings serves as a high-level guide for needed additional research. It is seen that most of the technologies are already mature enough to be used in an experimental if not operational mode, and that adaptation to the specifics of UAM operations is the primary task still to be accomplished. Three exceptions are fully autonomous operations, self-separation and collision avoidance, and failure mode self-mitigation. It is considered of highest importance for NASA to continue to lead in the pursuit of these technological advances, specifically applied to the needs of aviation, both manned and unmanned. For UAM it is a financial imperative and for piloted aviation it is a safety imperative.

Finally, the bulk of this analysis has applied to sUAS, the low altitude, small UAS expected to be the first to operate regularly in urban areas. The larger eVTOL air taxis and even larger hybrid powered inter-city UAS being invented will contain the same avionics and use much of the same infrastructure as today’s piloted aviation. The primary difference proposed in the ABTM for UAM concepts for these larger and higher altitude flights is the use of AFR for separation from conventional piloted traffic in mixed airspace. This concept is described in detail in [5] and would be supplemented in the terminal area with controller-drone Data Comm for sequencing and spacing to regular airport runways (when used) and for takeoff and landing clearance and taxi instructions at those same locations. AFR is equally valuable to both piloted and unpiloted flights at all operating altitudes and should be pursued by NASA in both contexts as a fundamental improvement to the safety, capacity and flexibility of both UTM and ATM.

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14. ABSTRACT The excitement and promise generated by Urban Air Mobility (UAM) concepts have inspired both new entrants and large aerospace companies throughout the world to invest hundreds 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 have received much less attention, however, and even though NASA's lead is advancing some promising concepts for Unmanned Aircraft Systems (UAS) Traffic Management (UTM), most operations today are limited to line of sight with the vehicle, 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 vehicle-based traffic management in the very low altitude airspace within a metroplex called UTM airspace in which piloted traffic is rare. A management scheme was proposed in that work that takes advantage of the homogeneous nature of the traffic operating in UTM airspace. This paper expands that concept to include a traffic management plan usable at all altitudes desired for electric Vertical Takeoff and Landing urban and short-distance, inter-city transportation. The interactions with piloted aircraft operating under both visual and instrument flight rules are analyzed, and the role of Air Traffic Control services in the postulated mixed traffic environment is covered. Separation values that adapt to each type of traffic encounter are proposed, and the relationship between required airborne surveillance range and closure speed is given. Finally, realistic scenarios are presented illustrating how this concept can reliably handle the density and traffic mix that fully implemented and successful UAM operations would entail.					
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