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Enabling Airspace Integration for High-Density On-Demand Mobility Operations

Eric Mueller,[i] and Parimal Kopardekar[ii]
NASA Ames Research Center, Moffett Field, CA, 94035

Kenneth Goodrich[iii]
NASA Langley Research Center, Hampton, VA, 23666

Aviation technologies and concepts have reached a level of maturity that may soon enable an era of on-demand mobility (ODM) fueled by quiet, efficient, and largely automated air taxis. However, successfully bringing such a system to fruition will require introducing orders-of-magnitude more aircraft to a given airspace volume than can be accommodated by the traditional air traffic control system, among other important technical challenges. The airspace integration problem is further compounded by requirements to set aside appropriate ground infrastructure for take-off and landing areas and ensuring these new aircraft types and their operations do not overly burden traditional airspace users and air traffic control. These challenges for ODM may be significantly reduced by extending the concepts and technologies developed to manage small unmanned aircraft systems (UAS) at low altitude—the UAS traffic management (UTM) system—to higher altitudes and aircraft with humans onboard in controlled airspace, or by equipping ODM aircraft with advanced sensors, algorithms, and interfaces. The precedent of operational freedom inherent in visual flight rules and the technologies developed for large UAS and commercial aircraft automation will contribute to the evolution of an ODM system enabled by UTM. This paper describes the set of air traffic services, normally provided by the traditional air traffic system, that an ODM system would implement to achieve the high densities needed for ODM's economic viability. Finally, the paper proposes a framework for integrating, evaluating, and deploying low-, medium-, and high-density ODM concepts that build on each other to ensure operational and economic feasibility at every step.

I. Introduction

A growing community of interest is forming around the concept of on-demand mobility (ODM) for aviation.[1,2,3,4,5] The goal of ODM's proponents is to allow people to get to their destinations more quickly than they can today in cars by using aircraft for at least a portion of the trip. This goal is realized today with the traditional, scheduled commercial air transportation system only when the overall trip length is greater than about 300 miles.[6] To realize door-to-door time savings for trips down to 20 miles, passengers would fly on small vertical take-off and landing (VTOL) aircraft that can be summoned at any time (i.e. "on demand"), depart from local take-off and landing areas (TOLAs), and land at a TOLA close to their final destination. Orders of magnitude more aircraft than operate today would be required for this transportation architecture to serve a significant proportion of the public. The capacity of the U.S.'s current air traffic control system in the metropolitan areas in which ODM would operate is already saturated by 24,000 daily commercial operations,[iv] and in its current from will not support widespread ODM.

The technical challenge related to airspace integration for ODM is to provide concepts, technologies and procedures that enable orders of magnitude increases in the capacity of the airspace for ODM vehicle types and operations. The FAA's NextGen program aims to modernize air traffic control (ATC) and aircraft systems in order to increase the capacity of the airspace and reduce delays.[7] However, the projected capacity increases over the 20-year period starting in 2006 are expected to be no more than 50%.[8,9] While this increase will be sufficient to accommodate

[i] Aerospace Engineer, Aviation Systems Division, M/S 210-10, AIAA Associate Fellow.
[ii] Senior Technologist for Air Transportation Systems, M/S 210-2, AIAA Associate Fellow
[iii] Aerospace Engineer, Dynamic Systems and Control Branch, M/S 308, AIAA, Senior Member.
[iv] https://www.faa.gov/air_traffic/by_the_numbers/

the increased demand for scheduled commercial air travel on large aircraft, it is far below what is required to enable an ODM air transportation system. Research efforts to significantly increase the airspace capacity for *traditional aviation operations* have focused on automating the services provided by ATC,[10] automating the operations of aircraft so they are not dependent on ATC,[11] or accessing under-used small airports and remote airspace with increasingly automated aircraft.[12] Research to enable airspace integration for ODM typically relies on aircraft being sufficiently equipped and automated that they can operate relatively independently from the existing ATC system and are therefore not subject to its capacity limits.[1,13] While research on a UAS traffic management (UTM) system[14] for small UAS (sUAS) operating at low altitudes is relevant for ODM, it will provide services appropriate for small UAS that don't always easily extend to ODM. For example, the risk of human injuries in the collision of two sUAS is very low,[15] while larger vehicles with humans onboard will present significantly higher risks and the separation services provided by a UTM-like system will have to be significantly enhanced for ODM. sUAS also have the freedom to take off and land nearly anywhere, while ODM aircraft will be restricted to a network of TOLAs and therefore require scheduling and spacing services similar to what is provided by ATC today. Finally, research on airspace integration for larger UAS assumes they will operate under ATC supervision (i.e. according to instrument flight rules [IFR]), a requirement that is fundamentally not scalable for ODM.

The contribution of this paper is to describe an evolutionary approach to enabling the aircraft densities required for ODM that relies not only on advanced aircraft systems but also automated airspace services provided by a system that would extend the concept of the UTM system (i.e. a "UTM-like system"). The intention of this document is to introduce the ODM concept and technical barriers to its implementation related to airspace integration, which is discussed in Section II. Several approaches to evolving the existing system from its current state to one that supports an ODM traffic management system are described in Section III, along with the air traffic services necessary to support this evolution. The description of enabling services in Section IV is intended to provide a framework for defining the operational concepts and supporting technologies and procedures that will enable the growth of airspace capacity for ODM from today's low levels to a future in which trips as short as 20 miles are routinely taken by air. These concepts, which must be described in significantly more detail than is done in this paper, will eventually form a research and technology development roadmap for the ODM community. Critical to this roadmap is that at each milestone a safe, economically viable, and minimally impactful ODM system exists that increases the system's capacity over previous instantiations. The paper concludes in Section V with a suggested research and flight test approach consistent with such a roadmap.

II. On-Demand Mobility Concept

This section describes the concept for ODM and its key details, principles for successfully integrating ODM with the existing airspace, and the barriers to building and operating such a system in the current National Airspace System (NAS).

A. Overview of ODM

Several aspects of ODM aviation in metropolitan areas are relevant to understanding airspace integration requirements and constraints. The aircraft are expected to be professionally piloted in the near term, and evolving towards full automation as necessary to enable high-density ODM operations. Fully automated, the ODM aircraft would carry only passengers who are not involved in the conduct of flight operations except to select the destination. ODM aircraft will be relatively small, designed for one to four occupants with gross weights less than approximately 6000 lbs. The aircraft require VTOL capabilities combined with low noise and sufficient range and speed to be competitive with alternative modes of transportation (typically cars) over short to medium distances (e.g. 20-100 miles).[4]

ODM aircraft under development typically fall into one of two configuration types. The first type are large multicopters classified by the FAA as rotorcraft because lift during all phases of flight is generated by powered propellers or rotors.[i] The second configuration type use powered-lift (e.g. tilt-rotors or -wings) for takeoff and landing but transition to wing-borne flight during cruise.[ii] Operationally, rotorcraft configurations will have relatively simple flight envelopes in that they can smoothly operate between hover and their maximum airspeed, which may be on the order of 60 kts (i.e. Volocopter). In comparison, powered-lift configurations will have much higher efficiency and cruise speeds, perhaps surpassing 200 kts (i.e. Joby S2), but are likely to have more complex operating envelopes. That complexity results from the transition between low-speed, powered flight and higher-speed, wing-borne flight,

[i] See Volocopter (www.e-volo.com), EHang (www.ehang.com)
[ii] See Joby S2 (www.jobyaviation.com), Vahana (www.vahana.aero)

which divides the flight envelope at speeds around 75 kts. To maximize range and efficiency, powered-lift configurations should use wing-borne flight except during takeoff and landing operations. The relatively short mission ranges for both types of vehicles limits the typical operational altitude, the ultimate selection of which is largely dictated by safety and airspace integration considerations rather than maximum aircraft performance. A third category, conventional take-off and landing (CTOL) aircraft, are most often used in an ODM context for flying hundreds of miles between airports that are underserved by scheduled commercial operations. Because these flights inherently traverse less-used airspace they do not face the same airspace integration concerns of the first two aircraft categories and so are not a focus of this paper.

Factors such as community noise, downwash, and the need for approach and departure paths clear of obstructions make it likely that urban ODM aircraft operations will be conducted from a network of appropriately sited and equipped TOLAs. Even in densely developed urban areas, an assessment of potential TOLA sites on the ground and on large rooftops suggest that the distance from any location to a TOLA may be under two miles.[4] From an airspace integration perspective, TOLAs may be located in very close proximity to each other (e.g. neighboring roof tops) and TOLAs at high-demand locations are expected to have multiple pads to accommodate several aircraft simultaneously.

Given that ODM aircraft will operate within a network of TOLAs, a complete trip, from a departure address to destination address, will include two short ground segments and an air segment. To minimize space requirements associated with TOLAs, parking spaces may be limited and ride-hailing services will be a common means of managing ground segments. It is expected that seamlessly integrated air-ground transportation services will typically be used to evaluate, arrange, and monitor all three segments of a typical trip as a single entity.[3]

The ODM reference scenario representing "high-density" operations, as it will be referred to throughout the paper, would consist of approximately 1200 aircraft operating simultaneously over a large metropolitan area (e.g. the San Francisco Bay area, New York City, the Dallas-Fort Worth metro area). This fleet size equates to approximately one aircraft per nmi^2, compared with typical maximum enroute traffic densities of about one aircraft per 250 to 500 nmi^2 (densities increase significantly near airports, but are still far lower than this ODM reference scenario). Such a fleet might average four trips per hour, each carrying two passengers, over a 16-hour day. This scenario could support approximately 150,000 passengers per day, which would make it an important travel mode alternative to ground transportation, but it would still represent a very small proportion of the overall transportation options available to the public (about 2% of the automobile trips taken in the San Francisco Bay area per day).

Table 1. Summary of airspace integration principles for ODM

1.	**Does not require additional ATC infrastructure**
2.	**Does not impose additional workload on ATC**
3.	**Does not restrict operations of traditional airspace users**
4.	**Will meet appropriate safety thresholds and requirements**
5.	**Will prioritize operational scalability**
6.	**Will allow flexibility where possible and structure where necessary**

B. Principles of Airspace Integration for ODM

The probability of success in reaching the ODM goal will be improved by aspiring to a set of airspace integration principles derived from past successful and unsuccessful research efforts. These principles are concisely described in Table 1. First, the airspace integration concept should not rely on additional, centralized ATC infrastructure. The ODM aircraft fleet or its supporting network of services will have to provide the capabilities necessary to operate at high densities, including accurate tracking of ODM aircraft locations and intent, and regulating the flows of ODM aircraft into TOLAs and transition corridors. Closely related to this principle is that ODM operations should not pose an additional burden on ATC workload, a factor that already limits airspace capacity in many regimes.[16] Instead, the services traditionally provided by ATC to ensure safety and efficiency will be the responsibility of the ODM fleet and supporting network. Third, no additional requirements, restrictions, or burdens will be placed on existing airspace users; the ODM aircraft will be strategically separated from traditional aircraft during the trajectory planning process. Fourth, ODM operations will meet an appropriate level of safety consistent with the public's expectation of commercial transportation, and the concepts, technologies, and procedures designed to support those operations will incorporate a safety threshold as a *minimum requirement*. The safety threshold will be determined using a risk-based approach that considers the operational area and use case, including proximate air traffic. Fifth, ODM concepts will be designed to facilitate scalability, specifically avoiding solutions that could enable higher densities in the near term but would not scale in the long term. Finally, operational flexibility, efficiency, and density are the key goals of the ODM concept, and the system will be designed to maximize these metrics while adhering to the safety requirements.

