ASSESSMENT OF AIR TRAFFIC CONTROL FOR URBAN AIR MOBILITY AND UNMANNED SYSTEMS

Parker D. Vascik, Hamsa Balakrishnan, R. John Hansman

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MIT International Center for Air Transportation (ICAT)
Department of Aeronautics & Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139 USA

Assessment of Air Traffic Control for Urban Air Mobility and Unmanned Systems

Parker D. Vascik, Hamsa Balakrishnan, R. John Hansman
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA, 02139, USA

***Abstract*— This paper assesses how the introduction of urban air mobility services and unmanned aircraft systems may challenge Air Traffic Control (ATC) in the United States and what opportunities exist to support these forthcoming operations. Four attributes unique to these emerging operations were identified that may challenge effective ATC. Each attribute concerned the scalability of current ATC systems to support a large number of new airspace users at low altitudes. Six potential operational limitations were identified that ATC may impose upon airspace users in an effort to manage increased traffic demand. The fundamental mechanisms that set the aircraft capacity of an airspace, considered to be a surrogate for ATC scalability, were determined. The influence of ATC system architecture, technologies, and operational factors on these mechanisms was diagramed. Finally, the ability of various new ATC approaches to support high density, low altitude operations were reviewed with respect to these mechanisms.**

Keywords – urban air mobility, unmanned aircraft systems, air traffic control, low altitude airspace

I. INTRODUCTION

Air Traffic Control (ATC) scalability was identified as a leading constraint for the operation of helicopter networks in the 1970's [1], Small Aircraft Transportation Systems (SATS) in the 2000's [2], and Urban Air Mobility (UAM) systems emerging today [3]. Despite dramatic differences in vehicle technologies and configurations between these three envisioned systems, the scalability of ATC to support these new operators was perceived as a common constraint. This indicates that ATC scalability is a constraint that is relatively independent of vehicle performance, but rather is highly sensitive to factors in the operational environment such as traffic demand patterns, airspace allocation, air traffic management, and air traffic controller workload.

The scalability of ATC is expected to become an increasingly more significant issue for aviation due to the proliferation of Unmanned Aircraft Systems (UAS) for both commercial and hobbyist purposes as well as the anticipated emergence of large-scale UAM systems that aim to provide passenger services within metropolitan areas. These new vehicles will frequently operate within 915 m (3000 ft) of the ground, in close proximity to one another or obstacles, and under the auspices of less experienced or even amateur onboard or remote pilots. As a result of these characteristics, the emerging UAS and UAM industries are anticipated to challenge the safe and efficient management of the National Airspace System (NAS) through current ATC methods [3].

Since 2015 NASA has worked with academia, the FAA, and industry to create a novel ATC system for low altitude airspace management, particularly for UAS. At the same time Amazon, Google, General Electric, Europe's SESAR, and numerous other entities have announced their own programs in this area. These developments indicate consensus that new UAS and UAM operators may not be adequately supported by the existing ATC system. However, despite significant investment in these systems and displayed prototype capabilities, their actual Concept of Operations (ConOps) and ultimate NAS integration plans remain unclear. This is due in part to the lack of an explicit identification of where current ATC capabilities are inadequate and must be augmented by these new systems.

This paper reviews the unique challenges that UAS and UAM operations will place upon the ATC system in the United States. A variety of shortfalls in the current system were identified that foreshadow an ATC scalability constraint for these operators. The fundamental mechanisms through which the scalability of ATC is limited were determined. Opportunities to support high-density, low altitude airspace operations were assessed in light of these mechanisms.

II. METHODOLOGY

Fig. 1 presents the analysis approach used in this study. First, an exploratory analysis of potential UAM systems in three U.S. cities was conducted to explicitly identify challenges for ATC that may manifest in response to these operations. Prior challenges experienced by ATC to support UAS in these cities were also identified. Los Angeles, Boston, and Dallas were selected for this analysis as they represent potential near-term markets for UAM and UAS operations, exhibit diverse airspace and air traffic ConOps, and have airport infrastructure located in varying proximity to the urban core.

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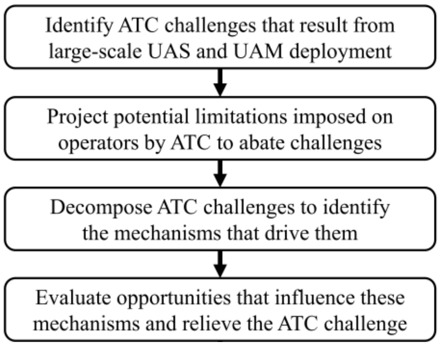

Figure 1. Analysis approach to evaluate ATC challenges.

