An Initial Concept for Intermediate-State, Passenger-Carrying Urban Air Mobility Operations

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This paper describes a general "vision" concept of operations (ConOps) for intermediate-state, passenger-carrying urban air mobility (UAM) missions that has been developed jointly by NASA and Deloitte with input from stakeholders in the UAM ecosystem. This vision ConOps provides a broad overview of some of the high-level requirements for realizing the simultaneous operation of hundreds of aircraft over a single metropolitan area in a wide range of weather conditions as conceptualized by many visionaries at the time of its publication. The concepts contained in this vision ConOps are intended to provide a starting point for further discussions and investigations into how UAM operations can be best enabled. Consequently, we also describe some of the areas where additional research is required before a detailed baseline ConOps can be finalized.

I. Introduction

Rising populations in and around cities and evolving preferences in housing and transportation are causing increasing mobility challenges in metropolitan areas. Just as municipalities began to build skyscrapers to take advantage of the vertical dimension in space-constrained areas, many are now proposing that new modes of mobility be added to urban and suburban areas that utilize all three dimensions of space to provide rapid transportation capabilities. A convergence of evolving technologies, such as electric propulsion and increasing levels of automation, along with the emergence of new business models, such as mobile application-based ride sharing, may enable the emergence of a new aviation market known as urban air mobility (UAM) to help address the mobility needs in metropolitan areas.

UAM has the potential to revolutionize mobility around densely populated metropolitan areas by providing a practical air transportation system for passengers and cargo. Novel aircraft designs with relatively low noise and high efficiency combined with innovative airspace operations management systems that can safely and efficiently manage large numbers of aircraft over small areas will be required to realize this ultimate vision. Furthermore, to be an effective means of transportation in metropolitan areas, UAM operations must be tightly integrated with local communities and existing modes of transportation. The concept of UAM offers the potential for aviation to become a practical part of daily life by moving flight origins and destinations much closer to where people live and work than traditional aviation.

Although the interest in UAM has markedly increased over the past few years, the notion of UAM can be traced back many decades. Helicopter airlines operated in multiple large U.S. cities from the 1950s to the 1970s providing

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short-range, vertical takeoff and landing (VTOL) air service to and from city centers. However, issues such as high operating costs and fatal accidents, along with the noise generated by the operations, ultimately led to the demise of many of these operations. Interest in short range travel into and out of city centers was revived with the advancement of the civil tiltrotor concept in the 1980s and 1990s; however, as of 2020, there has not been a civil tiltrotor aircraft certified by any regulator in the world, much less any commercial air service offered in such aircraft.

The more modern concept for UAM can be traced back to the early 2000s. Although civil tiltrotor research through the 1990s typically focused on vehicles capable of carrying on the order of 40 passengers, new concepts emerged in the early 2000s proposing considerably smaller aircraft for practical transportation. Specifically, the "personal air vehicle" (PAV) concept, which focused on vehicles of less than five passengers, was introduced by NASA in 2003 [1]. In 2010, the first electric VTOL (eVTOL) aircraft concept for UAM, a single-passenger PAV, was introduced [2]. This eVTOL aircraft, its general operational concept [3], and initial system studies of shared fleets of aircraft for on-demand aviation [4] helped spawn a community of interest around the concept of on-demand mobility (ODM), which has largely evolved into the passenger transport portion of the UAM community today.

NASA hosted a series of ODM Roadmapping Workshops from 2015 through 2017 during which challenges to enabling ODM were discussed and many different system and feasibility studies were presented. One of these studies quantified the potential time saving benefits from a notional UAM passenger transportation capability in the Silicon Valley area of California [5]. In this study, Antcliff et al. determined that door-to-door travel times within urban areas could be reduced by approximately 2.6 times compared to existing ground transportation, even when mode change time penalties were applied to UAM travel. Additionally, in approximately the same timeframe as the ODM Roadmapping Workshops, NASA's maturation of novel aircraft concepts featuring distributed electric propulsion, such as the GL-10 [6] and what would become the X-57 [7, 8], bolstered the credence of achieving aircraft with sufficiently low operating costs to support on-demand air transportation in small aircraft. Building upon NASA's work, Uber Technologies, Inc. published their "Elevate" white paper, which laid out a vision for a future aerial ridesharing UAM capability with two- to six-passenger aircraft [9]. Since these events, the UAM community has continued to grow, and today there are more than 200 eVTOL aircraft concepts publicly documented by the Vertical Flight Society [10].

In addition to the largely passenger-carrying-focused work on PAVs and in ODM, NASA also began projects in the early 2010s focused on unmanned aircraft systems (UAS). These projects have ultimately led to a new air traffic management philosophy that is being explored for UAM operations. Focused on small UAS (sUAS), the UAS Traffic Management (UTM) concept was introduced in 2014 and developed over the following years by a NASA project of the same name. The project, in partnership with the FAA, developed a framework for safely managing large numbers of sUAS operations that included transformational concepts, such as digital sharing of intent and a federated system in which third parties provide traffic management and other services [11]. This federated, service-oriented architecture relies on UAS Service Suppliers (USSs) for primary services, such as airspace authorization, and Supplemental Data Service Providers (SDSP) for additional specialized services, such as providing terrain data. The FAA formalized the concepts around UTM in two ConOps documents—the first released in 2018 [12] and an updated version released in 2020 [13]. Additionally, the FAA has developed and begun fielding the Low Altitude Authorization and Notification Capability (LAANC), which provides automated airspace authorization services in controlled airspace to drone operators via approved LAANC USSs [14]. These current and anticipated near-term drone operations will provide operational data that can ultimately support the extension of UTM-like airspace management concepts to other applications like UAM.

A. NASA UAM Strategy Background

NASA's Aeronautics Research Mission Directorate (ARMD) has continued studying the UAM mission since the ODM Roadmapping Workshops. In 2017, ARMD commissioned two market studies to explore the potential economic viability of UAM [15, 16]. These market studies indicated large markets may exist for UAM, but there are many technical, societal, and regulatory challenges that must be solved prior to UAM becoming a scalable operational concept, accessible to many citizens and businesses.

To help describe the goal for such a practical, widespread operational capability, ARMD has developed the following "UAM Vision Statement," which will later be referred to simply as the "UAM Vision" or "Vision," that serves as an underlying motivation for research into UAM.

> UAM Vision Statement: *Revolutionize mobility around metropolitan areas by enabling a safe, efficient, convenient, affordable, and accessible air transportation system for passengers and cargo*

This Vision is broad; it includes the transport of people and goods and does not specify approaches or solutions, such as aircraft sizes or modes of operation.

It should be noted that UAM is a subset of advanced air mobility (AAM), which NASA defines as safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions. Many use the terms UAM and AAM as direct synonyms, but this is inappropriate; AAM includes a more diverse range of missions and operating locations than UAM. Specifically, UAM includes only "local" AAM missions that occur around metropolitan areas, whereas AAM also includes transformational "local" missions outside of metropolitan areas and "intraregional" missions. The remainder of our discussion and the concepts we present in this paper are intentionally for the more narrow concept of UAM specifically.

1. UAM Organizational Framework

To help describe the UAM domain and organize its research in UAM, ARMD has developed an organizational "framework" consisting of five separate areas, or "pillars," that comprise all elements of the UAM ecosystem. This framework is shown in Fig. 1. The different ducted fans of the pentacopter[*] represent the different pillars, and descriptions of each pillar are provided in boxes adjacent to each ducted fan.

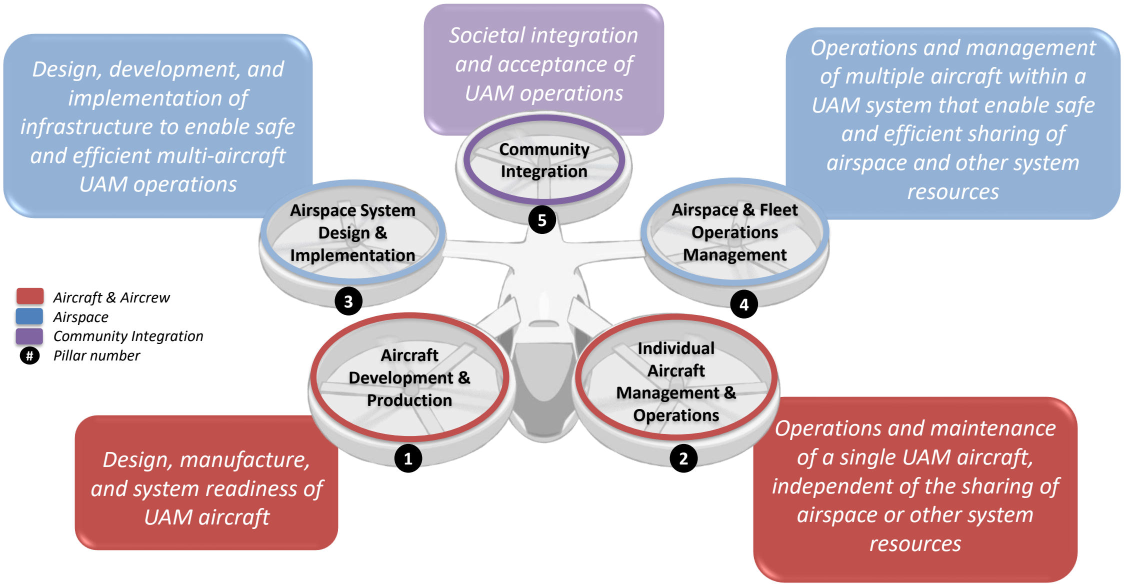

Fig. 1 NASA's UAM Organizational Framework.

The left half of the figure represents what is referred to as the "design" side of the framework, that is, it reflects the elements that must be addressed before the system can be fielded and begin operation. The right half of the figure represents the "operations" side of the framework, which encompasses issues that will arise once the system is operational. Note that the topmost fifth pillar, Community Integration, straddles this demarcation and must continuously be addressed throughout the system lifecycle. The bottom two pillars address vehicle-centered challenges, while the upper two symmetric pillars address airspace-oriented topics; this separation parallels the current aviation system, whereby access to airspace is predicated on vehicles being designed and operated safely. It is important to note that matters relating to the necessary infrastructure required to realize UAM are spread throughout multiple pillars, such as the Airspace Systems Design and Implementation pillar as well as the Community Integration pillar.