This airspace integration principle may be achieved by instituting "flexibility where possible and structure where necessary".[14]

C. Barriers to ODM in the Current NAS

This section uses the example of an ODM flight between Silicon Valley and San Francisco, CA, to illustrate many of the airspace integration-related barriers to high-density ODM operations and motivate the need for the airspace concepts and capabilities described in Section IV. Related research efforts have identified barriers to ODM in addition to airspace integration.[4,5] An examination of the San Francisco visual flight rules (VFR) terminal area chart, shown in Figure 1, helps illustrate these barriers for a concept in which ODM aircraft initially operate under VFR.

The northern and southern regions of the SF Bay area are separated by surface-level Class B and C airspace that extends to 10,000 ft, airspace in which a VFR aircraft requires ATC permission to enter (passing around or over such airspace would present a significant set of additional challenges). Receiving permission during busy periods at either of the respective airports (SFO Class B or OAK Class C) is not assured for even a small number of VFR aircraft. A related problem is that there are few defined airways between the two regions and no charted VFR routes exist in this airspace. The first airspace integration barrier is the fact that the number of VFR/ODM aircraft accommodated by the current airspace is unquestionably low, and further it is unquantified. Even outside the terminal airspace areas in Class E and G airspace, where VFR aircraft may operate without ATC permission, the ODM density at which existing VFR aircraft are impacted is unquantified. A precedent does exist for establishing VFR corridors through Class B airspace in which aircraft do not have to receive ATC permission (see Section IVB), but again the increase in capacity it affords is unquantified. Approaches will have to be developed to maximize the airspace capacity for ODM without impacting existing users or requiring ATC to provide individual permission to enter terminal airspace, which could increase ATC workload significantly.

A second airspace integration barrier is the ineffectiveness with which the see-and-avoid capability of VFR aircraft provides safe separation, particularly as operations increase in density. In theory, the enroute airspace capacity should be related to the effectiveness of see and avoid, but this effectiveness and the airspace capacity have not been quantified. However, a variety of surveillance services now available to all aircraft (e.g. TIS-B, ADS-R) are designed to improve the effectiveness of see and avoid, and new UAS detect-and-avoid (DAA) systems may be adapted to cockpits of manned aircraft to first augment and eventually replace vision-based separation with electronic separation entirely. At first, such systems will be used only to increase the density at which VFR operations are safe in visual

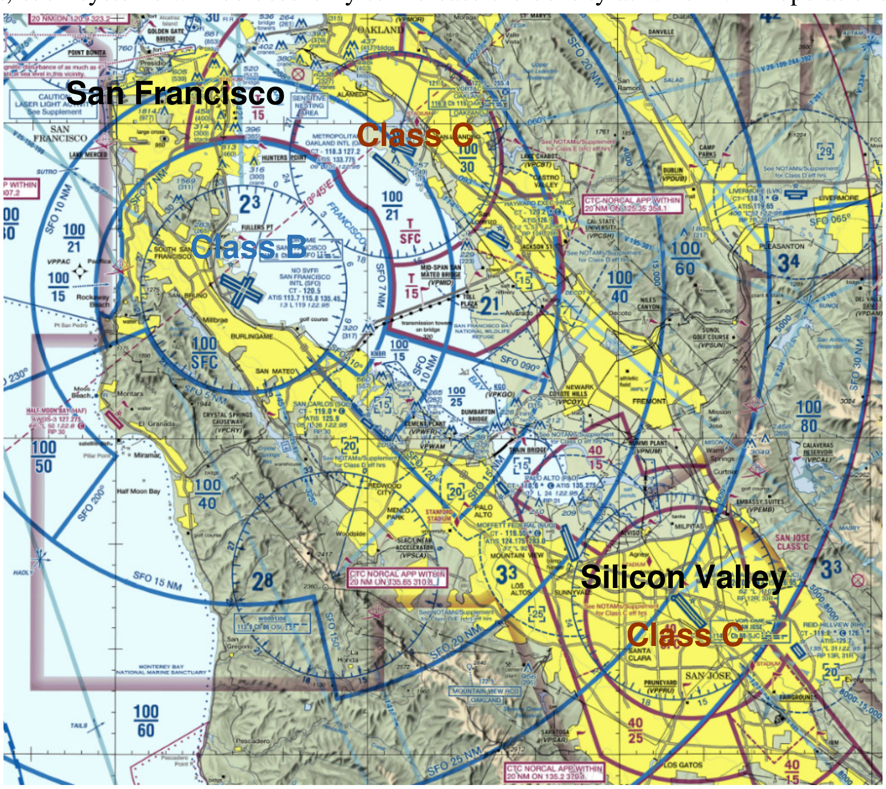

Figure 1. VFR terminal area chart for San Francisco Bay area (detail)

meteorological conditions (VMC). However, these capabilities should be directly applicable to the separation function under instrument meteorological conditions (IMC). The low-lying land in the northwest of Figure 1, roughly from SFO to the northern tip of the peninsula in San Francisco, is regularly blanketed by dense fog. A high-density ODM system cannot have access to key TOLAs shut down on most afternoons and evenings, so a third airspace integration barrier critical to enabling high-density ODM operations is the ability to preserve VFR-like operations and separation even under conditions of IMC. This barrier is a particularly high one because such operations require not only remaining well clear of other traffic, which was the sole required function for DAA systems, but also maneuvering, sequencing, and spacing relative to other aircraft, conducting precision approaches and departures, following navigation routes, and avoiding obstructions. These capabilities exist today for the most sophisticated commercial aircraft when receiving IFR ATC services, capabilities that must be replicated for ODM aircraft independently of ATC to surmount this barrier.

The fourth barrier to ODM is to select TOLAs consistent with community concerns like noise and ground vehicle congestion, obstruction-free approach and departure corridors, access to existing infrastructure, and proximity to popular passenger destinations to minimize door-to-door trip length. The complexity of building TOLAs in San Francisco to meet a subset of these requirements is evidenced by the current presence of only a single hospital helipad in the entire city.[4] These barriers may only be broken down when the wider public benefits from, and recognizes a need for, ODM operations and is consequently willing to tolerate additional aural and visual noise. As part of this exchange, ODM aircraft will have to significantly reduce their noise footprint, demonstrate high levels of safety for passengers and people on the ground, and provide significantly shorter door-to-door trip times at a reasonable cost. Finally, ODM aircraft will have to be sequenced and scheduled into the TOLAs efficiently so as to maximize the productivity of each TOLA.

The fifth airspace integration barrier is to ensure robust operational performance in the presence of contingencies. Nearly all ATC services depend on a single primary approach or concept, but require one or more redundant, independent backup approaches to guarantee safety. For example, large IFR aircraft are nearly always safely separated from each other by following procedures and receiving separation services from ATC, but they are still required to look out the window to see and avoid other aircraft and equip with an electronic collision avoidance capability. Similarly, ODM aircraft will likely require significant additional capabilities (including electronic collision avoidance and independent sources of surveillance data) that are employed only under unlikely contingency situations. This barrier will be removed by detailing the likely and consequential contingency situations and providing mitigations at the appropriate level of safety for every situation.

A sixth important airspace integration barrier for the medium to long term is how to structure airspace used by ODM aircraft and define ATC's role in support of the ODM concept. ATC will require a certain degree of control over ODM activities, ignoring those aircraft under nominal circumstances but retaining sufficient visibility into the performance of that system so that it can intervene when necessary to ensure the safety of the overall airspace. These interactions between ODM and ATC may have workload implications for controllers or present ODM capacity limits. At high densities it is unlikely that traditional VFR and IFR operations will be entirely unaffected by ODM, so mitigations will likely be necessary to ensure the objectives of traditional airspace users continue to be met.

III. Airspace Integration Strategies for ODM

The following section describes several different approaches to reaching the same final goal of deploying large numbers and densities of ODM aircraft anywhere in the NAS. Each approach leverages a different initial operating concept that is consistent with today's airspace regulations. While a different evolutionary path would be taken by each approach to achieve the final ODM goal, the technologies and procedures leveraged in those steps will frequently be common between the approaches.

A preliminary step exists in the introduction of new aircraft types and missions, and that is to obtain a certificate of authorization or waiver (COA). A COA allows aircraft and operations that do not comply with all applicable Federal Aviation Regulations (FARs) to employ alternate systems, technologies, or procedures to ensure such operations are safe and do not reduce the efficiency of the NAS. A typical example is the use of ground spotters or chase aircraft to comply with the "see-and-avoid" requirement (14CFR 91.113) by UAS. Although the use of COAs has become common for UAS, it is not a long-term or scalable approach to integrating ODM operations with the NAS.

A. Increasingly Automated IFR Operations

The typical approach used by many airspace integration research entities, including NASA, to improve the NAS or allow new types of operations is to evolve the roles and responsibilities of IFR aircraft or the ATC services that are provided to them. This is logical because the largest segment of the U.S. domestic aviation market, economically and by total passenger capacity, is commercial aviation that operates IFR under the supervision of an air traffic controller. Examples of important research efforts in this category that are relevant for ODM research include controller advisory tools for terminal area sequencing and spacing,[17] aircraft strategic[18] and tactical[19] separation, efficient trajectory optimization,[20] autonomous aircraft operations for traditionally IFR aircraft,[11,21] small aircraft transportation systems,[12] and demand-capacity balancing.[22]

In the last several years the airspace integration research community has been engaged in improving airspace access for a variety of non-traditional aircraft and their operations. The most relevant of these for ODM is the effort to introduce large UAS to the airspace as IFR aircraft.[23] That project developed important aircraft-centric technologies that have utility for ODM, including traffic displays,[24,25] separation algorithms,[26] and command-and-control communications radios.[27] Particularly important for ODM was research using simulations to quantify the risk of encounters that would result in unsafe separation between aircraft.[28,29,30] While the goal of this effort has been to make UAS operate in ways that are essentially indistinguishable from manned IFR aircraft, the technologies and functions necessary to do so could be readily used to increase the allowable density of ODM aircraft.

These research efforts on traditional IFR aircraft and UAS, along with their concepts, modeling and simulation infrastructure, algorithms, safety/capacity/efficiency metrics, human-machine interfaces, and other technologies can be adapted for ODM airspace integration solutions. However, the proposed increase in traditional IFR traffic volume enabled by these research efforts is largely incrementa,[l8] and occasionally quite optimistic,[31] but in no cases are the hoped-for increases more than a factor of five to ten above current traffic levels. As optimistic as these estimates are, they do not begin to approach the orders-of-magnitude increase in traffic density necessary to enable an economically viable ODM transportation system. For reference, the 3-nmi separation requirement for aircraft in busy terminal areas is shown as a red circle superimposed over the city of San Francisco in Figure 2. The current requirement would allow *a single IFR aircraft* to operate in each 1,000 ft layer above the city at a time—a city of 840,000 people and just under 500,000 vehicles registered with the Department of Motor Vehicles.[i] The allowable density of aircraft is actually even lower than implied by this figure: the separation requirement coupled with the controller's method of separating aircraft actually results in a maximum enroute density of approximately one aircraft per 250 to 500 nmi^2. This density is independent of the type of aircraft, it only matters how many aircraft are operating under IFR. Oakland Center high-altitude sectors 40 and 41, shown on the right side of Figure 2, have a maximum capacity of 15 or 25 IFR aircraft (depending on whether they're split or combined) and a total area of about 8,000 nmi^2. Achieving the densities required by an ODM system will require a different approach than is currently used to increasingly automate the flight decks of commercial aircraft and the duties of ATC, an approach that is not governed by IFR separation standards and capacity limitations.