Second, current ATC ConOps were reviewed to project how air traffic controllers may handle an influx of UAM or UAS operations, and what, if any, flight limitations may be imposed upon these new operators.

Third, the ATC challenges identified from the three city cases were considered in greater detail. A need to significantly increase the capacity of an airspace, defined as the number of operations that ATC can simultaneously support in an airspace, was perceived to be a common feature of each challenge. The various operational, environmental, and technical factors that influence the number of operations ATC can support were evaluated. Through influence mapping of these factors, the key "mechanisms" that control ATC scalability were identified.

Fourth, a variety of opportunities were evaluated that may increase airspace capacity. The influence of these opportunities on the key mechanisms was assessed. The magnitude of the increase in ATC capacity due to each opportunity was considered, and challenges for adoption were discussed.

III. ATC Challenges From UAM and UAS Operations

Emerging UAS and UAM operations may create a number of challenges for current-day ATC due to attributes unique to these operations including:

- a significantly increased number of total operations
- operations at greater densities than routinely seen today
- en route operations at lower altitudes than most today
- pilots, automation, and aircraft that may have widely varying performance capabilities and training

Each of these four attributes and the challenges they may create for ATC are discussed in the following sub-sections.

A. Increased Number of Operations

The FAA's Air Traffic Organization (ATO) currently provides ATC services to roughly 200,000 General Aviation (GA) aircraft and 7,000 commercial aviation aircraft within the NAS. The ATO handles roughly 50 million tower operations and another 43 million en route operations per year [4]. Despite the scale of these capabilities, the projected number of UAS and UAM operations far exceeds current capacity.

The FAA has registered over 900,000 UAS under 25 kg (55 lbs) since late 2015. By 2021 the FAA expects over 3.5 million hobbyist UAS and 400,000 commercial UAS to be in operation [4]. This represents a potential fleet size that is nearly 19 times as large as the combined GA and commercial aviation fleets today. While the utilization of hobbyist and commercial UAS is unlikely to be as high as that for the current aircraft fleets, the total number of UAS flight hours per day across the larger fleet may be on the scale of current operations.

Although UAM systems are at a lower level of maturity than UAS, Uber has proposed that by 2025 numerous cities in the U.S. may have 300-500 electric Vertical Takeoff and Landing (eVTOL) aircraft conducting up to 27,000 flights per day, per city [5]. In comparison, the ATO currently handles an average of 44,000 flights per day in the entire NAS [6].

B. Increased Density of Operations

If even a fraction of the proposed UAM and UAS missions materialized (e.g. conducting roughly half the daily flights of the entire current NAS above a single city) the increased density would present an unprecedented ATC challenge. First, the current voice-based communications methods used by controllers is unscalable to such flight densities. The number of controllers required to verbally command this density of operations, as well as the frequency spectrum that would be necessary to host these communications, would not be feasible without additional decision support or automation.

Secondly, existing surveillance and navigation technologies may be insufficient. If hundreds of UAM or UAS operations occur within a few hundred square miles of one another at low altitudes, current primary and secondary surveillance systems would be unable to provide effective surveillance. For example, [7] suggests that ADS-B may be unable to provide sufficient service at a density of five UAS per square mile unless the transmission power is significantly reduced. While this may be feasible for UAS operations, high densities of manned UAM aircraft operating at greater speeds than UAS may not be sufficiently served by a low power ADS-B option.

Finally, the current ConOps for ATC requires relatively large separation minima between all aircraft within Class B and C controlled airspace, especially in Instrument Flight Rule (IFR) conditions as displayed in Fig. 2. These required separations make the desired levels of flight density infeasible within a metropolitan area. While aircraft operating outside these airspaces or aircraft granted permission to apply visual separation in Visual Flight Rule (VFR) conditions may be able to operate with reduced separation minima, the capacity for pilots (either remote or onboard) to effectively see and avoid and operate safety at extremely high flight densities may become overwhelmed.