2. Barriers

There are many technical, societal, and regulatory challenges that must be overcome before the UAM Vision can be realized. In our terminology, these challenges are called "barriers," and barriers include any gap between the broad UAM community's current capabilities and what is required for UAM. Some barriers have potential solutions already known or likely paths to achieving solutions identified. In these cases, sufficient investment[†] is anticipated to generate

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[*] This aircraft design is purely notional and was selected for artistic effect.

[†] Investment is intended to be a broad term encompassing any expenditure of resources, including time and money. This investment may be made by a single organization or multiple organizations. NASA does not necessarily have a role in solving all of the barriers

viable solutions to overcome these barriers. However, in other cases, barriers may have no known solution and/or no known path to achieve a solution.

ARMD has identified 24 primary barriers associated with the five pillars of the framework, as shown in Fig. 2. These barriers are written at a relatively high level and are intended to encompass the known issues prohibiting the realization of the UAM Vision. Barriers were derived at the pillar level, enabling the enumeration of the key limiting challenges for each pillar as depicted in Fig. 2. However, certain challenges span multiple pillars, with some challenges spanning all pillars. Challenges that spanned all pillars were resolved into *crosscutting* barriers, of which seven primary areas are identified in the concentric circles spanning the pillars in Fig. 2. Although the 24 pillar-specific barriers may generally be addressed in a relatively self-contained fashion, these crosscutting barriers will likely demand system-level solutions that cannot be addressed in a stovepiped manner. A detailed description of these barriers can be found in Ref. [17], but a brief overview of the barriers in each pillar is provided here.

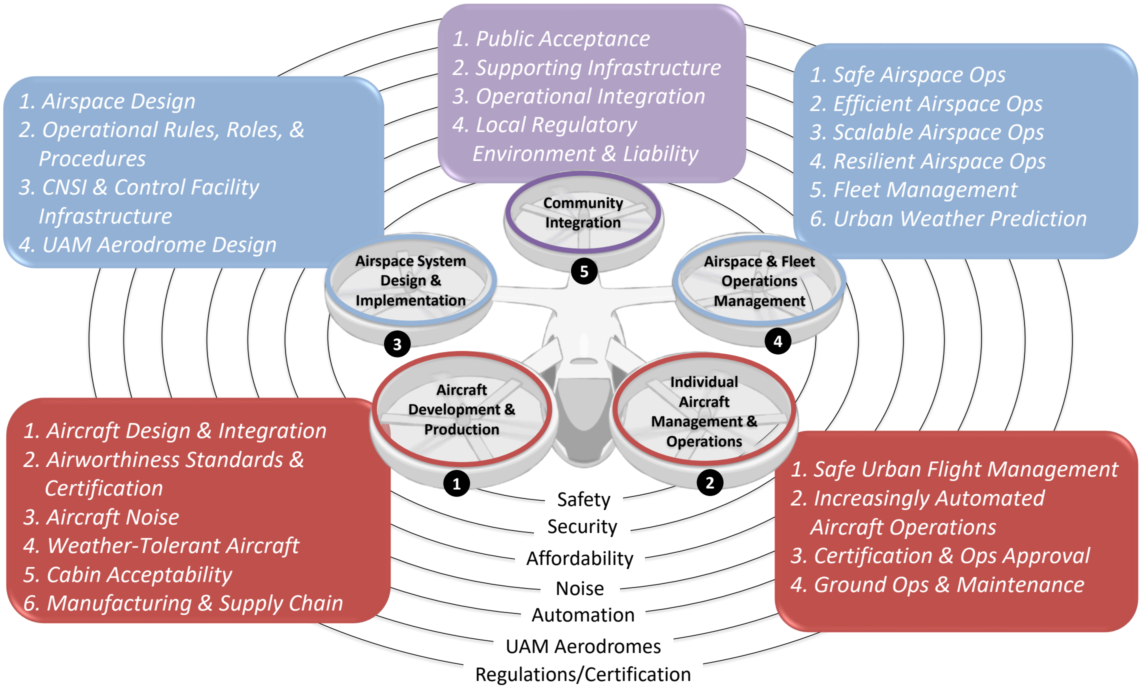

Fig. 2 Barriers associated with the five pillars of NASA's UAM Organizational Framework.

The barriers associated with the Vehicle Development & Production pillar address vehicle design, component integration, manufacturing, and certification challenges. Vehicle weather tolerance impacts the reliability of operations, as well as which markets may be viable. Issues such as vehicle noise and cabin acceptability will impact public adoption and acceptance.

Individual Vehicle Management & Operations encompasses challenges related to precision operations, pilot scalability, and operational safety, as well as increasing automation and continuing airworthiness of aircraft. Operator certification and operational approval for these novel operations is likely to be a key barrier for this pillar.

The Airspace System Design & Implementation pillar deals with the lack of airspace infrastructure for UAM, including communications, navigation, surveillance, and other information (CNSI) infrastructure sufficient for urban environments. Additionally, this pillar includes gaps in current airspace design and operational procedures for (a) operations supported by third party service providers and (b) increased numbers of aircraft flying in closer proximity to one another and to the urban environment than is typical in aviation today.

The Airspace & Fleet Operations Management pillar contains challenges related to managing higher volumes of air traffic in smaller airspace volumes than typically encountered in aviation. Additionally, it contains challenges focused on being able to sufficiently predict and account for the potentially unique environmental conditions present at lower altitudes and near cities. This pillar also includes challenges related to managing aircraft fleets in ways that enable operators to offer reliable UAM services to customers.

Finally, challenges associated with the Community Integration pillar include achieving public acceptance that UAM operations are a net benefit to their communities and can be integrated into individuals' daily lives in practical ways. This pillar contains challenges in developing the appropriate local regulations that will govern issues such as UAM port zoning and acceptable noise thresholds.

3. UAM Maturity Levels

NASA has developed the UAM Maturity Level (UML) scale to describe the maturity of the entire UAM ecosystem across all pillars of the organizational framework and to indicate how the UAM industry may mature over time. The UML scale contains six levels denoting a progression in capabilities, moving from testing through the realization of a ubiquitous air transportation system that would be just as accessible as traveling by ground vehicle today. The UML scale is presented in Fig. 3. The UML scale is described only briefly here; additional details are provided by Goodrich and Theodore [18].

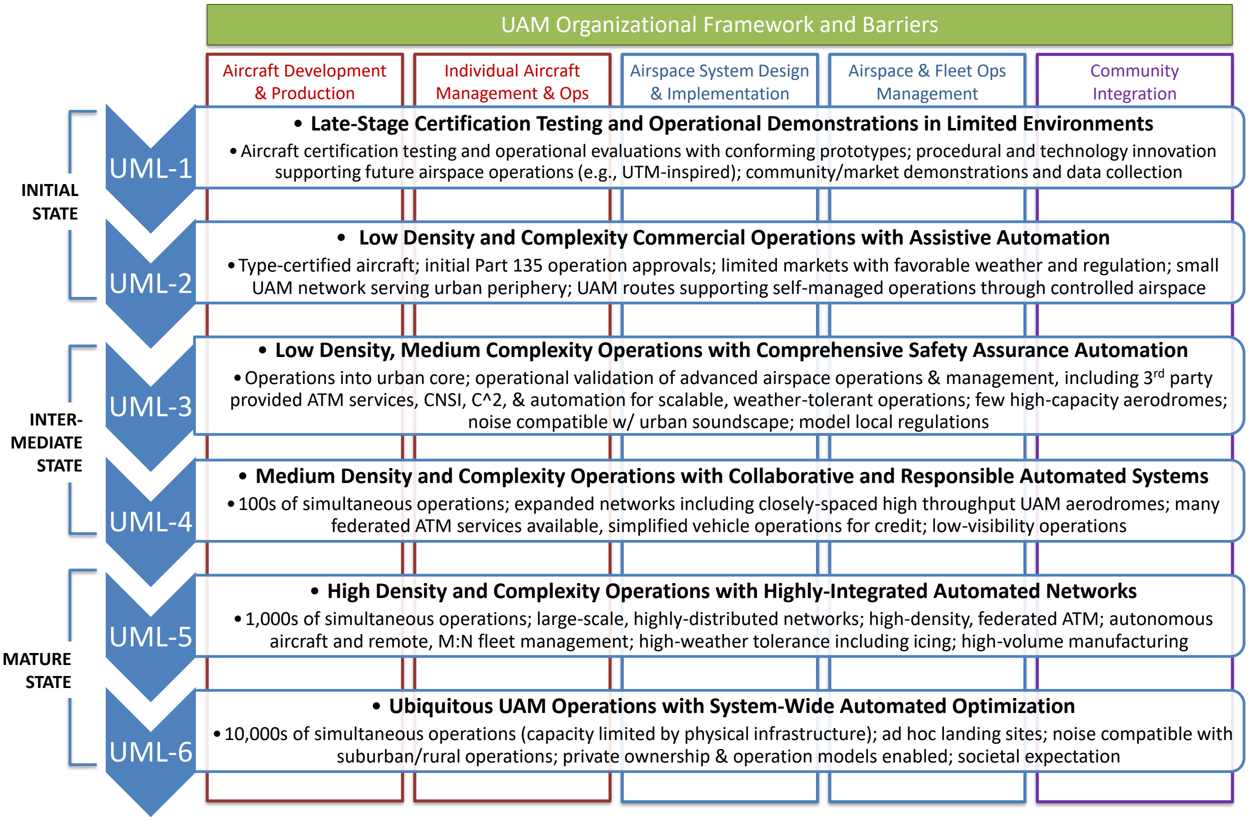

Fig. 3 Description of the Urban Air Mobility Maturity Levels (UMLs).