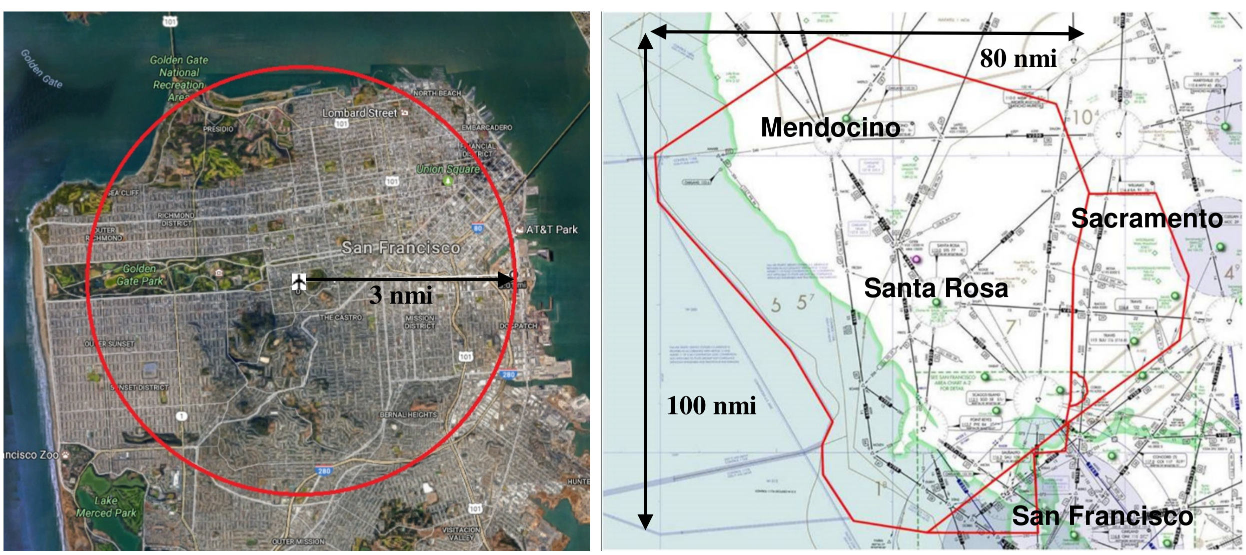

Figure 2. Terminal-area IFR separation superimposed over San Francisco (left), and Oakland Center (ZOA) sectional chart (right)

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[i] See https://www.sfmta.com

B. Increasingly Automated VFR Operations

A second starting point for the evolution of an ODM system uses the precedent of VFR operations. Although currently VFR flights are limited to operating in a subset of the airspaces and weather conditions available to IFR flights, they are not subject to the geographic traffic density limits of IFR flights (the sector "monitor alert parameter" values or traffic flow management initiatives). They may also determine the allowable separation between themselves and other aircraft, constrained only by 14CFR91.111 and 113 that they remain "well clear" of and not operate "so close … as to create a collision hazard" with another aircraft. When a pilot is onboard an aircraft (as opposed to remotely operating a UAS), the size of that "well clear" region is a subjective judgment. The degree of autonomy from the existing ATC system provided by VFR operations may prove a better starting point from which to evolve ODM capabilities "forward" to greater operational access, than starting from the greater operational access of IFR operations and trying to "roll back" the operational restrictions (capacity limitations and separation requirements) by automating flight deck and ATC functions. A summary of key operational differences relevant as starting points for ODM are summarized in Table 2.

Table 2. Summary of operational differences for ODM starting points

	VFR starting point for ODM	IFR starting point for ODM
Pros for VFR	No *explicit* ATC-imposed capacity constraints	Severe capacity constraints
	No ATC imposed separation standards	Large separation requirements: 3 nmi in terminal areas, 5 nmi enroute, 1000 ft vertically
	No ATC communication required in airspace Classes E and G	ATC approval required for all flight plan changes
	No flight plan approval required	Flight plan submission and approval required before departure
Cons for VFR	May not fly in IMC	Allowed to fly in IMC
	Excluded from airspace classes B, C and D without ATC communications	May fly in all airspace classes subject to capacity and separation constraints, additional limits in Class G

The critical question arising from a decision to start conducting ODM operations under VFR is how difficult will it be to add capabilities to the ODM aircraft or supporting UTM-like system to enable airspace access equivalent to that of IFR aircraft (and without its capacity limitations). When considering how a VFR operation must evolve to allow greater airspace access, it is useful to consider the factors that contribute to accidents when such aircraft encounter IMC. In other words, what circumstances preclude a VFR aircraft from operating in IMC? ODM aircraft will have to be able to deal safely with the following factors to begin to operate in a manner more akin to IFR operations:[32]

- Inability to separate from other aircraft because of the loss or degradation of their see-and-avoid capability.
- Adverse weather in which the aircraft is not capable of flying (e.g. severe icing), and the inability of the pilot to aviate and navigate under conditions in which they cannot reference out-the-window objects.
- Controlled flight into terrain.

The ability to operate in IMC is not the only distinguishing factor between VFR and IFR. Many ATC services are provided to IFR aircraft unrelated to separation in IMC (e.g. sequencing and scheduling), and similarly an ODM system that started under VFR operations would need to provide many of those additional services. For example, ATC balances the demand for and capacity of the airspace through a variety of mechanisms and regulates the flow of aircraft in and out of those regions when necessary. When airspace is systematically oversubscribed, the FAA can define special airspace constructs like arrival and departure routes, VFR transition corridors, and special flight rules areas to manage the demand and increase capacity. The ODM concept will have to consider how it will achieve the outcomes that these approaches deliver and how to design new approaches when necessary.

C. Expanded UTM-like Services

A third approach to introducing new aircraft types and operations to the NAS has its origins in 1981 with the FAA's model aircraft guidelines.[i] The freedom to operate those small aircraft so as to avoid any interactions with manned aviation became the precedent by which NASA's UTM system has gained the support of the FAA. The guidance provided by AC91-57A applies to unmanned aircraft (i.e. "drones" or model aircraft) under 55 lbs that are flown within line-of-sight distance of their remote pilot, and it describes a set of operating requirements distinct from either IFR or VFR. Although the current scope of the UTM system is only focused on these small aircraft types operating in uncontrolled airspace (generally altitudes below 700 ft), the concept it embodies may well provide a template for a new way of managing the operations of many types of future aircraft in the NAS, including high-density ODM.

The UTM system was designed around the same six airspace integration principles described for ODM in Section II0. In particular, it provides the air traffic services necessary to safely and efficiently manage small UAS (sUAS) at low altitudes without burdening ATC or impacting traditional aviation operations. The central agents in the UTM architecture, shown in Figure 3, are the UAS service suppliers (USS), which provide demand-capacity balancing, separation, sequencing, data exchange, trajectory planning and other services to a variety of stakeholders including the UAS operators themselves and public safety.[14] In some cases, multiple USS can each provide similar services to UAS operating in the same airspace (e.g. trajectory planning), while in others a single USS should be responsible for a given airspace or constrained resource (e.g. separation, sequencing). The USS can provide these services because they depend on information collected by supplemental data service providers, which manage data related to weather, airspace surveillance, terrain, and other relevant aspects of the sUAS operating environment.

The only two-way interaction USS's have with NAS systems is through the flight information management system (FIMS). The FIMS manages data flowing from the USS, including operational data and flight deviations that could impact the NAS, and sends constraints and directives to the USS for distribution to appropriate operators. The USS may also incorporate NAS data sources directly, for example those contained in the system-wide information

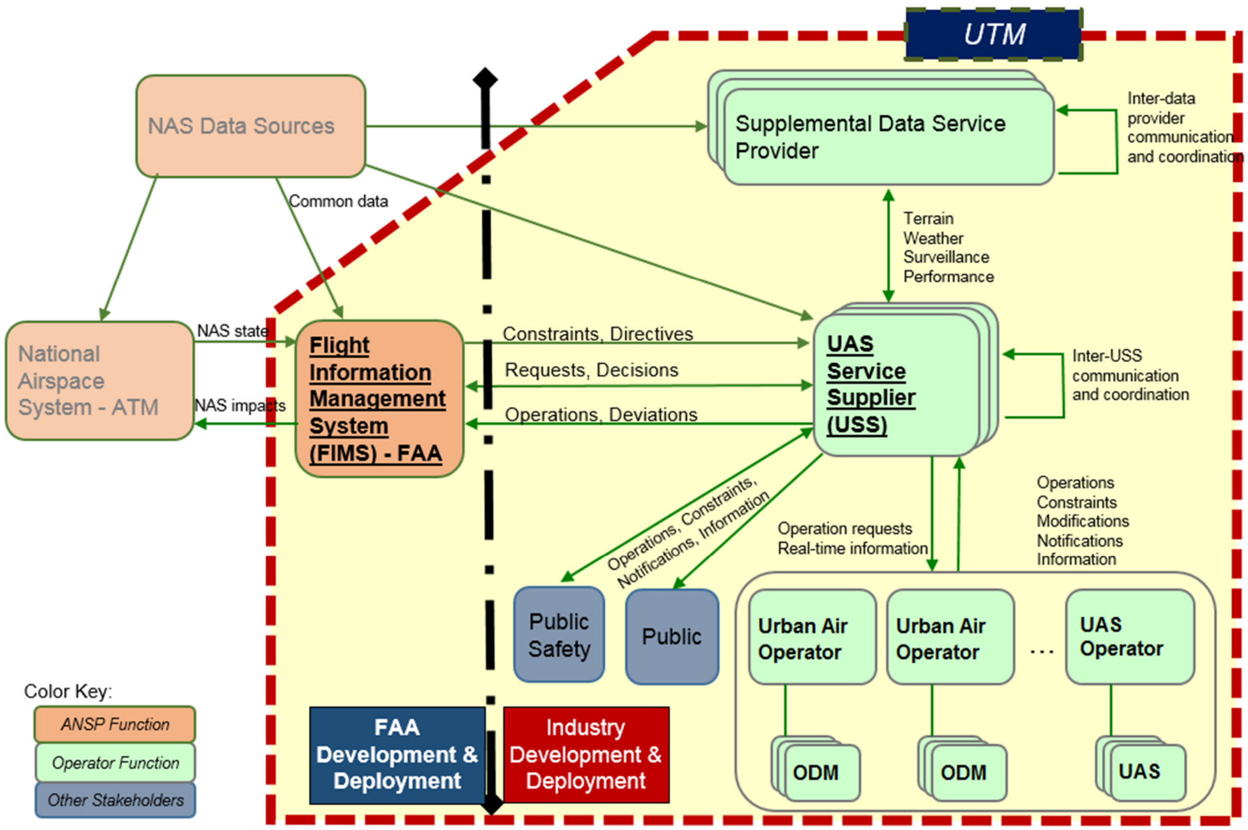

Figure 3. UTM System Architecture

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[i] See advisory circular (AC) 91-57, issued 06/09/1981, replaced by AC 91-57A on 09/02/2015 and updated 01/11/2016.

management (SWIM) system. This architecture has the benefit of allowing public or private interests to develop USS according to a well-defined interface that doesn't rely on government investment. The UTM system will be more responsive to the needs of users and able to take advantage of technological improvements. It will also provide a testbed for a set of relatively low-risk operations upon which may be built a safety-critical system that provides services to much larger aircraft in non-segregated, controlled airspace, even aircraft with humans onboard.