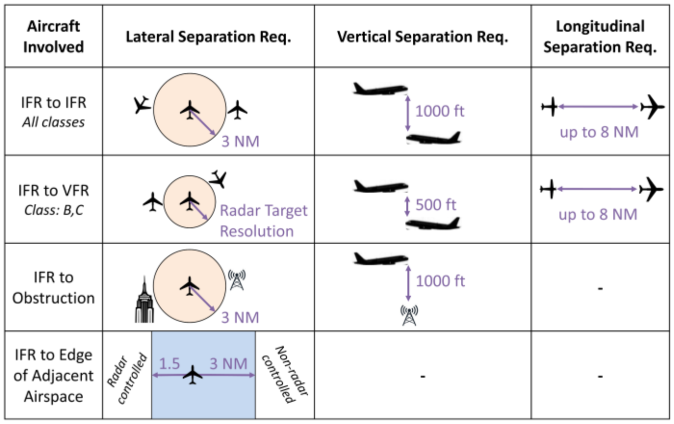

Figure 2 U.S. ATC separation standards for IFR terminal area operations.

C. *Low Altitude Operations*

The low altitude mission profile for UAS and UAM aircraft may further strain the ability of surveillance and navigation systems. Low altitude operations in mountainous areas or cities may encounter airspace that does not have surveillance coverage due to the line of sight limitations of these systems. Similarly, traditional navigational aids (VOR & DME equipment) may not provide reliable coverage for this reason. Secondary radar systems such as ADS-B have increased vulnerability during low altitude flight to jamming, signal insertion, or signal deletion. Finally, the use of Global Positioning System (GPS) technologies becomes less reliable at low altitudes due to signal multipath and urban canyon impacts. These situations not only challenge effective ATC, but they also challenge the fundamental ConOps of radio navigation or Performance Based Navigation (PBN).

D. *Heterogeneity in Pilots, Automation, and Aircraft*

The aircraft proposed for use in UAS and UAM missions may have dramatically different configurations, performance capabilities, and Communication, Navigation, and Surveillance (CNS) equipage than current aircraft or even one another. Furthermore, various operators propose to have different levels of flight automation. The wide variability of autonomy, aircraft capabilities, and equipage will create a mixed-performance challenge for ATC. Currently ATC often uses a ConOps that accepts efficiency losses and controller workload increases in order to accommodate the poorest equipped aircraft in the sky. The more disparate mixed-performance situation of UAS and UAM may amplify the adverse impacts of this ConOps.

While UAM aircraft are anticipated to initially be flown by professional, onboard pilots, most operators propose increasing levels of automation over time. Reference [8] reviewed a pathway to reduce piloting requirements for UAM systems by moving from professional, onboard pilots to remote pilots to 40-hour “user” pilots and ultimately to fully automated vehicles. With numerous eVTOL, UAS, and legacy aircraft potentially operating in the NAS over the next decades, a situation may arise where ATC must simultaneously handle aircraft with onboard pilots, remote pilots, pilots with reduced training, and fully automated pilots. In such a scenario controllers may experience significant variability in flight proficiency and communications medium (verbal vs. digital).

IV. Scalability Implications of Conventional Approaches to Manage Airspace

While each of the attributes of UAM and UAS operations presented in Section III were shown to lead to a variety of potential challenges for ATC, a common feature of the challenges is that they concern the scalability of the ATC system. An ATC scalability constraint is one where ATC becomes unable to support a sufficient number of aircraft operations in an airspace to meet the demands of operators at the times and locations they desire to fly. Such capacity constraints are a common feature of today’s ATC system. Demanded airport arrival or departure rates are frequently greater than the capacity of the nation’s busiest airports. Although less common, sector capacity may also be exceeded, especially in the presence of inclement weather.

The introduction and scale-up of UAM and UAS operations in the NAS is likely to exacerbate these existing capacity challenges. To address this, ATC may seek to resolve the capacity issue either by reducing the demand for an airspace/airport asset, or by increasing the capacity of the asset. Either pathway to address ATC capacity imbalance may result in ramifications that emerge as limitations to the operators or incurred costs for the Air Navigation Service Provider (ANSP).

The following discuss the implications of the conventional pathways used to manage airspace demand and capacity.

A. *Implications of a Failure to Manage Airspace Capacity*

A failure to balance aircraft demand for an airspace with the capacity of that airspace may lead to two potential situations depending upon if aircraft within that airspace are “controlled” by ATC or operating without ATC direction.

1) *Inability to Access Airspace*

If aircraft are operating under IFR, or if aircraft intend to operate within Class B, C, or D airspace, then these operators must contact ATC and are subject to the controller’s direction. If the traffic volume within an airspace managed by ATC reaches saturation, then a controller may limit further aircraft from entering that airspace (either from flying into it or departing from the surface into it).