The six levels of the UML scale are differentiated by three primary characteristics: 1) air traffic density, 2) operational complexity, and 3) reliance on automation. Air traffic density refers to the number aircraft operating over a given metropolitan area. Operational complexity is a combination of several factors, including weather tolerance (decreasing visibility in particular), increasing operational integration into densely populated areas, increasingly complex procedures (e.g., curved as opposed to straight in approaches into UAM ports), and increasing operational distribution. Generally, the levels of complexity and air traffic density increase with increasing UML, with only either complexity or density increasing at any one level. Reliance on automation indicates the degree to which human and machine agents are assigned functions and responsibility. Early UMLs assume higher responsibility levels for humans, whereas the latter levels have near-total responsibility held by automation.

The capabilities described by UML-4 align fairly closely with the mid- or far-term visions cast for UAM by many in industry, such as Uber [9]. Furthermore, the NASA-sponsored UAM Market Studies [15, 16] indicate that a UML-4 level of capability could result in substantial industry profitability. Consequently, NASA's current focus for research is helping the broad community reach UML-4.

B. Paper Scope

NASA and Deloitte with input from many interested parties have developed a vision concept of operations (ConOps) document for a passenger-carrying, UML-4 UAM transportation system [19]. This "vision ConOps" presents a generalized vision of the future with UAM and is designed to only imply high-level requirements on the UAM system, not dictate all the specific engineering details required to implement such a transportation system. This vision ConOps builds upon prior NASA UAM research, including the UAM Market Studies [15, 16], the work of Thipphavong et al. describing initial concepts for airspace integration of UAM [20], and the work of the Urban Air Mobility Coordination and Assessment Team, including the operational concept described by Price et al. [17]. Additionally, this vision ConOps considers the UAM research ConOps published by the FAA's NextGen organization in the summer of 2020, which is targeted at UML-2 operations [21]. The concepts put forward in the UML-4 vision ConOps can be considered an evolution of the UAM transportation system over time from the concepts in the UML-2 ConOps.

The vision ConOps is focused on passenger-carrying UML-4 operations for several reasons. First, market feasibility studies, such as the UAM Market Studies [15, 16], indicate that UAM markets are not likely to be accessible to the general public and achieve profitability until reaching a level of maturity approximately equivalent to UML-4. Second, passenger-carrying operations are emphasized due to the generally greater difficulty of these missions when compared to cargo transport. For minimum commercial viability, passenger-carrying missions will generally require larger payloads as well as more stringent safety and other requirements than cargo transport missions. Thus, a viable passenger-transport ConOps is also likely able to satisfy the majority of the needs of cargo-carrying missions. Finally, passenger-carrying UML-4 operations are not likely to occur in the near future, but they are also potentially obtainable within a reasonable timeframe (e.g., in approximately 15 years) with technological advancements that are conceivable today. If further-term operations (e.g., UML-6) were the focus, the number of advancements in capabilities needed would be so great that it would be incredibly difficult to define a credible ConOps and pathways to obtaining the desired capabilities. On the other hand, UML-4 operations are not directly achievable today or even within just a few years. By laying out a vision for a somewhat longer timeframe, we can help ensure that the decisions made in the near term are not counterproductive to advancing capabilities beyond the initial steps.

In this paper, we describe some of the major underlying assumptions and key principles of the UML-4 vision ConOps and discuss key areas where additional research is required before a final ConOps that can enable the envisioned capabilities can be completed. This paper will be unable to cover every element described in the more detailed vision ConOps, so the reader is encouraged to review the full vision ConOps for further information [19].

Because UAM is effectively an entirely new air transportation system, it is anticipated that UAM operations will be complex and there are many "unknowns" that can influence the success of the UAM industry. We acknowledge that this initial vision ConOps will be unsuccessful in predicting all of the unknowns. Therefore, we plan on the ConOps being a "living" document that is updated over time as new lessons are learned. Consequently, in this paper, we highlight some of the major areas where consensus has not been reached and/or key trades have yet to be (publicly) explored. These areas are prime candidates for future research.

II. Overview of the Passenger-Carrying UML-4 Vision ConOps

In this section, we describe the general contents of the passenger-carrying vision ConOps document [19], highlighting what are deemed to be some of the most significant points. It is important to emphasize that this "vision ConOps" is intended to provide a broad vision of a potential future UAM transportation system, which is a wider scope than simply those elements directly pertaining to the operations themselves. Additionally, this ConOps implies only high-level requirements and is not intended to prescribe a particular course of action to reach UML-4. Consequently, the level of detail is different from many ConOps documents.

The full vision ConOps document is primarily organized around the organizational framework and barriers described previously in Figs. 1 and 2. In the following subsections, we take a similar, but more succinct, approach that enables us to provide a slightly different perspective on the same content. We begin with an overview of key assumptions, actors, and terms, then move into a discussion of the operations from the perspective of an individual aircraft. Next, we describe the design of the airspace followed by how air traffic and fleet operations are managed. Finally, we summarize some of the key considerations around integrating UAM into the everyday life of citizens in metropolitan areas.

A. Key Assumptions, Actors, and Terms

Prior to describing the key concepts in the UML-4 vision ConOps in more detail, a basic understanding of some of the key assumptions, terms, and actors in the envisioned UML-4 system is helpful.

The following are some of the major assumptions inherent in the vision ConOps:

1) The vision ConOps assumes a UAM system based in the United States. Consequently, the roles of the civil aviation authority and traditional air navigation service provider are both fulfilled by the Federal Aviation Administration (FAA), and the FAA has the responsibility for regulating airspace operations throughout the entire National Airspace System (NAS). Additionally, the ConOps assumes the United States' legal framework and governmental structure. This assumption does not preclude the implementation of similar systems outside of the United States, but certain details may need to change to accommodate differences in other countries.
2) Passenger-carrying operations are the focus of the vision ConOps. However, cargo-carrying aircraft or other flight operations (e.g., aerial work missions) are also expected to be a part of a UML-4 future and will operate under the same rules. Certain elements of the ConOps that are specific to the payload will change for these missions, but the vast majority of the ConOps will remain the same.
3) Nominal operations begin and end from designated takeoff and landing areas called "UAM aerodromes" (to be consistent with the research ConOps set forth by the NextGen organization of the FAA for near-term UAM operations [21]).
4) UAM is a part of an intermodal transportation system, and UAM aerodromes are located strategically near other forms of transportation, including traditional commercial aviation, roadways, and rail stations, to reduce mode transfer times.
5) Although the FAA maintains full authority over the NAS, it does not directly perform all the same functions that it historically has for commercial aviation. Rather, the FAA is assumed to delegate many functions to operators and/or third parties who operate under rules and regulations adopted by the FAA. For example, traditional air traffic control (ATC) does not actively manage UAM air traffic in nominal situations.
6) Aircraft share information describing their intended operation (i.e., "intent information").
7) New or modified flight rules are required to enable UML-4 operations. Visual flight rules (VFR) are inadequate to accommodate operations in instrument meteorological conditions (IMC), but instrument flight rules (IFR) were not designed for the required close-proximity operations characteristic of UML-4.
8) There is an individual human as the pilot in command (PIC) for each aircraft. However, this PIC may change in flight, the PIC may be physically on the aircraft or located remotely, and this human individual may be PIC for multiple (though a small number) of aircraft at one time.
9) Many potential types of aircraft could perform UAM missions, and the vision ConOps is generally agnostic to specific aircraft types or performance levels. However, many believe that all-electric aircraft or some form of electrified propulsion is required in novel UAM aircraft, and, consequently, some elements of the vision ConOps include considerations specifically for these forms of aircraft. Additionally, specific elements of operations (e.g., approach and departure paths) will be specific to certain classes/types of aircraft and still-undefined rules may ultimately set minimum performance characteristics for certain operations. Additional research and development is required to provide these lower levels of detail before operations can be realized.
10) It is generally believed that many UAM aircraft will be parts of commercial fleets. Consequently, some of our terminology is more closely aligned with such operations. However, there is no prohibition of any business model nor any stipulation that aircraft must be a part of a commercial fleet. Individually owned/operated, public service aircraft, fractional ownership models, etc. are all possible/probable at UML-4, and this ConOps is intended to incorporate all business models.

The following are some of the key actors envisioned for UML-4 operations. These actors are briefly described here and additional details are provided in the subsequent subsections as appropriate.

1) Fleet Operator: The fleet operator is the entity responsible for operational control of UAM aircraft and fleet operations. Fleet operators may have responsibility for only a single aircraft (i.e., there may be a fleet size of one aircraft) or many. An individual who owns and operates his/her own single aircraft and organizations operating a fleet of multiple aircraft for commercial use are examples of fleet operators.
2) Provider of Services for UAM (PSU): Analogous to a UTM Service Supplier (USS), a PSU provides services to UAM aircraft that support operations, including being a primary means of enabling communication among actors in the UAM system.
3) Supplementary Data Service Providers (SDSPs): Services providers other than PSUs that provide services that support operational decisions.
4) Aircraft Crew: Human or humans who are partially responsible for the safe flight of an aircraft, sharing this responsibility with some automated system(s). Aircraft crew members are not traditional pilots, but perform

some of the same functions that pilots perform today, sharing the remainder with automation or other aircraft crew members.

5) UAM Aerodrome Operator: private or public entities responsible for ensuring the safety of individual takeoff and landing areas and ground services (embarkation, disembarkation, maintenance, etc.) provided at a UAM aerodrome.

The following are key concepts that will be used in the subsequent subsections to describe the envisioned UML-4 operations and are introduced here for easy reference and clarity.

1) PSU Network: The PSU Network is a digital interconnection of all PSUs in an area to provide a secure information exchange of data related to UAM operations.
2) Flight Information Management System (FIMS): FIMS is an application programming interface (API) gateway for data exchange between UAM users and FAA systems. FIMS delivers relevant NAS information and FAA directives to PSUs and provides the FAA access to any information it needs from PSUs.
3) Operations Plan: The operations plan is similar to a flight plan and contains flight path, planned departure/arrival times, alternate UAM aerodromes, and other data elements describing the operation. The operations plan is a primary means by which intent information is shared.