The UTM system is essentially an ATC system that runs in parallel to the traditional system but serves a different class of aircraft. While in principle UTM could apply to any aircraft, two fundamental differences exist between the vehicles intended to operate in UTM and those of ODM. First, people will be onboard the ODM aircraft, and, second, ODM aircraft will be interacting with other aircraft in controlled airspace to a much greater degree than sUAS will under UTM (because sUAS will largely operate in uncontrolled airspace at altitudes under 400 to 700 ft, while ODM aircraft will operate between perhaps 1,000 and 3,000 ft). The effects these differences have on the appropriate concepts of operation, procedures, and technologies for a UTM-like system that enables high-density ODM will be understood through research and development. Some of the differences are described in the context of specific capabilities required for ODM in Section IV.

The benefits of using a UTM system are similar for ODM and sUAS: they reduce the requirements on individual aircraft and therefore lower the barriers and costs for accessing the airspace. sUAS simply cannot perform all functions required for airspace integration because of size, weight, and power (SWAP) limitations. While ODM aircraft could provide most of the required airspace integration functions as they do today under VFR, they would need significant additional equipage and capabilities to operate at higher traffic densities, capabilities that would likely make them economically impractical. The ODM UTM system could offload those capabilities from the ODM aircraft, which would reduce the cost of individual vehicles and improve scalability. Further, once safety-critical airspace integration functions are being run in the UTM system separately from the aircraft, there will be little reason to have pilots onboard. Eventually, in conjunction with advanced vehicle automation, several pilots in a command center may manage a fleet of ODM aircraft to intervene in contingency situations, further lowering the costs of ODM operations and improving the scalability of the system.

The functional similarity between UTM services for sUAS and for human-carrying ODM aircraft should not lead to the conclusion that UTM can be immediately and trivially applied to enable this new type of operation. ODM will require services that sUAS do not: sequencing, scheduling, and spacing into capacity-constrained TOLAs, and trajectory planning that includes wake avoidance criteria. Even for those services that will be common, their safety thresholds and robustness to contingencies will be significantly more stringent. The aircraft separation service will be required to meet a threshold of no greater than about one collision per 10^7 flight hours, which is the required rate for large UAS interacting with VFR aircraft[33] and the achieved rate of IFR commercial carriers.[34] The UTM separation services will be required to meet orders-of-magnitude lower safety thresholds because collisions between sUAS will be orders-of-magnitude less damaging and deadly. Finally, ODM aircraft will routinely interact with VFR and IFR aircraft in controlled airspace, while sUAS operating under UTM will be largely separated from those aircraft procedurally or by notification.

D. Leveraging the Airspace Integration Approaches

The best approach to enabling an ODM air transportation system is likely to employ all three of the previously described airspace integration strategies. As shown in Figure 4, the starting point is the use of VFR operations and other procedural methods (see Section IVB) because those operations can be conducted today, they allow aircraft to take responsibility for their own separation, sequencing, and trajectory planning functions, are free from existing ATC capacity limitations because they do not burden that system when ODM density is low, and are relatively inexpensive

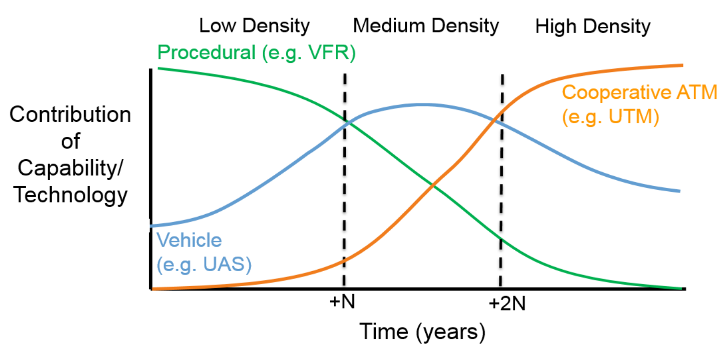

Figure 4. Notional contributions of different airspace integration solutions as a function of ODM aircraft density

because they require no new aircraft equipage. The development and deployment of new technologies and infrastructure will enable phases of ODM operations with successively higher traffic densities and less reliance on rigid procedures and airspace constructs.

While the starting point of VFR operations for ODM has a number of important characteristics, it is not a long-term solution because of safety and scalability limitations. Separation from other aircraft, terrain, obstacles, and weather (i.e., IMC) is provided by the pilot's vision and judgment. These and other required functions will benefit from the use of advanced onboard technologies to increase safety and aircraft density while relying less on airspace structure and other procedural mitigations. Responsibility for aircraft operations will continue to lie with the pilot and vehicle systems and not with ATC. The safety and density of ODM operations will increase significantly in this phase, but the increased cost of each aircraft will be commensurate with those benefits. Therefore this is not the long term solution for ODM.

Although the addition of vehicle technologies will enable greater density of the ODM system in the medium term, the additional equipage costs for each new ODM aircraft will limit the economic viability of the overall concept. As systems like UTM and their manned aircraft equivalents mature, investments in that infrastructure will partially relieve individual aircraft of the requirements to equip with sensors, algorithms, displays, and their associated flight-rated hardware (backup capabilities will still be required). Instead, a robust communications capability will allow networked infrastructure to provide these services, lowering the marginal cost of adding aircraft to the system. An important secondary benefit of having such a safety-critical communications capability and off-board air traffic services is that the pilot will no longer have a compelling reason to be located on the flight deck. Instead, remote command centers will allow humans to oversee the largely automated aircraft and intervene only when contingency procedures warrant. Procedural approaches to higher airspace densities will largely disappear except to provide continued service for traditional airspace users. This reliance on a matured, human-rated UTM-like system should greatly lower the marginal cost of additional ODM aircraft and operations and enable the high-density reference mission described in Section IIA.

E. Assumptions

This paper makes no explicit assumptions about the level of automation either onboard the ODM aircraft or in an external entity with some level of control over the aircraft (e.g. a fleet command center, similar to a traditional airline operations center, [AOC]). In most cases, either a human or automation system could perform the functions required for ODM aircraft to integrate in the airspace. However, the type of function being performed, the timeframe of implementation of the concept, and the availability of technologies make certain divisions of responsibility between human and automation and between onboard and offboard the aircraft more natural than others. Where appropriate, the natural division is described for each function required to integrate ODM with the airspace.

The approach proposed in the previous section to increase ODM capacity and efficiency incrementally by leveraging the procedures and technologies developed for related aviation applications is based on the judgment of the authors. It has been suggested that revolutionary, rather than evolutionary, changes in the autonomy of ODM aircraft will be developed and make the proposed approach obsolete. Although it is possible that a fully automated ODM aircraft could be developed, it is unlikely to obviate the need for the airspace integration approach described here. First, the key difficulty of airspace integration is that it requires interoperability with all other airspace users, a requirement that is relatively unaffected by the degree of autonomy of an individual ODM aircraft. Instead, the required degree of interoperability depends on where that aircraft would operate and which aircraft also plan to use that airspace. Secondly, a highly automated aircraft could remove the need for some externally provided airspace services. Such an aircraft is actually expected in the second phase of the proposed approach (see Section IIID), however it is expected to be more expensive than will be required for high-density ODM. Finally, attempting to completely automate an ODM aircraft without relying on a human pilot or external air traffic services may unnecessarily re-invent well-defined airspace integration capabilities and make such an aircraft more difficult to certify. For these reasons, an evolutionary, incremental approach to high-density ODM is preferred over reliance on a revolutionary approach.

IV. ODM Airspace Concept – Enabling Capabilities

Given that the approach to enabling ODM will begin with a level of airspace autonomy established by the precedent of VFR operations and will evolve with vehicle-centric technologies towards a UTM-like system, the services provided to IFR aircraft by the traditional ATC system will have to be replicated for the specific ODM application. These services do not stand by themselves, instead they are highly interdependent and integrated. As suggested by the nested functions in Figure 5, the relationship is not strictly hierarchical: "core" attributes like

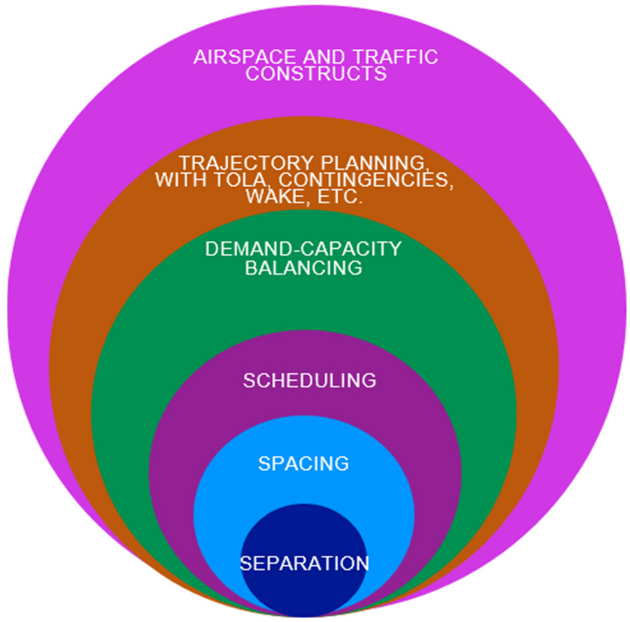

Figure 5. Layering of airspace integration capabilities required for ODM

separation must be considered by every other airspace integration capability, and "outer" functions like airspace constructs are designed to simplify the implementation of core functions. This section describes these interrelated services and capabilities and identifies relevant research that could be applied to ODM. Where appropriate, the solutions are described both from a near-term operational deployability perspective and a long-term scalability perspective. These capabilities are not intended to describe final designs or solutions, rather they are starting points for further trade studies based on data, analysis, modeling, simulation, and flight test.

A. Demand-Capacity Balancing and Airspace Flow Management

The airspace capacity for IFR aircraft has been established through historical experience, with enroute capacity governed by controller workload (particularly in maintaining sufficient awareness of the relative proximities and velocities of aircraft for conflict resolution purposes, along with managing aircraft handoffs with neighboring sectors and their associated frequency changes), terminal capacity by the allowable inter-aircraft spacing on arrival and departure procedures that is robust to contingencies, and airport capacity by wake separation requirements and runway occupancy times. Traffic flow managers use a variety of tools to predict the demand for these resources, and they use a multitude of procedural and technological approaches to ensure the capacity of each is not exceeded.

The airspace capacity for VFR aircraft is much less well established and rarely, if ever, explicitly quantified. In large part this is because the demand for such operations is usually low. However, in specific circumstances the demand does exceed the commonly understood capacity; in these cases procedural mitigations or equipage requirements are imposed to improve safety and efficiency. A common approach to increase airspace capacity during infrequent, high-volume events is to publish detailed procedures in a NOTAM[i] and rely on pilots' experience and judgment to follow them correctly. This approach has been generally successful, for example, at enabling a small Class D airfield (OSH) to become the busiest airport in the world for one week each year during the Experimental Aircraft Association's Oshkosh airshow with over 10,000 aircraft arriving and departing, although accidents are not uncommon.[ii] A commercial ODM air transportation system with paying customers will require a far lower risk tolerance that procedural approaches are unlikely to achieve for anything other than low-density operations.