An evaluation of Los Angeles, Boston, and Dallas revealed that surface-level controlled airspace that required contact with ATC to operate in covered approximately 43%, 65%, and 56% of the metropolitan area of these cities, respectively. ATC could therefore prevent UAM aircraft from accessing more than half of the surface area of a city if the flight capacity of the overlying airspace were reached. Furthermore, an evaluation of 32 potential UAM missions within these three cities found that 94% of these missions required entrance into one of these controlled airspaces [9].

UAS experience a similar challenge in terms of access to controlled and congested airspace. Title 14 of the Code of Federal Regulations (CFR)[1] Part 107 currently does not authorize flight within any controlled airspace or near airports, heliports, or seaplane bases without ATC authorization. Furthermore, the ATC authorization process for UAS uses predetermined facility maps that provide access to relatively few areas and altitudes in controlled airspace. As the number of manned and unmanned operations in metropolitan airspace increases, ATC may further limit UAS access to controlled airspace to provide priority and safety to manned operators.

Finally, the designation of Special Use Airspace (SUA) and especially Temporary Flight Restrictions (TFRs) may further reduce the capacity of airspace. While most commercial operations have traditionally been exempt from TFRs or relatively easily routed around other SUAs, UAS and UAM operators are likely to be flying at altitudes and in areas that will require entrance to this airspace. For example, within Boston TFRs are created overtop the city center around Red Sox baseball games, Harvard football games, and Boston College football games. Together these TFRs may exclude UAM and UAS flights from operating above a majority of the city center for 5.5 hours a day for as many as 100 days a year.

2) Reduction of Flight Safety

All aircraft operating in class G airspace or aircraft operating under VFR in class E airspace do not receive separation and routing services from ATC. While such "uncontrolled" operations may therefore not be susceptible to airspace access concerns during an ATC saturation situation, the lack of a centralized entity ensuring separation and managing aircraft flow may lead to another operational implication concerning reduced flight safety.

When aircraft operate without ATC services, flight safety is provided through a pilot's ability to "see and avoid" and pass "well clear" of other aircraft as described in CFR Part 91.113. There are also a set of general rules of the road that prescribe flight altitudes based upon heading and assign right of way. These basic principles enable aircraft to operate in visual conditions at much closer spacings than the standard radar separation minima applied by ATC. Furthermore, in areas of dense VFR traffic, such as overtop the Los Angeles International Airport or above the Hudson River in New York, special flight rules and communications protocols have been developed to enhance the safety of pilot self-separation and reduce pilot workload resulting from the flight density.

[1] All Title 14 references in this paper were from the electronic Code of Federal Regulations, http://www.ecfr.gov, retrieved from the version updated November 7, 2017.

Despite these capabilities, UAS and UAM operations may occur at extreme flight densities where the capability of pilots to effectively see and avoid all other aircraft in the airspace may be degraded. If relying upon current pilot decision support tools and equipage, these extreme flight densities may result in a reduction of the level of safety of these operations.

B. Implications of Demand Adjustments to Manage Capacity

Demand adjustments are frequently used in the current ATC system to strategically manage anticipated traffic volumes. Demand adjustments seek either to spatially or temporally disperse aircraft that would otherwise have converged on an airport or airspace volume and exceeded its capacity. To accomplish this task, a variety of decision support tools are used by controllers to determine if and when to implement any of a number of Traffic Management Initiatives (TMIs). A Ground Delay Program (GDP), Ground Stop (GS), or Airspace Flow Program (AFP) are common TMIs implemented by ATC if the capacity of an airspace or specific facility is anticipated to be exceeded. Each TMI (as well as others not introduced in this paper) may lead to an operational limitation for UAM or UAS flights depending upon when and how it is implemented

1) Ground Delay

If any of these three TMIs are implemented before an aircraft departs from its origin, then the aircraft may be delayed on the ground by ATC to temporally disperse aircraft arriving at a facility or sector.

Urban air mobility and UAS operations differ from traditional commercial aircraft operations in that the typical mission range of these operations is far shorter (<160 km or 100 mi). Ground delay is most effective when the planning horizon for the flight is short because knowledge about actual traffic flow and airspace capacity is more accurate. As a result, ground delays are applied first to operations originating nearer to the saturated airspace or facility. This means UAM and UAS operations may experience more frequent ground delays than current commercial operators.