B. Individual Aircraft Operations

Key challenges of individual aircraft flight operations at UML-4 include 1) operations in obstacle challenged urban environments, 2) operations in close proximity to other air traffic, 3) operations in low-visibility conditions, i.e. instrument meteorological conditions (IMC), and 4) efficiently utilizing scarce, shared system resources such as takeoff and landing areas. Of course, these challenges must be met with a level of safety compatible with the expectations of the FAA, travelers, and the over-flown public. Finally, supporting the ability of the UAM system to sustainably grow while meeting the high safety and performance requirements provides strong motivation to reevaluate traditional human and automation roles and responsibilities that have served commercial aviation well over many decades. Although this direction introduces risks that must be understood and responsibly managed during the development process, the long-term viability of UAM is in large part facilitated by increasing reliance on automation over time. UML-4 is likely to be an important transition stage during an evolutionary process. Aircraft are likely to be much more automated than today. Perhaps more importantly, safety-critical functions delegated to automation, such as highly augmented flight controls providing simplified control and hazard detection systems assuring awareness of traffic and other hazards in IMC, must be certifiable as “responsible” for performing these functions without relying on a skilled pilot to detect and mitigate system failures. At the same time, aircraft at UML-4 are *not* expected to have “full autonomy,” which is defined here as the technical capacity and regulatory authorization to operate without oversight by a responsible and qualified human supervisor during the conduct of a flight. Functions requiring active oversight at UML-4 will likely include a number of considerations beyond basic operation of the vehicle, for example: cabin supervision, particularly in non-normal situations; the ability to make observations of the general health of the aircraft and detect developing anomalies before they result in significant loss of performance and/or safety; and similarly, monitoring the overall performance of the automation while confidence is built up in its ability to conduct autonomous operations. As discussed more below, from a regulatory perspective, human supervision required at UML-4 will fulfill an updated interpretation of the roles and responsibilities of the PIC.

As something of a transitional phase in the development of autonomy, flight operations at UML-4 are expected to involve a range of human and automation agent combinations. Potential combinations are briefly outlined in the reminder of this section. These combinations are meant to be illustrative and not exhaustive. Additionally, to help describe these potential roles, four categories of flight management functionality from Wing et al. [22], which progress from higher level to lower level, are used. These categories are:

1) Mission Management: Planning and revising the overall mission, such as setting or changing a destination UAM aerodrome.
2) Flightpath Management: Setting and revising the aircraft’s flightpath to achieve the mission in an effective way.
3) Tactical Operations: Making modifications to the aircraft’s projected flightpath/state to ensure the safety of the aircraft in the short-term, typically in response to an unanticipated hazard (e.g., flock of birds), which generally ignores the overall mission objective until a safe state is restored.
4) Vehicle Control: Controlling the physical motions and actions of the aircraft such that it safely follows the trajectory and action plans developed in flightpath management and tactical operations.

In lieu of a traditional, highly skilled, onboard pilot, many aircraft at UML-4 are envisioned to have an aircraft crew: human(s) who share the responsibility for the safe flight of the aircraft with automated systems. In this paradigm, the aircraft crew provides higher-level "over-the-loop" monitoring of the mission and flight systems rather than the routine interaction with the flight controls performed by a traditional pilot. The supporting automation must be designed to satisfy safety cases that do *not* rely on "in-the-loop" interventions by the crew to "save the day." However, each aircraft crew is still expected to include a designated human PIC, but the PIC will be assisted by automation, other aircraft crew members (if part of the crew concept), and/or the fleet operator.

Aircraft crew encompasses a broad set of potential roles, and aircraft crew members do not necessarily have to be onboard the aircraft. Regardless of their specific role, each aircraft crew member receives training and certification at a level deemed appropriate by the FAA for their role in the operation. Although one member of the aircraft crew is designated the PIC, the PIC may change during a flight. The ConOps is agnostic as to the PIC being onboard or offboard as a remote PIC (RPIC). Additionally, an RPIC may be responsible for more than a single aircraft, although this division of attention may require the support of other human aircraft crew members. More detailed examples of potential aircraft crew members include:

1) Aircraft operator: Individual who oversees the operation of a single aircraft from either onboard or offboard the aircraft. The aircraft operator primarily provides the "mission management" for the operation, although intervention in aircraft flightpath management and tactical operations are possible. The aircraft operator is typically the PIC for the aircraft.
2) Multi-aircraft operator: Individual who oversees the operation of a small number (e.g., three) of highly automated aircraft simultaneously from offboard the aircraft. This individual is typically the PIC for each of the aircraft she/he oversees. It is likely that the aircraft under the command of a multi-aircraft operator would be conducting closely related operations, such as aircraft operating between the same UAM aerodrome pairs.
3) Second-in-command: Individual onboard an aircraft to assist with passengers (e.g., to help diagnose and assist with a medical emergency), help diagnose and treat emergency/contingency situations that may arise onboard the aircraft (e.g., recognizing/extinguishing an avionics fire), and provide greater awareness of the conditions onboard an aircraft to a fleet operator, multi-aircraft operator, or other entity not onboard the aircraft (e.g., visually observing an obstacle or other aircraft that may pose a threat to the aircraft). The second-in-command nominally operates under the supervision of a multi-aircraft operator. In situations where communication with the multi-aircraft operator is lost, the second-in-command may need to act independently to ensure the safety of the aircraft. This would be similar to the captain being incapacitated on two-crew aircraft today and may merit special handling by the rest of the system as an emergency situation.

For illustrative purposes, we briefly consider three aircraft crew archetypes that may be deployed at UML-4. Characterization of the aircraft crew archetypes below consists of a high-level summary of responsibilities of the 1) onboard automation, 2) any aircraft crew other than the PIC, and 3) the PIC. The archetypes are named according to the aircraft crew composition and locations: 1) onboard PIC with no additional crew, 2) single-aircraft RPIC with no additional crew, and 3) multi-aircraft RPIC with onboard, second-in-command (SIC). The three archetypes are each assumed to be supported by similar dispatch and mission planning functionality provided by the fleet operator. A delineation of responsibilities between the various actors for these three archetypes is given in Table 1. Table 1 illustrates the potential capability and responsibility allocations using the four categories of flight management functionality described above.

At UML-4, automation is expected to have responsibility for vehicle control in all cases, but different aircraft crew and automation roles may perform elements of the other categories (i.e., mission management, flightpath management, and tactical operations). In Table 1, the different aircraft crew members and automation are assigned either primary, secondary, or tertiary responsibility as shown for these various roles when there is shared responsibility for a function; in some cases, either the automation, PIC, or additional crew have full responsibility (i.e., there is no shared responsibility).

Table 1 Responsibility Delineations for Three Aircraft Crew Archetypes

		Archetype 1: On-board PIC with No Additional Crew		Archetype 2: Single-Aircraft, Remote PIC (RPIC) with No Additional Crew		Archetype 3: Multi-Aircraft RPIC with Onboard, Second-In-Command (SIC)		
		Automation	PIC	Automation	PIC	Automation	PIC	Additional Crew: SIC
Mission Management	Verification of operations plan from fleet operator	Primary	Secondary	Primary	Secondary	Primary	Secondary	Tertiary
	Maintenance of “standard” contingency plans	Primary	Secondary	Primary	Secondary	Primary	Secondary	None
	Oversight of overall mission continuation	Secondary	Primary	Secondary	Primary	Secondary	Primary	Tertiary
Flightpath Management	Monitoring of active flight plan	Primary	Secondary	Primary	Secondary	Primary	Secondary	Tertiary
	Optimization of active flight plan	Primary	Secondary	Primary	Secondary	Primary	Secondary	Tertiary
Tactical Operations	Detection of tactical hazards	Primary	Secondary	Full	None	Full	None	None
	Maneuver management for mitigation of tactical hazards	Secondary	Primary	Primary	Secondary	Primary	Tertiary	Secondary
Aircraft Control	Aircraft stability and trajectory control	Full	None	Full	None	Full	None	None
	Subsystem management	Full	None	Full	None	Full	None	None
Passenger/Cabin Management		Limited advisory functionality, such as monitoring of seatbelt status	Full	Primary	Secondary	Limited advisory functionality, such as monitoring of seatbelt status	None	Full

C. Airspace System Design

1. The UAM Operating Environment

One of the key elements of the UML-4 vision ConOps is the UAM Operations Environment (UOE). The UOE is a flexible area of airspace in which the majority of UAM operations, including the highest density operations, are contained. The UOE is similar in concept to, though distinct from, the UAS Traffic Management (UTM) environment. The UOE coexists with the traditional airspace classes (i.e., it is not itself a new class of airspace), and operations within the UOE are supported by third-party, federated service suppliers (i.e., PSUs). All flights within the UOE are required to abide by either (a) a new set of flight rules (i.e., something in addition to VFR and IFR) that are applicable across the NAS or (b) a set of rules that are specific to operations within the UOE. These new rules are required to enable the number and tempo of operations envisioned at UML-4 without (a) burdening the traditional ATC system, (b) being limited by the separation requirements of IFR, or (c) being limited by the weather requirements of VFR. These rules are assumed to require that all aircraft provide aircraft position and operational intent data to enable the safe management of air traffic within the UOE.

The UOE can extend into actively controlled airspace (i.e., Class B, C, or D airspace), which enables UAM aircraft to operate within this airspace while following the rules that govern the UOE and not directly interact with ATC under nominal conditions. However, to operate within the UOE in actively controlled airspace, aircraft must be equipped both for the UOE as well as the class of controlled airspace into which the UOE extends to enable safe traffic management in the event of off-nominal circumstances. Extending UOE into actively controlled airspace can enable UAM operations to reach existing airports or other locations that lie within actively controlled airspace.

The maximal extent of the UOE is defined and published on aeronautical charts. This maximal extent covers as small of volume as practical to enable safe management of the higher density of operations as compared to today that are expected at UML-4. The extent of the UOE must allow for aircraft to comply with relevant federal aviation requirements while enabling sufficient space for traffic to be safely separated. Furthermore, the maximal extent of the UOE is partially dependent on where PSUs are authorized to provide services and the geographical extent of the infrastructure required to provide those services. Consequently, the maximal UOE size and shape will vary with each metropolitan area based on the unique characteristics of each area, such as geography, infrastructure (e.g., buildings, communications, etc.), and so forth.

