Description of the NASA Urban Air Mobility Maturity Level (UML) Scale

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As part of its assessment of the nascent passenger-carrying urban air mobility (UAM) ecosystem, NASA's UAM Coordination and Assessment Team developed a framework known as the UAM Maturity Level (UML) scale. This framework is intended to have multiple applications including: 1) insight into the likely operational capabilities as a UAM air transportation system develops over time; 2) analysis of technology and regulatory requirements associated with the UAM maturation process; 3) assessment of the current maturity of various segments of the UAM ecosystem; 4) coordination of UAM ecosystem priorities and areas of emphasis; and 5) increasing community and public awareness of UAM and how it may affect mobility in the future. This paper describes the structure of the UML scale and its levels. The paper also describes candidate strategies for advancing between levels, along with associated regulatory gaps and considerations.

I. Nomenclature

AAM = Advanced Air Mobility
CAA = Civil Aviation Authority
CFR = Code of Federal Regulations
CNS = Communication, Navigation, and Surveillance
EASA = European Aviation Safety Agency
eVTOL = Electric Vertical Takeoff Landing
IFR = Instrument Flight Rules
IMC = Instrument Meteorological Conditions
PSU = Providers of Services to UAM
PSCP = Project Specific Certification Plan
TIA = Type Inspection Authorization
TRL = Technology Readiness Level
UAM = Urban Air Mobility
UCAT = UAM Coordination and Assessment Team
UML = UAM Maturity Level
UAS = Unmanned (or Uncrewed) Aircraft System
USS = UTM Service Supplier
UTM = UAS Traffic Management
VFR = Visual Flight Rules
VMC = Visual Meteorological Conditions

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II. Introduction

Urban Air Mobility (UAM) is envisioned to provide safe, affordable, and accessible aviation for transformative local and urban transportation, and be a complement to current transportation systems for travel within a given metropolitan area, as described by Thipphavong, et al [1]. Typical UAM trip distances are expected to be between 10 and 100 miles, and in a highly developed future state, UAM will extend automotive-like, on-demand personal mobility into the third dimension (i.e. flight) with potential benefits that include reduced travel-times, congestion, accidents, harmful emissions, and infrastructure requirements relative to current surface transportation systems. The realization of such a future capability depends on development of an essentially new air transportation system with dramatic advances relative to the current state of the art and practice in the areas of air vehicles and their operation; airspace system design and operations management; and community integration and acceptance. The required advances are sufficiently challenging that the system will almost certainly evolve over a period of several decades, and in a series of stages as novel technologies are developed, operational experience is gained and operations refined, and appropriate regulations and policies developed and adopted.

The NASA UAM Coordination and Assessment Team (UCAT) was formulated and chartered to identify the key vehicle, airspace and community integration challenges associated with UAM system development and deployment. The UCAT developed a framework called that UAM maturity level (UML) scale that is intended to categorize significant phases expected during the evolution of a UAM transportation system from the current state of the art to a highly developed, future state where UAM is a ubiquitous capability, similar to automobiles today. The UML scale was developed based combined NASA expertise and experience, as well as interactions with the broader UAM ecosystem including civil aviation authorities (e.g. FAA, EASA), aircraft developers (of both on-board and remotely-piloted), system and component suppliers, pilots, fleet operators, air navigation service suppliers, Unmanned Traffic Management (UTM) Service Suppliers (USS), supplemental data service suppliers, representatives of state and local governments, academia, and other government organizations. The UML scale was developed with a primary focus on the passenger-carrying use case, and while the scale does have some applicability to non-passenger carrying and/or non-urban missions, these use cases may have higher tolerances for risk and uncertainty, and may advance along different trajectories.

This paper describes the development of the UML scale, and details the various levels. It should be understood that the UAM maturity levels described in this paper are a projection of the possible introduction of UAM capabilities over time. While the projection is based on interaction with the ecosystem and expert opinion, the actual path is of course, unknown and may be quite different. Attainment of higher-levels of the scale require numerous, significant technological and economic advances and may not be reached even after several decades of development. The timeline to progress UAM system capabilities through the UML scale is probably the largest unknown, so no timeline is being offered in this paper for the scale, however factors that affect UAM adoption will be introduced and discussed.

The paper first describes the basic UML scale including the levels, key attributes and factors that could influence the timeline. Next is a description of the lower-level operational requirements and capabilities associated for each UML, along with a discussion of likely technical and regulatory advances required relative to previous levels. Finally a summary of the paper is presented.

III. Description of UML Scale

The UML scale is shown in Figure 1 and is composed of six levels, with the levels (except for UML-1 which will be discussed in the next section) being differentiated by a combination 3 primary attributes: traffic density, operational complexity, and reliance on automation. With the exception of UML-1, the levels represent operationally deployed capabilities and from the perspective of the technology readiness level scale (TRL) [2], have a TRL of nine.

Traffic density is a measure of the number of aircraft simultaneously aloft in a single, hypothetical, metropolitan area. Traffic density levels used in the scale are low, medium, high, and ubiquitous. “Low” indicates commercial traffic is present in a metropolitan area but with a small number of aircraft aloft (i.e. less than 100). “Medium” indicates hundreds of aircraft aloft. “High” indicates thousands of simultaneous operations and “ubiquitous” indicates tens of thousands or more.