2) Airborne Delay

In comparison to ground delay, airborne delay is almost exclusively used as a tactical measure to address imminent or actual airspace/airport saturation. In addition to addressing capacity issues, airborne delay may also be used for objectives such as reducing noise exposure to certain locations, metering arrivals to an airport, or avoiding a SUA. Airborne delay can be prescribed through a variety of mechanisms including:

- Rerouting of a flight on a longer path
- Time-Based Metering (TBM) requiring slower flight
- Minutes/Miles In Trail (MIT) behind a slower aircraft
- Assignment of flight to indirect procedures, or the use of tunneling and capping within terminal airspace

Airborne delay may be less common for UAS and UAM operations than current operators. The short duration of these trips better match the planning horizon of ATC and enable TMIs to prescribe ground delay rather than airborne delay.

C. *Implications of Supply Adjustments to Increase Capacity*

Air Traffic Control has a variety of mechanisms through which the aircraft capacity of an airspace may be adjusted. Airspace is currently divided into "sectors" which are volumes of airspace managed by an individual or team of controllers. The sectors have an aircraft carrying capacity that is dependent upon numerous factors. Fig. 3 displays how these factors (in orange) act through three fundamental mechanisms (in blue) to set the capacity of a sector. As a note, calculation of sector throughput requires consideration of aircraft performance, especially velocity, and was not included in this analysis.

The mechanisms identified as "structural factors" jointly set the theoretical capacity of a sector. The single "human factors" mechanism captures performance limitations of controllers and pilots that reduce the sector capacity from this theoretical limit to a practical (achievable) limit.

A majority of the structural factors in Fig. 3 are relatively static on the timescales required for ATC in terminal areas (minutes to hours). These include the ConOps deployed to manage the sector, the CNS equipage of the aircraft and controllers, and the influence of communities on operations. Similarly, the decision support tools available to pilots and controllers are also considered static for capacity management. While long-term investments in technology, procedures, or system architecture may influence these factors and result in an increase in sector capacity, these factors are not useful to adjust airspace capacity to meet demand from day to day.

Four of the factors in Fig. 3 were considered to be dynamic such that ATC could adjust them daily or hourly to affect capacity. These dynamic factors include the designation of SUAs, layout of airspace geometries, staffing of ATC facilities, and accepted traffic mix and aircraft sequencing.

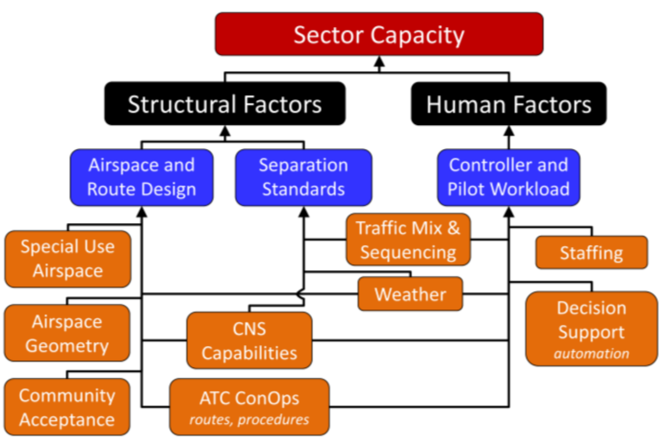

Figure 3. ATC sector capacity influence diagram.

These dynamic mechanisms and factors may be exercised to increase the practical capacity of a sector and result in two additional implications for ATC and operators.

1) *Increased Financial Burden on ANSPs and Operators*

Technological development, such as collision avoidance technologies, advanced CNS, and controller decision support tools, have dramatically increased the density of flight over the past fifty years. However, current efforts by the FAA's NextGen program to adopt further technologies such as ADS-B surveillance and PBN have been contested due to the expense to operators of adopting these systems. Further increases to airspace capacity to support UAM and UAS operations would likely be associated with additional financial burdens on both the ANSP and the operators.

2) *Rationing of ATC Services to Prioritized Users*

Sector capacity is reduced as a consequence of supporting aircraft with heterogeneous pilot skills, flight performance, and automation. The FAA may increase sector capacity (in some cases dramatically) simply by prioritizing airspace users who offer better performance and equipage. The so called "best-equipped, first-served" model would replace the traditional "first-come, first-served" (FCFS) model used by ATC today. Doing so would increase airspace practical capacity through the "traffic mix" and "CNS capabilities" factors from Fig. 3.

The implication of such rationing is that low performing, less equipped aircraft may have limited access to, or be excluded from, specific airspace. Transition away from FCFS is already evidenced by CFR §107.37, which gives all other airspace users total priority over small UAS, and by some large European airports that effectively prohibit GA operations.