Although the maximal extent of the UOE is static, the extent of the UOE that is available for operations can change over time (i.e., the available extent is "flexible"). For example, if the flow pattern at a nearby major airport changes, the available UOE may change to avoid potential traffic conflicts among UAM aircraft and traditional commercial airliners. Changes in the available UOE likely occur on the order of a few times per day, and these changes, and the current extent of the available UOE, is reported in the PSU Network.

A graphical representation of a notional metropolitan area with a UOE is shown in Fig. 4. In this figure, the maximal extent of the UOE is denoted in yellow. The maximum altitude of the UOE is increased over the tall buildings that represent a downtown area to enable flights to occur at safe altitudes over the buildings; the maximum altitude of the UOE is reduced over other areas to avoid impacting as much airspace as practical.

Not all UAM operations will be contained within the UOE as depicted in Fig. 4. Although the highest number of operations will fall within the UOE, some aircraft will frequently travel outside the UOE. Aircraft flying outside the UOE must follow the requirements of the airspace they operate within, including using available flight rules and satisfying equipage requirements.

The UOE is not limited to only UAM aircraft. Other aircraft may fly in the UOE if they able to safely participate in the management and separation of traffic within the UOE, most likely through a connection with a PSU. Additionally, the UOE may have one or more PSUs providing services throughout the entire volume or just a portion of it.

2. High-Density Routes

It is anticipated that in order to achieve the high load factors and high aircraft utilization likely required to provide a per-trip cost that is affordable to the general public, many UAM operations are likely to occur between locations where demand is consistently high. This clustering of operations is expected to lead to the need to manage high traffic density between particular UAM aerodromes and the natural development of high-density routes.

High-density routes are dynamic based on demand and are managed by PSUs according to consensus standards that are approved by the FAA. For example, some high-density routes may be configured to enable increased volumes of air traffic to fly into town during the morning "rush hour," reconfigured to handle more balanced traffic flow during

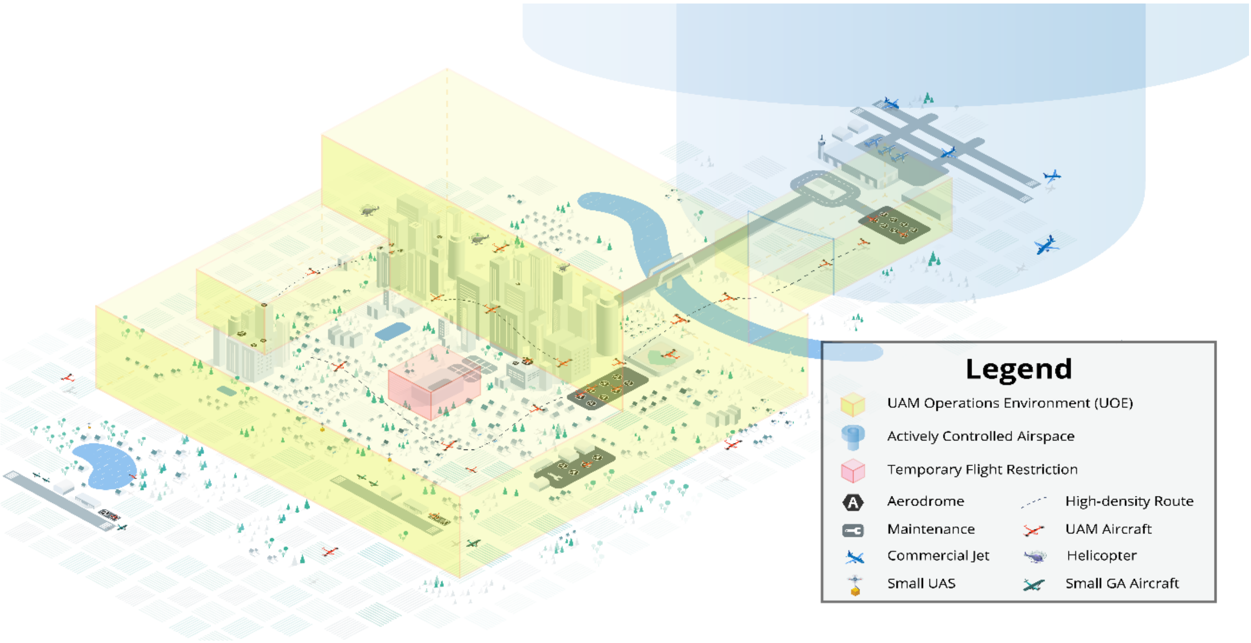

Fig. 4 An artistic depiction of a notional metropolitan area showing a representative UAM Operating Environment (UOE).

the middle of the day, and then modified to enable a large number of flights to travel out of town during the evening "rush hour." Developing the rules for dictating traffic flow along these routes will require deliberate engagement with a diverse group of stakeholders to ensure equitable airspace access and address public concerns over issues such as noise while maintaining the safe and efficient flow of a large number of aircraft. Due to their dynamic nature, high-density routes are not charted in a traditional sense, but information about the high-density routes, such as status ("active" or "inactive") and configuration (e.g., increased flow in one direction), is available via the PSU Network.

High-density routes exist solely within UOE areas and require more advanced capabilities for managing aircraft than other areas of the UOE. Consequently, high-density routes will likely be supported by increased air and ground infrastructure as compared to the remainder of the UOE. For example, high-density routes are likely to be supported by enhanced micro weather sensing and prediction, augmented CNSI infrastructure, and higher-capacity UAM aerodromes when compared with other areas of the UOE.

D. Airspace & Fleet Operations Management

The density and tempo of UAM operations at UML-4 cannot be supported by existing air traffic management (ATM) procedures and practices; ATC workload limitations as well as existing rules and procedures preclude scaling UAM operations to the traffic levels necessary to meet projected demand in the UOE. ATM service provision at UML-4 is envisioned to reside with UOE users to allow for scalability of UAM operations without overwhelming traditional ATC systems and minimizing impacts on existing airspace users. The FAA retains authority over the UOE and delegates service provision to qualified UOE users (i.e., PSUs), while ensuring the rules and procedures governing UAM operations support safe and secure UAM operations as well as equitable airspace access.

Rules for the user-provision of ATM services are anticipated to be developed by the UAM ecosystem (i.e., fleet operators, municipalities, UAM service providers, and other UAM stakeholders) and approved for use by the FAA to ensure these Community-Based Rules (CBRs) [21] meet the aforementioned safety, equitability, and security requirements that would otherwise be assured by FAA service provision. User provision of services at UML-4 relies on a communications network connecting service providers with fleet operators, UAM aircraft, aerodrome operators, and each other. Fig. 5 depicts the key components of this network: FIMS, PSUs, SDSPs, UAM fleet operators, and UAM aircraft. At UML-4, the network also communicates with UAS Service Suppliers (USSs) to support integration with UTM operations and Public & Safety entities (e.g., law enforcement).

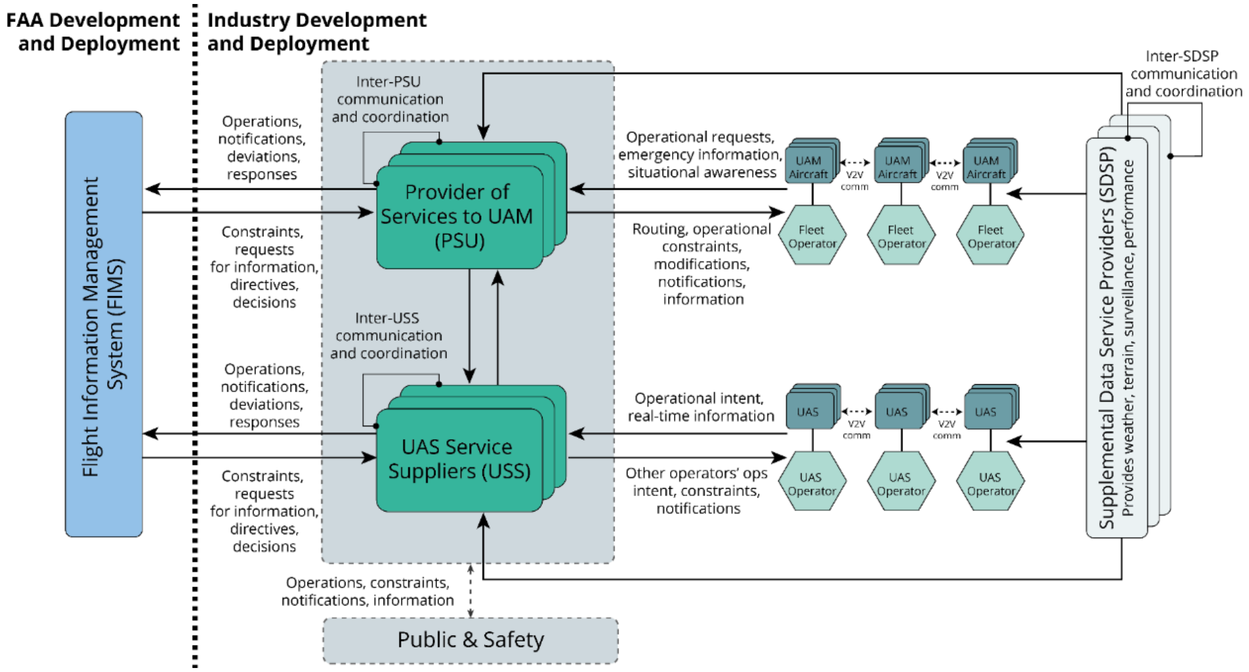

Fig. 5 UAM communications network architecture.