The capacity of a given airspace for VFR-like operations with additional automation features will have to be determined as a first step in balancing capacity with demand. Capacity will not be a single, absolute value; instead, it will be a function of the allowable risk of adverse aircraft-to-aircraft interactions with the potential for collision. The threshold for this risk may be determined by many factors, including the requirements of the regulators, public perception, and insurers, but the particular threshold will be combined with research data indicating the capacity that corresponds to this risk. Airspace capacity may be a function of many factors in addition to risk, including the types

[i] See https://www.eaa.org/~/media/files/airventure/flyingin/2017-airventure-notam-final-%2003-29-17.pdf
[ii] See https://www.ntsb.gov/_layouts/ntsb.aviation/brief.aspx?ev_id=20070801X01080&key=1

of ODM operations and aircraft, the time of day, weather conditions, vehicle-specific reversionary capabilities, and historical traffic scenarios. ODM airspace demand-capacity balancing will likely follow a more automated model of the procedures and tools used to manage IFR demand today.

In today's airspace, traffic flows are managed to balance capacity and demand largely in and around the terminal areas (on arrival and departure procedures) and the runways. The ODM system will likely require flow management in these airspaces as well, with the airspace outside the vicinity of TOLAs only reaching saturation at high density levels. The (initially) small number of TOLAs will likely be an immediate limiting factor on the capacity of the ODM system, with the passenger disembarkation/embarkation time or refueling/recharging time governing that limit. For TOLAs at which aircraft may taxi to a parking spot (i.e., a vertiport) rather than dwell on the landing pad (i.e., a vertistop) the limiting factors may be the pad occupancy time, the wake and inter-aircraft separation requirements during departure and arrival, and/or community noise concerns. The capacity limits on airspace constructs like airways (i.e., highways in the sky) and ODM corridors are likely to be determined by wake vortex separation requirements, navigational and surveillance systems accuracies, the timeliness and degree of control that may be exercised over the vehicle's trajectory, and contingency procedures. Preserving a reasonable traffic flow or density appropriate for a given airspace is a key strategy to ensure that tactical functions (e.g., separation, spacing) will be safe and efficient.

Flow controls to balance demand and capacity are usually implemented on a strategic level by comparing the predicted number of operations in a given period for a given resource (e.g., TOLA) to a fixed, maximum allowable number of operations. When this occurs in the traditional ATC system, specific flow control procedures are implemented: ground-delay or ground-stop programs, severe weather avoidance routes, or TRACON arrival metering through miles-in-trail requirements. A UTM-like system could play this role in low-density ODM operations because of its ability to aggregate and analyze proposed flight plans, which could be extended to predicting when pre-determined safety thresholds will be violated and triggering the activation of capacity-balancing procedures. The UTM system has already conducted flight demonstrations of the ability to ingest flight plans and notify other users when operations would conflict.[35] Such pre-determined procedures are likely to be overly restrictive for high-density operations, and instead advanced vehicle or UTM functions would manage flows in near real time by considering the specific capacity-limiting factors rather than applying a generic limit.

B. Airspace constructs

Airspace constructs are broadly defined as a set of procedures, equipment and operating requirements, and training standards used in the traditional ATC system to improve operational safety and efficiency and accommodate certain limiting characteristics of the aircraft and ATC equipment. For example, airspace classes have been established to differentiate the densities and types of operations contained within them and compensate for the limitations of aircraft and ATC systems and personnel. Low-altitude uncontrolled airspace (Class G) is not covered by ATC radar and so no IFR services are provided, largely restricting those airspaces to VFR traffic. Airspace above 18,000 ft (Class A) is primarily used by jets flying at high speeds, speeds that make the pilot's use of see-and-avoid for separation impractical, and therefore VFR aircraft are prohibited from operating there. Terminal radar approach controls (TRACONs), which surround large airports or clusters of airports, have established capacities based on arrival and departure procedures, and demand-capacity balancing is achieved by metering arriving aircraft into that airspace and regulating the departures of aircraft from airports and runways in the TRACON. New airspace classes are unlikely to be defined for ODM aircraft, though in the long term ODM operations and concentrations may be sufficiently different from traditional users that a benefit may exist to standardizing ODM airspace access.

Fixed infrastructure and human cognitive limitations have necessitated the segmentation of enroute airspace into centers and sectors. Sectors are the basic airspace unit for which one or two controllers provide all air traffic services, and the sectors' capacities are driven by human workload limitations. National-scale flow capacity limitations are determined by these human constraints. Airways were defined to allow aircraft to navigate using radio beacons (VORs and DMEs[i]) before GPS became available. Aircraft flying in different directions along the airways separate by altitude using a procedure known as the "hemispheric rule," and the required 500 ft vertical separation between IFR and VFR aircraft is a result, in large part, of the altitude measurement accuracy of a barometric altimeter. ODM aircraft should not be subject to these requirements because they will operate VFR at low altitudes in which the hemispheric rule doesn't apply; however new airspace regions may need to be defined within the ODM system that are used to balance ODM aircraft capacity and demand. These regions would not affect the operations of traditional airspace users, but the regions' capacities could be determined in part by the activities of those users.

[i] VHF omnidirectional range (VOR) beacons and distance-measuring equipment (DME)

VFR corridors provide routes for VFR aircraft to pass through busy terminal areas (Classes B/C/D) with less disruption to IFR aircraft and ATC. One of these corridors, a special flight rules area (SFRA) over Los Angeles International Airport, is unique in allowing VFR aircraft to pass through Class B airspace at specific altitudes without receiving permission if they follow appropriate procedures (see Figure 6). This SFRA may set an important precedent that allows ODM aircraft to fly in airspace that would traditionally be off-limits to such operations.

A common feature of these constructs is that they require airspace users to follow pre-established rules that reduce the occurrence of situations requiring a tactical resolution. This reduction in tactical resolutions does not require coordination with other users or ATC (i.e. airspace structures/constructs have reduced the burden or workload on other NAS participants), and it reduces the required scope of air traffic services, potentially at the expense of airspace efficiency and capacity. In general, more sophisticated services or degrees of coordination may increase capacity and efficiency by removing the constraints of airspace constructs,[36] a theme that will be critical to the feasibility of high-density ODM operations. However, the airspace constructs in the traditional ATC system will likely undergo only evolutionary changes over the next several decades,[7] which means that a new system supporting ODM operations will largely have to complement these existing airspace constructs.

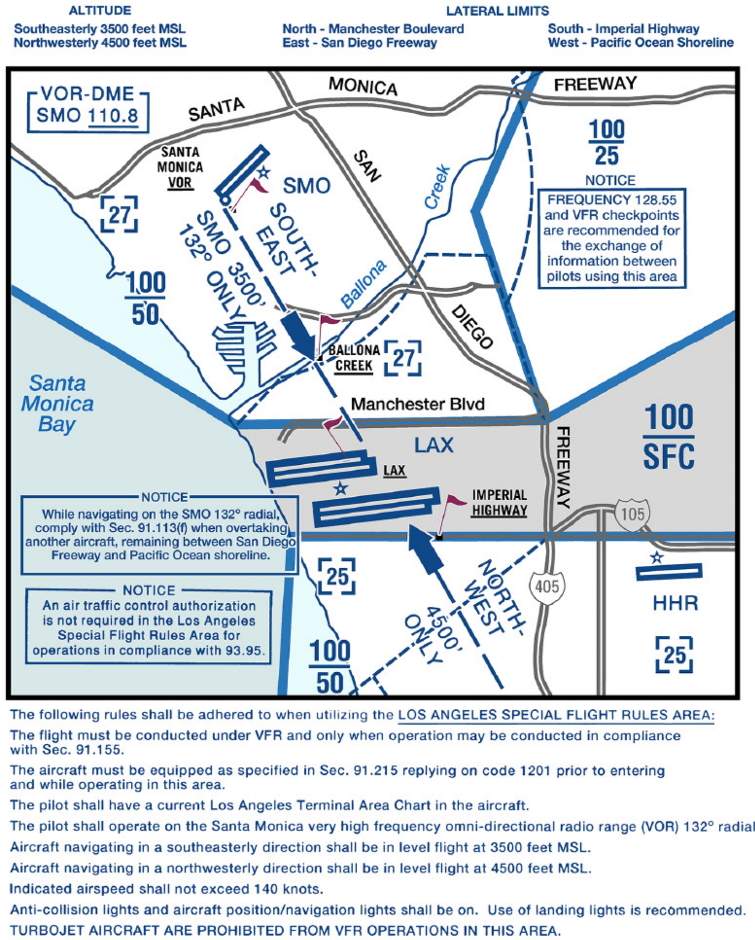

Figure 6. Los Angeles Special Flight Rules Area

Airspace constructs that apply only to ODM aircraft are likely to play an important role in enabling low- and medium-density ODM operations. For example, corridors may be established for ODM aircraft with published procedures and supporting navigation and in-trail spacing systems that allow much more dense and closely spaced operations than are typically possible with traditional VFR aircraft. ODM aircraft could equip with a wide-area augmentation system (WAAS)-enabled GPS system to achieve an appropriate level of required navigation precision (RNP)[15] and set a transponder code common to ODM aircraft in a published corridor (e.g., 1204). With an automatic dependent surveillance-broadcast (ADS-B) Out/In system, they would broadcast accurate position and velocity information to neighboring aircraft, allowing other ODM aircraft to infer which aircraft are conforming to ODM corridor procedures. They would be equipped with a relatively short range, forward facing radar or lidar (range of about a mile, consistent with Oshkosh's suggested ½-mile minimum in-trail spacing) to satisfy wake separation requirements from in-trail aircraft and to provide an active, non-cooperative backup collision avoidance capability that augments ADS-B. The aircraft equivalent of "on ramps" and "off ramps" would be defined by procedures. These procedures would also specify operational requirements (e.g., maximum and minimum velocities, altitudes), pilot training requirements, equipment requirements, and contingency procedures. Airspace structures designed to enable dense UAS operations could provide other initial design points for ODM.[37,38] These airspace constructs may be able to achieve medium-density ODM operations with technologies already deployed across a variety of commercial operations; the procedural and other requirements could be determined through a series of technology integration flight tests.

Although highly constrained airspace corridors are likely to play an important role in low- and medium-density ODM operations, the use of airspace constructs to reduce the requirements on vehicle systems should be minimized in the long term. Instead, aircraft will be allowed to operate everywhere outside the high-density corridors of the traditional airspace users (e.g., approach and departure corridors of large transport aircraft), and real-time exchange of state and trajectory data will enable separation, sequencing, and spacing applications rather than relying on procedures. This change will occur when the current and future states of ODM aircraft are known to high accuracy and a distributed or centralized system is able to quickly and efficiently detect and resolve airspace problems (e.g., potential collisions, failures to meet scheduled times of arrival at TOLAs). A UTM system could be the repository for this current and predicted state information, allow algorithms access to the repository to solve the problems, and distribute resolutions over a robust communication network to appropriate aircraft. However, a significant amount of information is required in addition to aircraft states: the allowable aerodynamic maneuvers of aircraft, their remaining useful range, meteorological conditions, the effects of contingencies, and many other factors. The challenge of building a UTM system to support high-density ODM operations will largely be one of understanding all of this information in real time (rather than relying on procedures and constructs to dictate many aspects of the system's state), reasoning about how to drive the system to the desired overall state, and distributing appropriate courses of action to all relevant agents in a timely fashion.