V. Challenges and Opportunities for Air Traffic Control of Low Altitude, Urban Airspace

The issues faced by ATC to support a significant number of new UAS and UAM airspace users indicate that large-scale changes to the mechanisms controlling airspace capacity will be required. This section reviews opportunities and challenges that exist to adjust the key factors identified in Fig. 3 to increase sector capacity. The discussion is intended to survey numerous proposals and opportunities; a detailed analysis of each proposal is not presented.

A. *Special Use Airspace and Airspace Geometry*

From a structural standpoint, the larger an airspace the greater its capacity should theoretically be. However, in practice the capacity of a controlled airspace sector is typically limited by controller workload rather than aircraft spacing limitations. For example, helicopter operators in São Paulo and Boston are limited to simultaneously operating a small number of helicopters (six in São Paulo) in airspace close to the major airports due to workload limitations of the often single air traffic controller authorizing their flights.

One potential approach to increase airspace capacity is to leverage dynamic sectorization. The concept proposes to dynamically adjust sector geometries to more efficiently distribute aircraft between an overburdened sector and a nearby underutilized sector. Such proposals therefore better utilize existing controller resources to support temporary concentrations of air traffic. However, the approach may not effectively support high-density operations in an urban area because the anticipated number of UAM and UAS operations may exceed the pooled controller resources of even numerous sectors. The controller resource challenge is exacerbated by the small operating area of UAM and UAS systems which may be on the scale of a single low-altitude sector.

A second approach to increase sector capacity is to reduce the volume of controlled airspace and transition to airspace where aircraft can operate without a controller. This may be accomplished through the creation of a Special Flight Rules Area (SFRA) or through the reclassification of parts of Class B, C, or D airspace as Class E or G airspace [10]. The purpose of such airspace re-allocation is to remove limitations imposed by controller workload and ATC separation standards enabling the sector to operate at a capacity limited solely by the workload and safety comfort level of the pilots. The Hudson River SFRA in New York is an example of this approach. The airspace above the river was "cut out" of the surrounding Class B airspace. Over 60,000 helicopter operations occurred in this SFRA in 2015 without ATC support.

A potential consequence of scaling back ATC services to increase airspace capacity is a reduction of flight safety. Despite this concern, the FAA recently developed a program for UAS that leverages implicit low altitude airspace cutouts. The Low Altitude Authorization and Notification Capability (LAANC) designates specific volumes of controlled airspace below 122 m (400 ft) as permissible for UAS to operate in when granted a 3rd party (non-ANSP) automated authorization.

B. Community Acceptance

Local communities have increasingly influenced when, where, and how many aircraft can operate in airspace near or above their jurisdictions. Aircraft and helicopter operations, especially those occurring at low altitudes or on the surface, may expose individuals to significant levels of noise. If sufficiently annoyed by such operations, communities may pursue a variety of legal, regulatory, or zoning pathways to limit aircraft operations or restrict airport/heliport development and usage [10]. Furthermore, community appeals to the FAA or courts may result in restrictions to procedure design, airport operations, and overflight of some areas.

For example, community activism in Phoenix, Charlotte, Boston, and Baltimore in recent years has created national profile political and legal challenges to the FAA's implementation of new PBN approach and departure procedures in these areas. While these new procedures were intended to increase efficiency and safety, they are now being reconsidered and even rolled back in response to mounting community pressure. Urban air mobility and UAS operations will occur at lower altitudes and in closer proximity to residential communities than traditional aviation operations increasing the probability of community acceptance concerns.

C. Communication, Navigation, and Surveillance

While radar separation and radio communications have remained relatively unchanged for the past 50 years, a variety of emerging CNS technologies offer new opportunities to reduce separation minima, enable more efficient route and procedure design, and reduce controller and pilot workload.

First, data communications are emerging to replace voice-based communications. This system will increase the speed and clarity of communications between aircraft and ATC while reducing workload. Data communications may therefore be an early step to address the density of anticipated UAS and UAM operations. However, a limitation of the data communication technology is that it transmits over a Very High Frequency Digital Link (VDL) which is limited primarily to line of sight. While this is acceptable for commercial aircraft that rapidly climb to altitudes well covered by VDL transmitters, UAS and UAM operators in urban areas may fly at altitudes below the horizon or otherwise obstructed from the VDL transmitters.