The FIMS will be developed and deployed by the FAA and serve as a conduit of information to and from FAA systems. FIMS will provide airspace constraints (e.g., temporary flight restrictions, configuration of proximate controlled airspace) and support safe UAM operations by maintaining a database of performance authorizations for UAM fleet operators. A performance authorization is an approval from the FAA that a particular operation, including the entities performing the operation, meets regulatory and safety requirements. A fleet operator obtains a performance authorization based on the aircraft, PIC, aircraft crew, supporting services, and locations of flight (e.g., a high-density route). PSUs verify that each operations plan submitted by a fleet operator has an appropriate performance authorization via FIMS. PSUs provide or support flight planning and authorization, demand-capacity balancing, conflict detection, surveillance, separation, and more. Multiple PSUs may operate within an area, enhancing redundancy and resiliency of UAM operations. Collectively, all PSUs within an area are referred to as the PSU Network. SDSPs provide data services (e.g., weather, surveillance, in-flight entertainment) to the PSU Network, fleet operators, and UAM aircraft. Specific roles of PSUs and SDSPs with respect to provision of UAM services is defined by FAA qualification requirements for safety-critical services (e.g., surveillance or separation services) and by CBRs for an area. For example, at UML-4, PSU certification requirements will likely require that PSUs support flight planning by providing strategic conflict detection of proposed operations through sharing of operational intent. PSUs may additionally offer resolutions to the fleet operator for any detected conflicts (e.g., a later departure time or a different route) and provide surveillance to fleet operators in support of tactical separation. Alternatively, surveillance may be provided by a SDSP.

The UAM communication network at UML-4 shares intent information with USSs to foster safe interaction between UAM and UTM operations. UOE typically overlays UTM airspace, which is assumed to extend from ground level up to 400 ft above ground level, but UAM aircraft may need to transit UTM airspace to land at or takeoff from UAM aerodromes. Shared intent with USSs will enable coordinated UAM/UTM movements by reducing interactions, thus enhancing safety.

Operations in the UOE within actively controlled airspace will present challenges for ATC as well as for other aircraft within that actively controlled airspace. Although ATC separation services are not planned to be utilized for UAM aircraft, ATC needs to be aware of the UOE to provide clearances within controlled airspace that avoid the UOE. Aircraft within the UOE may be displayed on the controller's display when requested and as necessary to provide situational awareness (e.g., during declared emergencies). Under nominal operations, IFR aircraft will not be cleared through the UOE due to the additional workload this would create for controllers. However, VFR aircraft meeting UOE requirements (e.g., ability to transmit position data) may be allowed to transit the UOE.

Management of fleets is the responsibility fleet operators who are supported by service suppliers. Fleet operators are expected to utilize advanced methods and technologies to efficiently manage their fleets for their particular mission(s), ultimately achieving high aircraft utilization and high average load factors even in the presence of contingencies and off-nominal events (e.g., an aerodrome closing due to a fire).

It is envisioned that UAM weather systems at UML-4 will help enable operations in a wider variety of weather conditions than today. Achieving sufficiently high-performing urban weather systems will be dependent upon many factors, including locally tailored, denser data collection systems; standards around weather data performance, data interfaces, and SDSPs; improved modeling and forecasting tools; and updated policies and regulations. One operating aspect being pioneered through updated standards for UAM is the transition to performance (quality) data standards as a replacement for both the certification of weather sensors and the requirement for the fleet operator or pilot to be responsible for the quality of the weather data. Utilizing data performance standards also supports the use of a wider variety of data sensors, including specially designed sensors as well as sensors that are part of the "Internet of Things." Another unique operating aspect is the potential to update weather-related flight rules. This possibility exists as a result of the transition to performance-based standards recognizing that each of the multiple UAM aircraft configurations will have different weather tolerance and performance capabilities and thus be capable of operating safely in different weather conditions (e.g., one vehicle may be capable of safety operating in zero visibility whereas another may have sensors that require 0.5 mile of visibility). Lastly, to achieve UML-4, installing and operating weather supporting systems will likely require a significant shift to third-party service providers. The federal government is expected to continue to provide weather data, but not at the resolutions required for safe operations at the envisioned densities.

E. Community Integration

The community integration pillar captures the barriers associated with the integration of aviation at the local level. Some aspects of community integration are similar to existing aviation operations, although the number of interfaces with and impacts on the community are likely to be significantly greater in UAM. For example, locating a UAM aerodrome will have similar considerations as the siting of an airport, such as integration with other transportation systems and the impact of operations on noise levels; however, there are likely to be many more UAM aerodromes than typical airports in a metropolitan area, which increases the difficulty of successfully integrating UAM into the community. Other aspects are new with UAM partly because of new technologies (e.g., electrical demand due to electric vehicles) and partly because of the degree of local integration (e.g., privacy concerns due to vehicles flying at lower altitudes over peoples' houses). The discussion of community integration in this subsection is organized around the four barriers within the community integration pillar as shown in Fig. 2. A driving assumption in the vision ConOps is that the challenges described below will be largely solved by UML-4.

1. Public Acceptance

Public acceptance includes challenges impacting both the flying and non-flying public. The consumer has to believe that UAM will enable them to arrive at their destination unharmed and that the benefits provided (e.g., time saved, additional mode option) are commensurate with the costs (e.g., fare price, likely mode change requirement). For the non-flying public, the system also needs to provide at least indirect benefits to them, such as through expanded employment opportunities, with low perceived costs, such as increases in noise levels. The system also must not negatively impact their safety or right to privacy. Public acceptance will be a challenging barrier to overcome because many aspects of acceptance are not easily quantifiable and are likely to change over both time and place. To achieve UML-4, there must be sufficient public acceptance to provide both an adequate customer base and community support of the operations and required infrastructure.

2. Supporting Infrastructure

Most consider UAM aerodromes when envisioning supporting infrastructure, but there is an array of supporting infrastructure that must be developed to support UML-4 operations. Challenges related to community integration of UAM aerodromes include how to maintain them, how to control access to them, how to ensure they continue to meet safety codes (e.g., building and fire codes), and how to pay for them. Another challenge that must be solved is the fielding of sufficient recharging and/or refueling infrastructure. For operations in all-electric aircraft, which are envisioned by many for UAM, modifications to the electric grid, including the potential for additional power generation and energy storage systems, will be needed to supply sufficient electrical power to the needed locations at the proper time for charging. Fuel distribution and storage solutions will be required for other types of aircraft (e.g., hybrid-electric or hydrogen-powered aircraft). Other supporting utilities at UAM aerodromes, such as water, sewer, and telecommunications, must also be considered. Infrastructure to support communications, navigation, surveillance, and other information sharing needed for safe flight operations (e.g., weather) must also be deployed across metropolitan areas in ways that are resilient (e.g., to severe weather), as well as scalable and affordable.

3. Operational Integration

UAM must be operationally integrated into the transportation ecosystem of metropolitan areas to provide true transportation benefits to passengers and value to the area. UAM aerodromes are a prominent element within the operational integration challenge. Specifically, the aerodromes must be wisely located and designed so that they ultimately increase the overall capacity and resiliency of the broader transportation system without causing negative impacts to other modes, such as traffic jams on roads near passenger drop-off or pick-up locations. Additionally, to be truly integrated into a practical multimodal transportation system, passenger and cargo safety and security must be assured through means that enable rapid movement through UAM aerodrome terminals to keep mode change times short.

4. Local Regulatory Environment & Liability

The last barrier within community integration includes the local regulatory environment and liability. This challenge can be viewed from the perspective of knowns and unknowns. For decades, local governments have been addressing the writing, updating, and enforcing of policies, rules, regulations, and ordinances surrounding business permitting, land use, zoning, noise, building codes, and fire codes. So, although the processes for developing UAM-related policies, rules, regulations, and ordinances exist, there are challenges around gaining the knowledge and experience with UAM and its impacts so that the actions taken ensure the safety and rights of the local citizens while allowing for business opportunities and citizens to receive the benefits associated with UAM. An unknown is how the FAA will manage UAM operations in partnership with the state, regional, tribal, and local governments. It is not expected that the FAA will cede its authority to these entities, but it is anticipated that the FAA will work closely with or even potentially delegate some responsibilities to localities. This could include the responsibility to conduct public hearings for the approval of or changes to approach and departure routes to UAM aerodromes or to ensure aerodromes continue to satisfy design circulars. Liability is similar to local regulations. The framework and processes for determining liability exist, but there are challenges associated with regulating and assessing the risks of both a new mode of transportation and the new technologies that enable it. Local regulations and liability risk factors must be sufficiently mature to enable the envisioned density, complexity, and automation associated with UML-4.

III. Key Areas Where Additional Research Is Required

In this section we discuss areas where more research is required before a more detailed ConOps can be completed and UML-4 operations can be realized. These items indicate prime areas for researchers to conduct investigations over the coming years to help define a feasible and efficient UML-4 transportation system. The items discussed in this section are far from an exhaustive list of the required research areas and are provided as examples based on the authors' thoughts and experiences.

Areas of further research are organized under the following four subsections: crosscutting & systems issues, aircraft & airmen, airspace, and community integration. These subsections are a simplification of the organizational framework shown in Fig. 1 and mirror the structure of the Advanced Air Mobility Ecosystem Working Groups that NASA started in 2020 to bring a broad and diverse group of stakeholders together to discuss issues and accelerate the development of safe and scalable advanced air mobility flight operations [23].

A. Crosscutting & Systems Issues

There are many systems integration and crosscutting issues spanning the ConOps that warrant further research. Issues such as automation, security, certification and regulation, affordability, and UAM aerodromes are interwoven throughout the ConOps and are discussed in the following subsections. The crosscutting issues of safety, noise, weather impacts, environmental impacts, flight rules, data sharing, and maturing the transition from early operations to intermediate ones are discussed in this subsection.

Safety is an emergent property of a system. Overall system safety depends not only on the safety of the individual components but also on the safe interaction of those components with one another and their environment, making it a truly integrative and crosscutting issue. Research relating to the means and methods needed to determine the acceptable level of safety for novel UAM operations is critical. Integrating tools and techniques from both the design and operational side of safety assessment is vital for novel systems like UAM that possess no historical data. Additionally, safety of a complex system often requires a layered approach that considers not only the design and operational components, but also temporal and special elements. The development of safety services that span these domains and their integration into an in-time aviation safety management system is an important area of study to help enable safe UAM operations. Special attention is required at the boundaries between traditional disciplines due to the diversity of potential safety services (e.g., aircraft separation, battery status, aircraft structural health etc.) and expected complexity of UAM operations.