C. Sequencing, Scheduling, and Spacing

When the demand for a TOLA, VFR/ODM corridor, or other limited airspace resource exceeds its capacity, it is necessary to regulate the flow of aircraft accessing that resource. This process is done today by implementing procedural and operational requirements, for example requiring voice coordination with an ATC tower at a controlled airport and recommending communication over a common traffic frequency at an uncontrolled airport. In more complicated situations—for example arrivals into metroplex terminal area airspace—the flow may be regulated dynamically by human controllers using sequencing, scheduling, and spacing algorithms.[39] The former approach, which is used with VFR aircraft today, will satisfy safety requirements only when a TOLA is used infrequently. For TOLAs or corridors in which multiple aircraft routinely require access, it will be necessary to have some form of positive control. The airspace integration principle of minimizing new ATC infrastructure dictates that a control tower at each TOLA or corridor to communicate by voice with ODM aircraft will not be a scalable solution. Instead, automated sequencing, scheduling, and spacing (SSS) algorithms will be required.

The typical approach for an SSS algorithm is to determine the sequence in which aircraft are permitted to access the resource, schedule the access time according to the time the resource is required and the aircraft's position in the queue, and finally space the aircraft so that they arrive at the constrained resource point at the scheduled time. For IFR aircraft entering a terminal area, a first-come, first-served procedure determines the arrival sequence.[39] The schedule is then set according to the resource usage time, however this schedule may not directly translate into inter-aircraft spacing requirements for VTOL ODM aircraft because of their large range of allowable airspeeds.

Several options exist for the architecture of SSS concepts. In the near term, with lower densities of aircraft and fewer TOLAs, each vertiport or vertistop could manage its own arrival and departure queue and broadcast instructions to ODM aircraft that are produced by an algorithm similar to the FAA's Time-Based Flow Management (nee Traffic Management Advisor).[39] The aircraft themselves would plan paths to arrive at the appropriate time corresponding to their position in the queue, with strategic deconfliction of their paths perhaps assisted by published arrival and departure routes. Such routes would be akin to simplified versions of the standard instrument departure (SID) and standard terminal arrival routes (STARS) that are used by aircraft in the existing ATM system.[40] NASA's Small Aircraft Transportation System (SATS) project successfully flight tested an automated, centralized sequencing and scheduling algorithm that could be extended to ODM operations.[41] Tactical conflicts between aircraft using the same TOLA could be managed by cooperative or centralized algorithms modeled after approaches being tested for busy IFR terminal areas,[42,43,44,45,46,47,48] however these algorithms are designed to assist an air traffic controller in the traditional ATM system. The concepts of operation of these algorithms could be adapted so that the SSS and separation approaches for ODM require no human oversight and can operate in a fully automatic mode.

In the longer term, interactions between aircraft arriving at and departing from nearby TOLAs and the higher overall density of aircraft suggests that safer and more efficient SSS operations will be possible if a centralized algorithm is aware of the overall traffic situation and can make equitable decisions considering the preferences of all ODM system users. An alternative is to modify the algorithms and interfaces so that they work in a distributed architecture with each pilot negotiating and managing conflicts and queue placement, modifications that have been demonstrated to be feasible, efficient, and safe.[49,50]

D. Separation from other Aircraft

Ensuring that aircraft maintain appropriate separation that reduces the probability of collision to an acceptable level is a fundamental function of ATC and a responsibility of all pilots regardless of the flight rules under which they are operating. While the requirement to "see and avoid" other aircraft has been deemed sufficient for VFR aircraft separation in most circumstances, the limitations of that capability are responsible for a variety of mitigating procedures (e.g., following VFR corridors in terminal areas and receiving permission to enter them) and equipment requirements (e.g., transponder equipage above 10,000 ft and at any altitude while in a terminal area). While ODM aircraft will be subject to those same requirements from the start, higher ODM densities will require additional procedural and technological solutions. Special approaches may be required for ODM aircraft to successfully separate from aircraft during the merging operations that accompany sequencing procedures because of the highly constrained nature of those operations.

Traditionally, separation between aircraft is achieved with a multi-layer mitigation strategy that will likely also apply for ODM aircraft. At the longest time horizons aircraft are strategically separated using the types of procedures and airspace constructs described in Section IVB: aircraft fly at different altitudes along airways depending on their direction of travel, which reduces the frequency with which aircraft need to deviate from their planned route of flight to avoid another aircraft. Similarly, VFR corridors through terminal areas (see Figure 6) ensure that such aircraft do not intersect busy IFR arrival and departure routes. In the near term, a UTM-like system may serve a role in flight planning before aircraft take off by checking proposed ODM routes of flight against other current ODM routes, the filed flight plans of IFR aircraft, and historical traffic patterns of all aircraft to minimize the likelihood of aircraft interactions.

The second layer of aircraft separation mitigations is referred to as separation assurance. In this layer, aircraft continue to be safely separated from each other, but within a time horizon of about one to ten minutes (depending on the application and types of aircraft) it is predicted that aircraft may violate the relevant separation requirement, resulting in an unacceptable probability of collision. The separation maneuvers used in this phase are not urgent, so resolutions may consider flight path efficiency. This function is the responsibility of human controllers (ATC) with the assistance of a conflict alert (CA) software function for IFR aircraft, though pilots of such aircraft also bear responsibility for remaining well clear of other aircraft when weather conditions permit. ATC does not take primary responsibility for separating IFR and VFR aircraft, though it will alert both aircraft if their workload permits. The pilots of VFR aircraft bear essentially sole responsibility for determining the appropriate separation distance and employing their "see and avoid" capability to maintain that distance, though such pilots may request that ATC provide them traffic advisories for proximate aircraft.

Pilots of UAS, which are currently required to operate IFR if they wish to enter controlled airspace, are also responsible for remaining well clear of other aircraft using a DAA capability. An example of a DAA display, including the traffic and alerting symbology and maneuver guidance, is shown in Figure 7.[26,51,52,53,54,55] For low-density operations, ODM aircraft will operate VFR, and so it will be the pilot's responsibility to see and avoid other aircraft consistent with today's rules and procedures. The UAS DAA systems could be adapted for use in the cockpit to assist the pilot in separating from other aircraft at medium densities, and eventually such systems should allow pilots to operate in a VFR-like fashion even under IMC. This concept of VFR operations in IMC has been the subject of research for decades,[56,57,58] with the largest barrier to its feasibility being the demonstration of an electronic means of

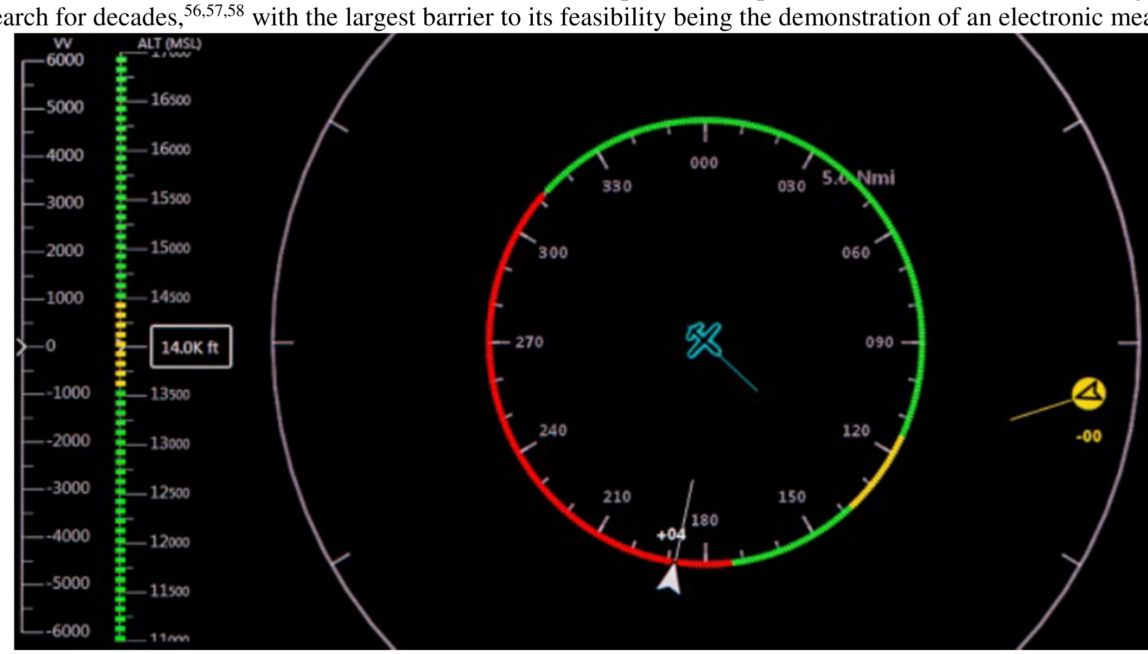

Figure 7. Prototype UAS DAA display and algorithm

self-separating from other aircraft—a capability that DAA systems provide—and adapting regulations to allow such operations. To achieve high densities in the long term it will likely be necessary to employ a centralized separation service that can optimally deconflict aircraft trajectories with knowledge of the entire airspace, which is theoretically more efficient than individual agents making "local" separation decisions without knowledge of the "global" situation.[59] Algorithms for this capability have been described in detail and thoroughly evaluated.[19,45,60,61,62]

The last layer of aircraft separation, operating at less than a minute to potential collision, is referred to as collision avoidance. In this phase the aircraft encounter has already proceeded to the point where the probability of collision is unacceptably high, and the only priority of the two aircraft is to maneuver to increase separation and avoid a near mid-air collision (NMAC). The Traffic Alert and Collision Avoidance System (TCAS) is mandated on all large aircraft and provides both warnings (traffic alerts) and suggested maneuvers (resolution advisories) to assist pilots in avoiding collisions. A new system called airborne collision avoidance system X (ACAS X) is under development and will be deployed on aircraft within several years.[63] Both of these systems operate onboard the aircraft and collect surveillance data on potential intruders from cooperative Mode C/S transponders and, for ACAS X, from ADS-B. It is an important characteristic of the system that it operate onboard the aircraft with minimal dependence on external systems because the timeframe for action in collision situations is short and because it must operate even if it loses its communications link with ATC. ODM aircraft will likely adopt this same collision avoidance architecture, initially equipping with TCAS for added safety despite the lack of a regulator requirement to do so. In the medium term, ACAS X or its extension designed for unmanned aircraft, ACAS Xu,[64] could be adapted for ODM aircraft. In the long term, new formulations of ACAS X—for example those appropriate for multi-rotor[65] or tilt-wing/rotor aircraft— would provide a final safety layer for high density ODM operations. The need to operate even without a communications link suggests that this capability will not reside in or be provided by a UTM-like system, and onboard computational requirements to support the algorithm should be minimal.[66]

ODM aircraft will maintain separation from other aircraft using a variety of approaches for each separation layer that depends on the type of intruder being avoided. Table 3 indicates the primary approaches used to ensure separation as a function of intruder type and the density of ODM operations. For low-density VFR operations, the current separation methods are largely preserved: ODM aircraft avoid busy IFR arrival and departure routes (i.e., segregation), and use "see and avoid" coupled with visual cueing from ADS-B In capabilities for separation from remaining IFR and VFR (including ODM) aircraft. sUAS will be confined to lower altitudes than ODM aircraft and are thereby segregated, while airspace constructs (AC) assist the pilot in using "see and avoid" to separate from other ODM aircraft.