Cell phone networks have been considered by some researchers as an alternative communication system that overcomes the coverage challenges of VDL [11]. With existing, near ubiquitous coverage in urban areas and experience supporting volumes of communications multiple orders of magnitude above those of current day aviation, mobile operators may be well suited as new communications providers for low altitude ATC. However, a variety of challenges exist for cellular-based aircraft communications. These include resolving cell saturation from long distance airborne signal propagation to multiple towers and hardening the cell infrastructure to provide the high levels of availability and integrity required for aviation systems.

In terms of navigation, the development of satellite-based Performance Based Navigation (PBN) is positioned to increase structural airspace capacity by permitting closer route spacing, more direct routes, and operations nearer to obstacles [12]. For example, converting a traditional victor airway to a PBN Required Navigation Performance (RNP) 0.3 helicopter route reduces the required route containment boundaries by 85%. With integrity requirements of 10^{-5} containment violations per hour, assignment of an RNP route by ATC may also reduce controller workload as continual surveillance may not be necessary. However, despite these potential benefits of PBN, the high costs of equipping aircraft and developing the necessary ground infrastructure, as well as the potential for GPS jamming or spoofing, represent implementation and transition challenges.

Finally, surveillance of low altitude UAS and UAM operations is especially challenging. Traditional primary radars are unable to resolve many UAS due to their small cross section. Operations of these aircraft are also likely to occur at altitudes or in airspace outside the scan range of traditional radars. Legacy transponders do not have a sufficient number of channels to function as a secondary radar source, and potential saturation limitations of ADS-B have been identified [7]. Furthermore, reliance upon secondary radar for surveillance may not be sufficient as operators can deactivate this equipment, many UAS are not fitted with emitters, and these systems are vulnerable to jamming, insertion, or deletion.

D. ATC Concept of Operations

Various ConOps may be deployed by ATC based upon the conditions of the operation and the technologies available to the controller and operators. Three high-level ATC ConOps are currently used or have been proposed for future implementation. These ConOps vary the flight procedures of an airspace, airport configurations, procedure assignment protocols, communication protocols, and service priority schemes to influence the capacity of an airspace sector.

The three high-level ConOps are briefly introduced and discussed below.

1) Airspace Based Operations

Nearly all aircraft operations occurring in controlled airspace today are managed under an airspace based operations ConOps. In this paradigm, separation management, trajectory assignment, and other responsibilities for in-flight aircraft are transferred from one sector to another sector and handled tactically by controllers within each sector. There are a number of decision support tools that seek to control system load within any sector or airport, however little strategic planning of individual flights or coordination between sectors is conducted. Airspace based operations are unlikely to be feasible for the densities of flights anticipated for UAS and UAM networks.

2) Trajectory Based Operations

A core concept of the FAA's Next Generation Air Transportation System is a transition from airspace based operations to Trajectory Based Operations (TBO). TBO leverages situational knowledge of aircraft locations and intended trajectories available through PBN to conduct ATC system management on a regional or national scale, rather than from sector to sector. System wide communication between sectors (as well as airports) and collaborative decision-making with operators is proposed to remove many inefficiencies of airspace based operations, reduce workload, and enhance predictability. Furthermore, the relatively short distance and duration of UAS and UAM trips removes many of the system state uncertainties that currently challenge TBO for traditional ATC. Despite this advantage, TBO may face implementation and transition challenges due to the high level of equipage new and legacy users must adopt to operate under this ConOps.

3) Free Flight Operations

While TBO relies upon the prediction of the future states of each aircraft to prescriptively assign conflict free trajectories before takeoff, a "free flight" ATC ConOps allows operators to dynamically define their own trajectories subject to reactive tactical conflict resolution by pilots or on-board software. Vehicle to Vehicle (V2V) communication technologies are anticipated to expand the conflict awareness horizon of pilots effectively increasing free flight network stability. Potential benefits of free flight operations are to remove the expense of centralized ATC through the delegation of separation responsibility to aircraft and increase trajectory flexibility. Free flight operational ConOps are regularly used today in uncontrolled airspace where pilots reactively self-separate visually using simple right of way rules. Recent research by [13] & [14] indicates that a free flight ConOps with autonomy may support increased densities of en route operations, but acknowledges that free flight is less effective in environments with non-participating agents. Emerging operations in low altitude airspace may potentially be supportable by a free flight ConOps, but intruder UAS present a unique challenge.