Noise is a key crosscutting barrier to the realization of UAM operations and a likely driving factor in determining whether such operations will be accepted. Specifically, aircraft and rotorcraft are frequently named in noise nuisance complaints around airports by their surrounding populations [24, 25]. Work by Yedavalli et al. [25] cites noise as one of the top three issues that impact public perception related to potential UAM operations. It is not only the amount of noise produced, but also the character of the noise that drive community acceptance. Although novel aircraft designs offer a promising means to mitigate noise generation, special attention must be paid to addressing the fact that noise can also be a proxy for other concerns, such as visual pollution or safety worries. Furthermore, as operations begin to scale, fleet noise becomes a substantial issue. Increased numbers of operations at low altitudes in general combined with the possibility of many aircraft repeatedly flying the same precision route may act to amplify noise concerns. Means of mitigating fleet noise issues need to be considered carefully. Similarly, community ambient noise levels and the time of day during which operations occur will play a significant role in establishing what acceptable noise thresholds may be for individual municipalities.[‡] Thus, establishing adequate and appropriate noise standards for vehicles and fleet operations is a key area of research. The ability to model, simulate, and assess individual aircraft and fleet noise is vital. Similarly, establishing and validating appropriate metrics for quantitatively and qualitatively describing adequate thresholds for vehicle and fleet noise is essential.

Conventional weather issues such as lightning, icing, low visibility, and wind shear are all relevant to UAM and are not likely to be ameliorated by conventional techniques. For instance, techniques like delaying, path-stretching, and rerouting flights to avoid adverse weather are not particularly transferable to the domain of short-duration, on-demand UAM operations for which time savings and convenience often form the foundation of the business case. Moreover, the demand for and scalability of UAM operations will depend on being able to provide a highly reliable and predictable service with on-time arrivals at the desired destination. Studies need to be performed to determine which strategies could be used to mitigate the effects of adverse weather and assess the degree to which operational uncertainties around weather may influence demand. Additionally, enhancements in micro-weather measurements, reporting, and prediction may provide other means of increasing the resiliency of operations or at least predicting when UAM operations may be unable to occur further in advance with greater accuracy. Additional research into not only measurement and prediction techniques, but also the market impacts of these advancements would be beneficial to the UAM ecosystem.

Similarly, environmental impacts of UAM, which are intertwined with affordability considerations, are another area for further exploration. The use of hybrid propulsion systems may increase vehicle range relative to purely electric vehicles, but this will likely increase vehicle emissions. Similarly, vehicle occupancy is a central factor in determining the cost as well as emissions per passenger mile. Research regarding the viability of pooled on-demand operation as well as the percentage of unoccupied flights required for fleet management would provide further insight on environmental impact. Likewise, vehicle lifecycle costs and emissions, which include both maintenance and retirement, should be explored carefully due to the lack of standardization surrounding materials, equipment, and novel technologies being proposed for the design and production process.

UAM operations for UML-4 will require either a totally new, alternative set of flight rules to existing VFR and IFR or modifications to existing flight rules. However, it is important to note that regulatory changes typically take many years (e.g., five or more years) to enact. This clock will only start after the UAM stakeholders and community have a clear idea of the nature of the changes needed to enable UML-4. The research community has a large role to play in defining viable alternatives to VFR and IFR. Additionally, these regulatory changes must be supported by an appropriate body of evidence in order to be considered for rulemaking, and developing this body of evidence is an important task for the research community.

Achieving UML-4 will require significant changes in multiple portions of the Federal Aviation Regulations (FARs) beyond the flight rules, such as a means to accommodate and grant access to the NAS for highly automated, safety-critical

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[‡] Although federal regulations govern aircraft certification requirements, localities may pass noise ordinances that impose more strict standards. We are considering the local noise ordinances in this discussion.

systems that perform human-oriented tasks. Research into means of providing regulatory flexibility without detriment to the overall safety of the national airspace system, such as CBRs, is required. Similarly, the roles and responsibilities of the PSU, fleet operator, and PIC/aircraft crew across all functions, such as strategic deconfliction, tactical deconfliction, and collision avoidance, need to be clearly defined.

It must be remembered that the NAS has multiple stakeholders operating legacy systems. Achieving UML-4 may provide significant public good but may also entail new mandates on existing operations, such as increased equipage requirements on VFR aircraft. Significant research is needed into determining how to balance these very different perspectives in an equitable manner.

Data sharing is also a fundamental issue in envisioned UAM operations, as security and privacy concerns surrounding operational data, passenger data, and overflown areas will impact whether businesses, customers, and overflown third parties are likely to embrace the service. Research into effective, efficient, and secure means of exchanging operational intent and real-time operational data is required. Additionally, a balance ensuring the personal safety and security of the passengers with the privacy of any data they are required to submit must be developed. The development of community-endorsed standards for data sharing, privacy, and security for these operations is an essential research area.

B. Aircraft & Airmen

Aircraft capable of efficient and resilient operations are a foundational element of UAM. Achieving this capability depends on many things, including: the design and development of suitable aircraft designs, including all necessary subsystems; development and implementation of appropriate system and design (i.e., type) certification standards; an ability to cost effectively produce aircraft conforming to their type certificate; approved procedures for maintaining and assuring the continuing airworthiness of the aircraft; and the development of appropriate aircraft crew qualifications and associated training programs. As mentioned earlier, for reasons such as high operational precision, safety, and scalability of human resources, sustained growth of UAM is likely to depend on the integration and utilization of aircraft automation with higher levels of performance and accuracy; fault-tolerant operation; and simplified human interaction as compared to the current state of the art. Increasingly automated operations also elevates related concerns such as cyber and physical security as humans become more dependent on highly automated systems and less aware of the details of their implementations.

Given the foundational role that advanced UAM aircraft designs play in assessing the feasibility and desirability of UAM, aircraft design may be the system element that has received the most attention thus far. That said, the relative novelty of many aspects of UAM configuration development, including their many novel sub-elements, means that significant needs and challenges remain in this area. Key areas of research related to vehicle development include many aspects of aeromechanics with particular emphasis on acoustic predictions and noise reduction technologies. Additionally, needs exist for improved design and performance analysis tools, including means to validate vehicle performance and controllability through all parts of the flight envelope, with an emphasis on transition flight and in the presence possible failure conditions (e.g., a motor inoperative). Other challenges include the development of energy storage systems and powertrain design for the novel distributed electric propulsion systems typically embodied in UAM configurations.

Beyond addressing these challenges from the perspective of candidate aircraft configurations and designs, these same challenges are present from the perspective of developing appropriate certification requirements and associated means of showing compliance with the certification requirements. In addition to the aeromechanics and power system challenges mentioned previously, the complex nature of UAM aircraft systems, along with proposed operation over densely populated areas, is likely to motivate more thorough system safety analysis and elevated system development assurance levels. From a safety perspective, there is particular interest in better understanding the interactions between design safety and operational safety considerations. For example, increasingly stringent system design safety requirements (e.g., development assurance levels with more "9s") have the potential to reduce operational safety if, for example, the requirements result in additional burdens being placed on aircrew members whose limitations are often only partially considered in the supporting analysis (e.g., SAE ARP4761 [26]).

The ability to cost-effectively produce UAM aircraft is likely to benefit from the development and integration of scalable design and manufacturing methods. Historically, small aircraft have been produced in relatively low numbers, making upfront capital investments in advanced manufacturing uneconomical and/or risky. If UAM market demand grows, relatively large numbers of aircraft will be required to be produced annually—perhaps on the order of thousands or tens-of-thousands versus the tens or hundreds for small general-aviation aircraft today. At the same time, the development of lower-cost forms of highly automated manufacturing may be applicable to UAM production, even at relatively low, initial production levels. Examples of these technologies include additive manufacturing and robotic composite manufacturing. Similar to the need for certification requirements and compliance methods for aircraft designs, aircraft production, including parts and subassemblies, typically requires certification of the manufacturing process. Thus, there is a need to develop new certification standards for advanced manufacturing technologies and methods.

Operations at UML-4 are expected to entail several broad, new, human-automation teaming concepts for the operation of individual aircraft and aircraft fleets. Fundamental to the entire area of human-automation teaming is understanding and succinctly specifying and designing for appropriate roles, responsibilities, and authorities of human and machine agents within a system given their capabilities and limitations in combination with the situations that may be encountered over the lifetime of the system (potentially, billions of hours). Under current regulations and supporting interpretations, the PIC of an aircraft is required to have a detailed understanding of the inner-workings of the aircraft and the ability to intervene in the operation of systems at a relatively low level (e.g., the ability to monitor and control each individual engine of a multi-engine aircraft). At UML-4, human agents are expected to be supported by automation capable of performing integrated tasks (e.g., management of the integrated propulsion system) in a manner that eliminates the need for low-level monitoring and interventions by humans. From a research perspective, developing and being able to certify the automation and human elements of novel teams involves several unique challenges. For example, as alluded to earlier, optimizing design and operational safety considerations would benefit from more holistic consideration of human performance capabilities and limitations in the system design and safety assessment processes. For the novel human-automation teaming concepts envisioned for UAM, this is particularly challenging as both human and automation elements in the system may have roles and responsibilities for which relatively little operational experience exists. Also, UML-4 may be something of a transitory stage in the evolution of increasingly autonomous systems and operations. The desire for sustained evolution suggests that the underlying roles and tasks of humans in the system could change much more rapidly than what we are accustomed to in aviation today, resulting in the introduction of a new set of dynamics within the human-automation team.

C. Airspace

Development of a mature ConOps for UML-4 will require research addressing a broad array of UOE airspace-related challenges, including airspace design, separation management concepts, regulatory changes, procedure and operating rules definition, and integration with existing airspace users.

UML-4 brings significant increases to UAM traffic complexity and density. The UOE must accommodate both high-density routes and other UAM operations (possibly including legacy corridor-based operations). Strategies to define and identify usable UOE airspace need to be developed that minimize the impact of UAM on existing operations and the community (e.g., due to noise). Research into the sizing, flexibility, high-density route usage, and dynamics of UOE design and configuration to support efficient and safe UAM is crucial to a well-defined UAM ConOps.