To separate at higher densities in which see and avoid is no longer effective, the ODM aircraft will rely largely on a DAA system adapted for use in a "locally piloted" aircraft cockpit (i.e., a traditional cockpit with an onboard, rather than remote, pilot). Because many ODM operations are expected to occur in large metropolitan areas that are within the "Mode-C veil," the mandate for aircraft within the "veil" to equip with ADS-B beginning in 2020 means nearly all IFR and VFR aircraft will provide accurate GPS-based state data to the DAA system. An onboard, forward facing radar or lidar system will provide the required residual safety factor for those few remaining aircraft not equipped with ADS-B in this airspace, and it will also serve to "confirm" that ADS-B targets are real (i.e., not spoofed). This active surveillance capability will also be useful for ODM aircraft in a corridor or airway to maintain appropriate separation from aircraft ahead of them in the corridor. Vehicle-to-vehicle (V2V) communications technologies, perhaps based on longer-range versions of automotive V2V capabilities,[67] may augment the surveillance data being collected by the DAA system and include trajectory and vehicle intent information that improves predictions of the future positions of aircraft, which has been shown to increase the capacity of a given airspace.[68,69]

To reach high ODM densities it will likely be necessary to unify the separation services described here for all aircraft with the other services described in this section (e.g. sequencing, spacing) in order to optimize the system using a "global" view of its state. Although traditional IFR and VFR aircraft would continue to separate themselves using see and avoid and ATC, ODM aircraft would rely on UTM-like services to provide surveillance information on all airspace users, traditional and non-traditional, and provide coordinated conflict resolution maneuvers to the ODM aircraft. Airspace constructs designed to reduce the complexity of aircraft encounters would be removed because high accuracy state and intent data would be available for most aircraft. DAA systems would provide a backup separation and collision avoidance capability to satisfy a number of contingency conditions (e.g., loss of comm. with UTM, lack of surveillance data for an intruder), a capability likely to require an onboard non-cooperative sensor. The V2V capabilities used in earlier ODM system designs are likely to continue playing a role in separation at high densities, perhaps augmenting the UTM separation service if the V2V capability has lower information latency. A UTM-like system is likely to be the primary enabling capability for separation of ODM aircraft in high-density scenarios.

Table 3. Separation architecture for different aircraft classes

Aircraft pairs	**Low Density**	**Medium Density**	**High Density**
ODM-ODM	See and avoid, AC, ADS-B	DAA, V2V, AC	UTM, V2V, DAA
ODM-IFR	Segregation, see and avoid, ADS-B	DAA, ADS-B	UTM, DAA
ODM-VFR	See and avoid, ADS-B	DAA, ADS-B	UTM, DAA
ODM-sUAS	Segregation	V2V, DAA	UTM, V2V, DAA

E. Separation from Obstacles

Avoiding obstacles during low-altitude arrival and departure flight is perhaps the most challenging separation problem for aircraft flying to non-traditional TOLAs, primarily because at low altitudes such obstacles are far more common than aircraft.[70] Unlike terrain, the locations and heights of obstacles have usually not been mapped in sufficient detail to do "open loop" avoidance of them. Instead, onboard direct detection of local obstacles by each aircraft will likely be required. In the near term, the requirement at traditional airports to conduct a hazardous obstructions survey would be extended to vertiports and vertistops, particularly because the number of such TOLAs is going to be limited by community siting and noise concerns. In these cases, simply following charted arrival and departure procedures and observing minimum obstruction clearance altitudes (MOCAs) may be sufficient for low- to medium-density ODM operations. For high-density operations to be feasible, the number of TOLAs must be greatly expanded, and it may be more cost effective to use short-range onboard sensors adapted from the autonomous driving industry to complement obstacle databases that may be weeks or months old. To the extent that medium-density ODM operations are enabled by onboard sensors for aircraft separation, it may be possible to use the same sensors and closely related algorithms to also separate from obstacles.

F. Separation from Terrain

The low altitudes expected for ODM operations and the need to "squeeze" between hilltops and the bottoms of Classes B and C airspace shelves in some areas make terrain avoidance a critical safety function for an ODM air transportation system. Existing terrain-aware advisory systems (e.g. GPWS and TAWS[i]), potentially combined with synthetic vision, can reduce the probability of controlled flight into terrain, but they require direct human action to follow recommendations. The automatic ground-collision avoidance system (auto GCAS) has already been deployed on military aircraft and is reported to have saved lives.[71,72] The system has been adapted and flight tested for small UAS[73] and has been adapted using optimal control methods for large military transports.[74] Preliminary investigations suggest that it could be readily adapted for VFR and ODM aircraft.[73] The operational maturity of such systems on related aircraft types suggests that a technological solution to this problem could be available in the near term.

G. Wake Avoidance

Aircraft wake turbulence hazards for small VTOL aircraft are of particular importance in four flight situations: 1) close-proximity flight during approach and departure operations; 2) close-proximity operations in the immediate vicinity of TOLAs; 3) encounters with non-ODM aircraft wakes; and 4) ownship wake hazards (e.g., vortex ring-state). Considering these hazards in order, the in-flight wake hazard between small aircraft sized for ODM operations (i.e., nominally less than 8,000 lbs) is generally minimal and addressed by observing the "well-clear" separation standard required by 14CFR91.113 for all operations. While the specific definition of "well-clear" for piloted aircraft is left to the discretion of the pilot, in practice the separation margin used by prudent pilots to assure avoidance of a collision risk is also sufficient to avoid a significant wake hazard. It is relevant to note that the arrival procedures used for the annual EAA AirVenture airshow[ii] provide guidance for arriving VFR aircraft to maintain an airspeed of 90 kts and remain separated in-trail by at least ½ mile (20 seconds or greater at 90 kts).

During TOLA operations such as vertical takeoff, landing, hover, and hover-taxiing, the general recommendation for conventional helicopters to mitigate rotorwash hazards is to maintain at least 3 rotor diameters of separation from other airborne rotorcraft.[75] The applicability of this rule of thumb to powered-lift type VTOL aircraft will need to be evaluated, as their generally higher disk loadings compared to helicopters may result in increased rotorwash velocities.

Wake hazards from non-ODM aircraft results primarily from the desire to minimize path deviations when operating in proximity to the approach and departure paths of commercial airports. In addition to the separations imposed by ATC for IFR aircraft (e.g. nominally, 3 nmi horizontally or 1000 ft vertically), the wake hazard behind

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[i] Ground proximity warning system (GPWS), terrain awareness and warning system (TAWS)
[ii] See https://www.eaa.org/~/media/files/airventure/flyingin/2017-airventure-notam-final-%2003-29-17.pdf

large transport aircraft could require additional separation margins to ensure safety. An augmented reality system that allows real-time wake vortex visualization could reduce these margins.[76]

Finally, a hazard that exists for VTOL and not fixed-wing aircraft results from the ability of VTOL aircraft to fly slowly forward while descending steeply. Such a trajectory risks allowing the aircraft to settle into its own downwash, which can result in a loss of vehicle control. This phenomenon, known as "settling with power" or "vortex ring-state," will need to be considered during the design of ODM approach procedures and airspace operations.[77]

H. Trajectory Planning

An automated system will be required to plan an "optimal" trajectory for ODM aircraft from origin to destination while respecting airspace rules, avoiding other aircraft, meeting a scheduled time of arrival, and conforming to ODM system requirements. The current procedure for creating and filing a flight plan, particularly between non-traditional departure and arrival TOLAs, may take a VFR pilot several hours. The pilot must select a route appropriate for their navigational capability (GPS or radio beacons) while avoiding airspace classes that may not be available to them, select an altitude appropriate for terrain and obstruction clearance, check the flight information services (FIS) to ensure weather conditions are appropriate for their level of training and the aircraft's capabilities, review airport departure and arrival procedures, compute the desired airspeed, time, and distance to ensure the aircraft's range is sufficient with fuel reserves, and identify backup landing sites.

The planning process for ODM trajectories must occur very quickly, not only to provide an ODM aircraft with a feasible route of flight but also to simply determine whether a VFR flight to the selected destination is allowed (e.g., does not pass through weather conditions below VFR minima, does not require permission to pass through Class B/C airspace at a busy time). Although sophisticated flight planning software does exist,[i] it is designed to work through a human-computer interface that is not appropriate for the iterative search techniques commonly used by trajectory optimization algorithms.[78] Even for low-density ODM operations, an automated system will be necessary to determine the feasibility of VFR flight plans and select a route that respects known ATC system constraints and avoids traditionally busy traffic areas. This automated capability could likely be deployed on individual aircraft because interactions between ODM aircraft will be unlikely at low densities, but it would require real-time insight to the current state of the airspace.

When ODM aircraft density reaches medium and high levels, the interactions between ODM aircraft in the airspace and, most importantly, at TOLAs mean significant capacity and efficiency benefits will result from jointly planning the trajectories rather than individually optimizing them. Airlines plan and revise their operations today in flight operations centers (FOC), which typically require massive infrastructure investments and large numbers of people to complete manual tasks related to flight planning. The growing access to electronic information, the need to conduct complicated route planning for vehicles with few passengers at low cost, and the dynamic nature of ODM operations suggest that most of the trajectory optimization must be done automatically.[3,79] The ODM system will accurately track, in real-time, the locations and intentions of ODM aircraft and provide that data to the FAA's system-wide information management (SWIM) network to avoid burdening existing infrastructure with this additional requirement. Large ODM fleet operators may choose to implement their own planning systems, or UTM-like services—with their built-in access to databases of information about the state of the airspace—could provide a common planning capability across many ODM operators.

I. Take-off and Landing Areas

Traditional airspace integration research on the operations of large IFR aircraft usually considers the number and locations of airports to be fixed. For sUAS, any moderately sized open area may serve as an airfield, so TOLAs for such aircraft are not a major research consideration. In contrast, ODM operations must originate or end at dedicated TOLAs that have not yet been selected, though considerable effort has been devoted to understanding the requirements and potential sites for TOLAs in the San Francisco Bay area.[4] That TOLA selection is open-ended means that ODM research must consider the interplay between the selection of TOLAs, the design of the ODM airspace, and the definition of airspace access requirements.

The choice of TOLAs affects the airspace integration concept in several important ways. First, if the TOLA is within the boundary of Class B, C, or D "surface areas" (i.e. terminal airspace reaches down to the surface/ground), then ODM aircraft will have to receive permission to enter that airspace and follow ATC instructions while enroute to or before departure from the TOLA. The decision to grant access to such airspace is likely to lie with a tower controller (potentially a TRACON controller) and be subject to their current workload, so the airspace capacity supported by all the TOLAs in a given terminal area is likely to scale only with that workload and not according to

[i] See https://www.foreflight.com/products/foreflight-mobile/

the number and proximity of TOLAs. Secondly, the proximity of TOLAs to each other (in any airspace) will determine whether they can be used independently, or whether interactions between their arriving and departing aircraft will constrain their collective capacity. The capacity of interacting TOLAs will be significantly affected by approach/departure procedures, SSS algorithms, and separation requirements.