E. Staffing and Decision Support

Controller staffing decisions by the ANSP directly impact the workload mechanism and the capacity of an airspace sector. ATC towers at major airports may vary staffing levels from a single controller during low demand periods to as many as a dozen controllers during peak demand periods. Increasing the number of controllers may enable a sector to approach its theoretical capacity limit determined by structural factors; this is common in terminal airspace where separation minima rather than controller workload dictate achievable throughput.

The number of aircraft that have been supported in an airspace sector in VFR conditions through unconstrained controller staffing and special airspace and route design approaches the operational densities proposed by UAM and UAS operators. Fig. 4 displays the number of aircraft operations handled within the Oshkosh terminal-area airspace before, during, and after the EAA AirVenture Oshkosh Airshow. The days leading up to 7/21/2017 show around 400 tower operations per day with the airports standard controller staffing and sector design. However, during the dates of the airshow (7/22-7/30), the airport increased the number of controllers to as many as 64 and implemented special procedures in order to support over 3000 operations per day.

Challenges of an Oshkosh-like approach to increase ATC capacity includes the integration of complex VFR procedures with nearby airport operations in congested urban areas. Furthermore, the costs of additional controller staffing may not be supported by UAS or UAM operations. Finally, the accident rate at major airshows has been higher than for commercial operations. The development of more mature decision support and automation technologies to support air traffic controllers is a potential opportunity to address these challenges.

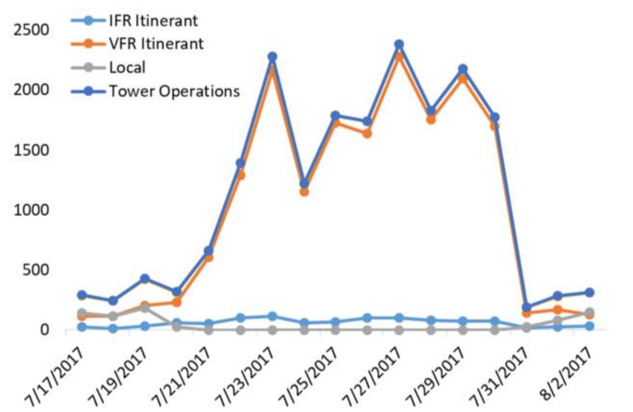

Figure 4 ATC operations at Oshkosh Airshow. *Source FAA OPSNET.*

F. Traffic Mix and Sequencing

Different classes of aircraft require different longitudinal separation minima for wake vortex considerations and cruise at different speeds. Therefore the traffic mix that enters a sector and the sequencing of these aircraft impacts the achievable airspace capacity. UAS and UAM systems are likely to benefit from operators with vehicles of relatively similar size and separation requirements. Such homogeneity will reduce the challenge of sequencing for wake vortex interaction. However, these vehicles are also likely to have diverse performance characteristics, especially cruise speed, that make the impact of the traffic mix more pronounced. The mixing of slow and fast aircraft reduces the capacity potential of a sector by increasing controller workload and potentially leading to larger separation requirements to accommodate variable closing rates.

VI. Conclusion

Unmanned aircraft and urban air mobility systems have the potential to bring thousands of new aircraft and hundreds of thousands of new annual operations to the airspace above metropolitan areas. This research introduced four potential challenges regarding the anticipated number, density, altitude, and diverse characteristics of these new operations and operators that may constrain the scale-up of ATC services. Six implications that insufficient ATC capacity may have on the operation of UAS and UAM were discussed including delays, fees, safety issues, and rejection of access to saturated airspace.

The capacity of a low altitude airspace sector was used as a metric to assess ATC scalability. Sector capacity was decomposed into fundamental influence factors and the "mechanisms" they act through. Using this decomposition as a framework, a variety of opportunities to increase sector capacity by adjusting these factors through technological or operational means were investigated, and the benefits and challenges of these opportunities were discussed.

The analysis suggested that IFR operations are capacity limited by structural factors of the current ATC system, most specifically the large required separation standards. While new technologies have dramatically improved CNS capabilities over the previous decades, the separation standards have not correspondingly been reduced. Additional opportunities to reduce IFR separation standards were identified in the CNS capability and ATC ConOps factors, but faced challenges in terms of cost, feasibility to support low altitude operations, and implementation.

VFR operations were perceived to be capacity limited primarily by the controller and pilot workload mechanism. A variety of potentially viable approaches to reduce workload were discussed. Operations at the EAA AirVenture Oshkosh Airshow were reviewed as an example of how high VFR flight densities of small aircraft is achievable through changes to the controller staffing, airspace geometry, and ATC ConOps factors.

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