The interactions between UAM aerodromes and PSUs is a key research area that will define the domains of the UAM aerodrome operator and PSUs with respect to scheduling and sequencing operations into and departing from aerodromes, how contingencies requiring alternate landing locations are managed, and the level of trajectory precision required to support operations on high-density routes between high-demand aerodromes.

A number of challenges are presented by the transition away from ATC separation provision that is key to achieving UML-4 traffic levels. Separation standards consistent with the increased traffic density and tempo must be developed; these standards are likely to be developed in a community-driven process that must address the safety, technological, and human factors challenges unique to the UOE. Traditional approaches to quantifying collision risk might be applied but require development of representative UAM traffic models (e.g., traffic demand, aircraft performance characteristics, and flight performance models) to assess risk via established methods using encounter geometries and rates derived from such models. Research into effective utilization of humans and automation in mitigating collision risk through demand-capacity balancing, strategic deconfliction, tactical deconfliction, and collision avoidance is required to develop technological requirements, such as alerting and guidance criteria, as well as effective maneuver guidance for tactical separation. These requirements and their associated risk mitigation performance present a tradeoff between UAM operational cost and collision risk. Acceptable collision risk for UAM can only then be evaluated in terms of community acceptance versus the utility offered to that same community.

The shift from ATC-managed to community-managed operations also requires new approaches to certification and/or qualification of safety critical systems. Research into methods to demonstrate means of compliance to regulatory and qualification requirements for PSUs and safety-critical SDSPs is needed. Additionally, the method to review and authorize non-safety-critical SDSPs for use in the UOE must be developed. Further, changes in how weather products are certified should be considered to allow for a shift to weather data performance standards instead of certifying sensors, thus allowing a diverse solution set to address the weather forecasting and measurement needs of operations in the UOE.

Procedures and operating rules for UML-4 are envisioned to be developed by the UAM community to address the unique needs for operating in the UOE. Methods to develop these Community-Based Rules (CBRs) are necessary and must establish the processes required to develop CBRs, modify CBRs, and identify or establish the regulatory means to delegate authority to users (fleet operators) and/or third parties (e.g., PSUs). The delegation of traditional ATM functions encapsulated in the CBRs will require verification of an operator's ability to meet the performance requirements associated with an operation; this verification is encapsulated in a performance authorization. Performance authorization content, approval processes, and flight planning requirements to support their use need to be established. PSUs will support a number of key functions at UML-4, including (but not limited to) verification of performance authorizations, flight planning and strategic deconfliction, and sharing of operational intent for common situational awareness while other services will be provided by SDSPs. Which services are provided by PSUs, the minimum set of PSU services required for qualification, and which services are provided by SDSPs are all key research areas needed to define UAM operations at UML-4. The PSU Network and broader UAM Communication Network must ensure compatibility (and in some cases interoperability) between services, their suppliers, fleet operators, and aircraft technologies. As such, data exchanges (based on standards or CBRs) will be required to facilitate the (potentially) many services that will simultaneously support UAM operations and ensure a common operating picture for functions such as weather data distribution, scheduling, and separation for high-density routes and UAM aerodromes.

It is important to note that at UML-4 the UOE is not a new class of airspace; the UOE exists within existing airspace class(es). Although deliberate airspace and procedure design decisions are likely to minimize interactions with traditional airspace users, research is needed to bring clarity to how these interactions can safely occur within the UOE and when UAM operations exit the UOE. UAM aircraft operating into and out of some aerodromes may interact with UTM aircraft, and methods for coordination of these similar systems should be investigated. VFR flights will operate near the UOE and possibly within the UOE if certain requirements can be met. Specific performance, equipage, communications, and intent sharing requirements that can allow VFR flights to safely transit UOE are of particular interest. Lastly, research into effective and predictable contingency management strategies and procedures for UAM flights that exit the UOE and enter controlled airspace is needed to ensure that ATC has the situational awareness to effectively manage the contingency without adversely impacting the safety of existing airspace users and without routinely impacting the efficiency of these operations.

D. Community Integration

Public acceptance is derived from a wide variety of factors, perhaps most principally a demonstration of safety. Due to the excellent safety record of traditional commercial aviation, much of the aviation community's practical experience with public acceptance is from addressing concerns around airports and the customers' flight experiences. However, focusing on flight experiences and UAM aerodromes alone will be insufficient to gain acceptance of UAM on the scale and breadth needed to have commercially viable markets. Consequently, understanding the additional challenges related to public acceptance of UAM is a ripe research area.

Ultimately, public acceptance is composed of multitudes of personal assessments. These assessments include weighing benefits, affordability, accessibility, convenience, and perceived safety amongst many others. Determining which factors are considered highly important to most individuals can provide insights into system design requirements and potential evolutionary market pathways for introducing and maturing UAM systems in manners that are generally acceptable to the public. However, these generalized conclusions from personal assessments are likely to vary from location to location, which implies that studies for many localities are likely required in these public acceptance studies. Ultimately, each locality will need to assess how UAM can be incorporated in ways that benefit the social and economic welfare of its citizens in order to gain public acceptance.

Although the basics of UAM aerodrome design can likely be gleaned from existing operations with helicopters and other aircraft, application of the general principles from these existing operations to novel aircraft configurations and their associated operations will be required. The ultimate size, configuration, performance characteristics, failure modes, propulsion system architectures, and weather tolerance of novel UAM aircraft will drive UAM aerodrome design factors, such as the takeoff and landing area size, required safety setbacks, and additional safety features (e.g., fire suppression systems). Studies that analyze anticipated performance of an array of projected aircraft and make associated recommendations on UAM aerodrome design requirements would be beneficial because of the long lead times and costs associated with obtaining and preparing urban real estate for UAM operations. Additionally, a common taxonomy of

UAM aerodromes would provide benefits to the UAM community.

When considering electric UAM aircraft, much additional research is needed. Although some concepts and general guidelines for supplying power for charging vehicles have been considered (e.g., [27, 28]), additional research into how the charging infrastructure and electric UAM aircraft, especially fleets, can be integrated into the electric grid is still required.

The interfaces between UAM and other modes, including emerging ones, is another general area with open research questions. Evaluating projected traveler preferences and behaviors can help inform which modes of transportation may be most logical to connect with UAM and provide guidance on how UAM can be best integrated into the local transportation system. For example, although it may seem logical to co-locate UAM aerodromes with public transit stations, if users of UAM typically prefer to connect with other modes, such a private car to their home, there may be limited benefits from such aerodrome placement. Additionally, research into the data sharing requirements and mechanisms between transportation modes to enable seamless mode transfers would also be beneficial.

It is likely that both national and local codes and laws will evolve over time and that both will inform the other. Opportunities exist for systematic study of which codes and laws are most likely to benefit from beginning at the national level and which would benefit more from beginning locally. Additionally, although having relatively standardized codes and laws nationally (and internationally) supports uniformity and the ability of companies to operate in multiple locations more easily, locality-specific tailoring of codes and laws is still likely required for certain issues. Intentional evaluation of which codes and laws are most logical to standardize nationally versus which should be more locally tailored can help the industry to thrive nationally while also respecting local needs.

As stated in the assumptions above, it is expected that the FAA will delegate some functions to third parties who would operate under the FAA's rules and regulations, and these third parties could include state and local governments. These functions could include approving or ensuring compliance with various aspects associated with aerodromes, such as changes to approach and departure paths. Local authorities will likely be able to request the opening and closing of airspace, such as for a public event or an emergency. Research is likely needed to support the decision of which functions will be delegated, how the rules and regulations for these functions will be equitably enforced, and how to best gather public inputs on the multiple issues the local governments will face.

IV. Summary & Path Forward

As technologies have evolved and societal needs have shifted, the vision of bringing aviation into daily life has moved from the realm of science fiction to a realistic, fairly near-term possibility. We have described in this paper some of the high-level concepts for how novel uses of aviation for transportation around metropolitan areas may become feasible while also discussing some of the challenges that remain to realizing this vision. These concepts are described in more detail in a "vision" ConOps document describing intermediate state UAM operations that NASA and Deloitte have developed in collaboration with stakeholders from across the UAM ecosystem [19]. We have discussed some specific areas where further study and research are required to define more detailed ConOps.

Since the initial vision ConOps is focused on the needs of a UML-4 system, additional work is required to define the evolution of the system to ultimately achieve the UML-4 capabilities. The ConOps document will be broadened over time to include considerations for near-term integration of UAM into the National Airspace System, which is likely to build on the FAA NextGen Organization's v1.0 UAM ConOps [21]. Additionally, the ConOps will also be expanded to include an anticipated progression of operations over time that considers the evolution of conventional, UAM, and other emerging operations. This expansion of the ConOps will be enabled by reassessing the state of the art of all other airspace operations, with a particular focus on other emerging aviation markets. For example, as sUAS operations increase over the urban airspace, the UAM ConOps will naturally need to keep pace with compatibility and interface requirements between relevant technologies and procedures that will enable safe and efficient operations, as well as allow fair access to airspace for all.

As changes are made to the ConOps, all stakeholders must be drawn into the change validation process to ensure a consensus understanding of emerging UAM operations. The UAM ConOps, as it evolves, is planned to be used to capture the assumptions and tradeoffs made via multiple UAM stakeholders to harmonize with rapidly evolving industries and aviation applications, as well as accommodating current players. This inclusive approach will define clear operational boundaries for UAM and capture the needs and desires of the many different stakeholders of the National Airspace System.

Acknowledgments

We would like to thank NASA's Aeronautics Research Mission Directorate (ARMD) for their support of this effort. Multiple entities within ARMD have directly supported this work, including the Advanced Air Mobility Mission Integration Office; the Advanced Air Mobility Project within the Integrated Aviation Systems Program; and the Air Traffic Management eXploration and System-Wide Safety Projects within the Airspace Operations and Safety Program.

Contributions to the Vision Concept of Operations have been made by many individuals from across NASA, Deloitte, the FAA, and the broader UAM stakeholder community. We are grateful for the engagement of so many visionary and intelligent people, and we look forward to continuing to refine these concepts together into the future.

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