TOLA site selection is complicated by many factors in addition to the concept for airspace integration, including community noise concerns, connection to existing transportation networks for the "last mile" leg, and complex land use regulations. ODM concepts frequently envision automobile ride-hailing/sharing to connect TOLAs with passengers' final destinations.[3,4] This approach leads to TOLAs situated near significant road infrastructure, for example in the middle of "cloverleaf" highway interchanges and the parking lots of industrial parks off highways, which has the advantage of nearby highways masking the noise from ODM aircraft. Another solution is to co-locate the TOLAs with existing mass transportation hubs like train and subway stations, ferry terminals, and airports.[2] Connecting to mass transit leads to an ODM design with smaller numbers of significantly larger aircraft, which is more akin to the hub-and-spoke network of the current air transportation system. The low-density ODM system will likely use these TOLAs and existing public and private helipads. As the utility of the ODM transportation system is more widely recognized and the benefits of medium- to high-density operations spread to members of the general public, it is likely that TOLAs will be built in convenient local areas (e.g. parks, parking structures in commercial districts). In general, the capacity of the ODM airspace is likely to be constrained for the foreseeable future by the number and placement of TOLAs rather than the other airspace integration considerations, just like the traditional NAS is constrained by airport capacity.

J. Contingency Management

There are several different scales of contingency scenarios: those that affect an individual aircraft; those that affect multiple aircraft within the ODM fleet; and those that affect the air transportation system more generally, including ODM aircraft, UAS, and traditional manned aviation. Examples of vehicle-level contingencies are the loss of an electric motor, complete loss of electrical power, loss of the ability to communicate, loss of an onboard separation-assurance system, or a medical emergency on the aircraft that requires priority routing and handling to the nearest TOLA. Examples of fleet-level contingencies include the loss of a vertiport (e.g., caused by an accident on the pad), requiring multiple inbound aircraft to be rerouted, degradation in the accuracy of a global navigation satellite system (GNSS, e.g., GPS, GLONASS, Galileo), the formation of a hazardous weather system, or outages and degradations of UTM-like services. Contingencies affecting the larger air transportation system could include a large passenger aircraft making an emergency return to the airport that cuts through an ODM corridor, or a blunder by an ODM aircraft near an airport that requires redirecting large numbers of both traditional manned aircraft and, consequently, ODM aircraft. It should be noted that a vehicle-level contingency, while directly affecting only a single aircraft, will often impact multiple aircraft and require a change in the way the ODM infrastructure provides services (e.g. delaying the arrivals of other aircraft to a TOLA so a high-priority flight can land). In rare cases, vehicle-level contingencies—for example navigation system errors that result in an ODM aircraft blundering into the airspace of a major airport—could precipitate system-level contingencies.

An important distinction between ODM and UTM contingencies is the way in which respective aircraft can be returned to a safe state without compromising the safety of other airspace users or people and property on the ground. In both UTM and automotive applications, "safe-ing" the vehicles is relatively easy: a car can pull off to the shoulder or simply stop, and a small UAS can deploy a parachute or find a small, unused patch of ground on which to make an emergency landing. For the safety of passengers and crew in the ODM aircraft and for bystanders on the ground, "safe-ing" the ODM aircraft may only be accomplished by landing at select locations. Provided that emergency landings are rare, acceptable emergency landing sites may be placed in locations that would be unacceptable for routine use. For example, lightly traveled surface streets, remote areas of parks or other open space, and even waterways (for appropriately designed aircraft) could provide a density of emergency landing sites sufficient to improve the safety of the ODM system while reducing vehicle redundancy and reliability requirements.

K. Other Considerations

A significant number of other airspace integration considerations exist in the development of a high-density, safe ODM system, but they are out of scope for this paper. Important issues to address in the future include geofencing, all-weather and nighttime operations, wind and weather predictions, community impact including noise, privacy, and public acceptance, contingency procedures, and the specific technologies required to enable the air transportation system described in this paper. Further information about these issues may be found in a variety of sources.[1,3,4,5,80]

V. Research Approach for ODM Airspace Integration

The central research question for ODM airspace integration is to determine the contributions that combinations of concepts, procedures, and technologies can make to safely increasing airspace capacity for ODM operations. Additional factors that will contribute to airspace capacity are the specific types of operations conducted in that airspace (e.g., short intra-urban area flights vs. longer regional transportation), the geographic regions in which operations are conducted (including the existing airspace design and presence of traditional airspace users), and the meteorological conditions typical of the area (not simply the degree of VMC vs. IMC, but adverse conditions like icing, sleet, and snow). The expected outcome of the research is depicted in a notional way in Figure 8: a series of incremental capacity increases enabled by different concepts and technologies. Determining the capacity of a given sequence of steps within the complicated multi-dimensional estimated-capacity function would require holding other factors constant, and hence many different geographic regions and ODM operational scenarios would require their own step sequences.

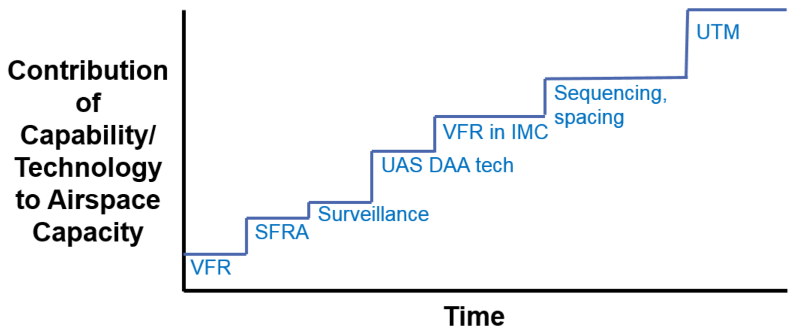

Figure 8. Notional research approach for determining airspace capacity

An important aspect of an airspace integration concept, particularly one that introduces new operators and new control paradigms (i.e. a UTM-like system), is a clear delineation of responsibilities between the air navigation service provider (ANSP), aircraft, and the agents that control the aircraft either onboard (i.e. a pilot) or remotely (i.e. a fleet operations center). A notional assignment of these responsibilities is shown in Figure 9. The ANSP represents the existing air traffic system, and its responsibilities are to provide constraints to the ODM system and intervene only when necessary to balance capacity and demand or provide directives about the use of particular airspace. The operations center may help direct the activities of a fleet of aircraft, similar to a taxi dispatcher or airline operations

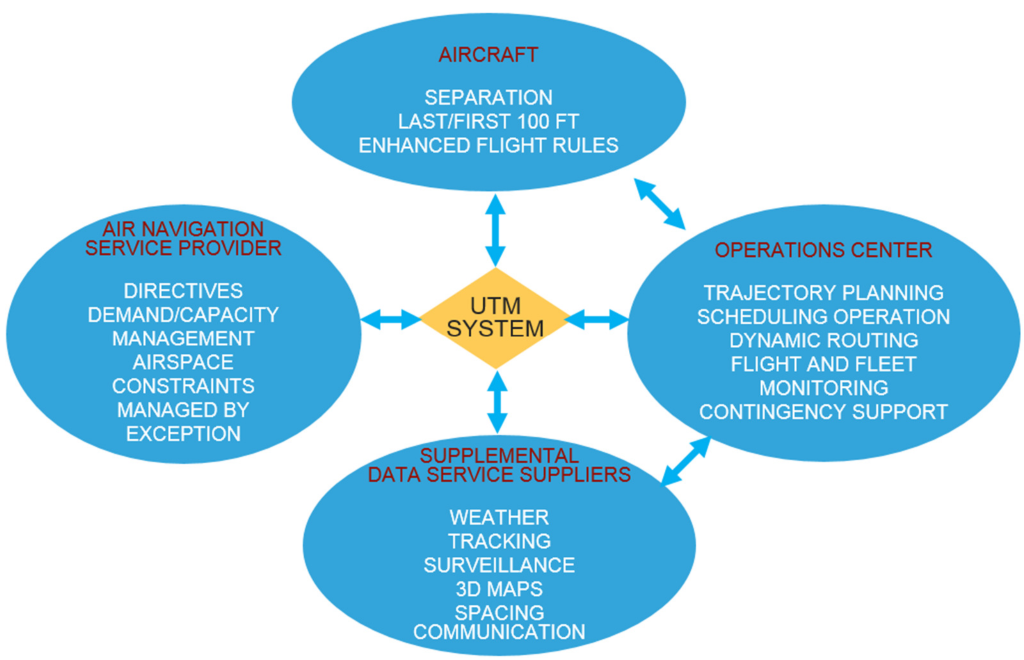

Figure 9. Notional division of airspace integration responsibilities between agents

center. In longer-term concepts in which the ODM aircraft are UAS, remote pilots may manage aircraft from the operations center, intervening only when necessary to deal with contingencies. A UTM-like system is envisioned to be the central agent that coordinates these functions for a given division of responsibilities.

The preceding discussion should have conveyed the notion that low-density ODM operations can be flown today, and that, with the integration of relatively mature technologies, a safety case could be presented for medium-density operations. A dual research approach may therefore be warranted. First, a near-term, low-density concept of operations should be developed and the associated procedures and technologies integrated for a *proof-of-concept flight test*. This flight test would show ODM operators, aircraft and technology manufacturers, regulators, and traditional airspace users how to safely launch initial ODM flights without making investments in solutions that are unlikely to increase airspace capacity. A sufficiently motivated and cohesive ODM community could accomplish such a flight test within three to five years.

The second approach, which would be carried out in parallel to the first, would be an *integrated research and development effort* designed to understand what combinations of concepts, procedures, and technologies would enable medium-density ODM operations. Candidate solutions would be modeled, analyzed, and simulated for their contributions to airspace capacity. The most promising combinations of candidate solutions would be evaluated in high-fidelity human-in-the-loop (HITL) simulations that include both pilot and controller subjects. These HITL simulations would verify the results of analysis and fast-time simulations by directly incorporating human performance. The combination of solutions that best fits the needs of the ODM community would become the template for the integrated flight tests in a follow-on phase that enables medium-density ODM operations. This spiral development process, in which analyses, simulations, and flight tests at all levels of fidelity are leveraged to support increases in ODM airspace capacity, may be the most efficient way to meet the near-term needs of commercial interests, the longer-term mandates of research institutions and academia, and the requirement to incrementally evolve the complex ATC system for regulators to ensure safety.

VI. Conclusion

This paper has attempted to lay out a vision for a new air transportation system built on the principles of ODM and describe an approach to evolving the current system towards the goal of high-density ODM operations. That approach leverages the precedent for VFR operations and employs advanced vehicle and UTM technologies, concepts, procedures, and capabilities that are or could soon be available. The paper describes how the air traffic services normally provided by ATC to IFR aircraft would have to be replicated for an ODM system using this approach, and describes how those services would work together. Finally, a high-level research approach for ODM is described that relies on spiral development to demonstrate the goals of deployability and scalability.

The next steps for this research are to develop a series of concepts at each ODM density level that logically build on each other, relying to the maximum extent possible on capabilities developed in previous phases. Each concept will be supported by ODM air traffic services that are enabled by available technologies. The concepts will be evaluated through analysis and simulation for their potential capacity increases. Those expected increases will have to be validated through pilot- and controller-in-the-loop simulations because the capacity is likely to be a function of human constraints and workload in the near term and midterm. Finally, flight tests will need to be conducted with combinations of available technologies, showing that a given density of operations is possible with realistic uncertainties, latencies, and human performance. This cycle should repeat itself in order to constantly push the capacity of the system to higher levels and bring the benefits of ODM to the general public.

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