Complexity is a combination of: maximum potential capacity (i.e. throughput) at major UAM-ports (“ports”); the level of distribution of the port network (i.e. the number of ports) which influences routing complexity; the level of weather tolerance (primarily the ability to operate in low-visibility conditions); the integration with other vehicle types (i.e. non-UAM vehicles, helicopters, UAS, etc.) and different airspace classes; and the level of operational integration

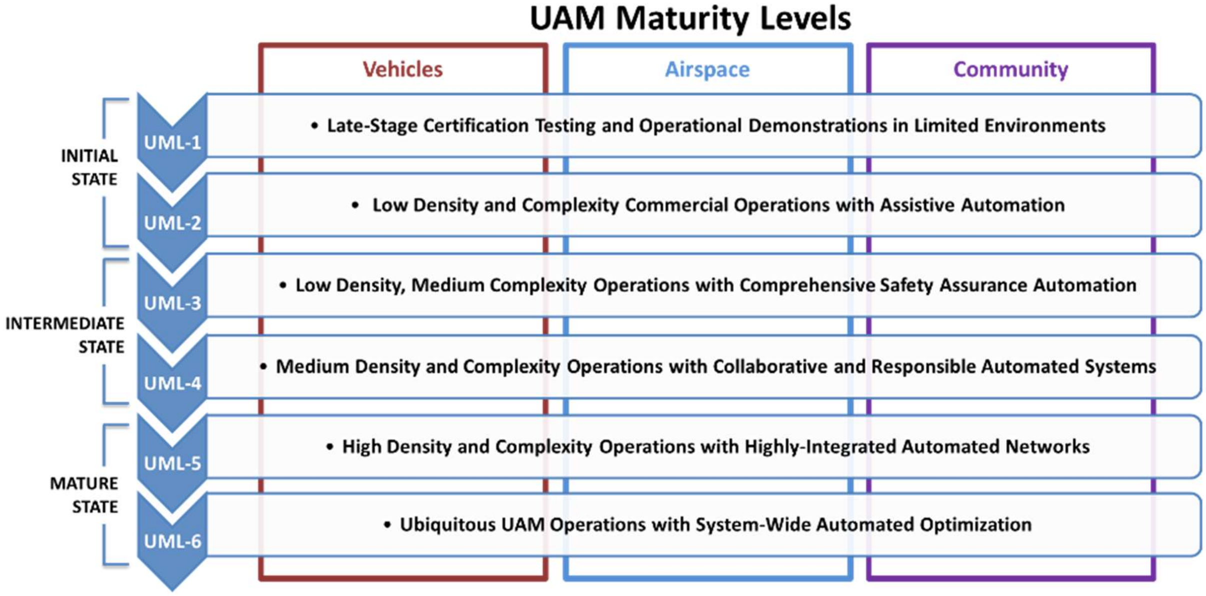

Figure 1. Urban Air Mobility Maturity Scale

into densely populated areas. Similar to traffic density, the levels used in the scale are low, medium, high, and ubiquitous. Low indicates ports are limited to low-tempo operations; small numbers of ports (e.g. nominally, ten or less); operations in visual meteorological conditions (VMC) only for navigation and deconfliction with other traffic; and generally not operating from ports situated in densely populated areas (e.g. no rooftop ports in these areas). Medium indicates some ports may operate at high tempos and/or flight operations can occur without external visibility (i.e. flights can operate in instrument meteorological conditions (IMC)), and strategic deconfliction with other traffic. Medium complexity also indicates a network of ~tens of ports and that operational safety has been demonstrated such that operations in close proximity to densely populated areas (e.g. rooftop urban vertiports) are routinely approved for high-volume, commercial operations. High-complexity indicates the combination of high-tempo ports, a highly distributed port network (e.g. ~hundreds of ports), visibility-independent operations, and operations in close proximity to densely populated areas. Ubiquitous complexity indicates an even higher level of vertiport distribution, exceeding hundreds of ports across a metropolitan area and may include ports integrated into neighborhoods or even personal residences, and a federated airspace system design and management structure that provides efficient and equitable access to all vehicle types.

Automation reliance indicates the degree of integration and level or trust/responsibility held by automated systems across the UAM system. The automation reliance levels used in the scale are assistive, comprehensive safety-assurance, collaborative and responsible, highly-integrated automated networks, and system-wide automated optimization. "Assistive" indicates reliance on lower-level automated functions (e.g. highly augmented flight controls) with limited integration and that human agents retain full-responsibility for operational safety. The "comprehensive safety-assurance" level indicates automation with the capability to provide safety-critical monitoring and interventions mitigating a wide range of specific hazards within the system (e.g. ground collision avoidance, traffic collision avoidance, etc.), significantly improving the safety of the system, but with human agents still retaining full-responsibility for operational safety. The "collaborative and responsible automation" level indicates automation which is assured to perform specified functions such that human monitoring and mitigation of potential failures of those functions is no longer necessary. At this level, the roles and qualification requirements of human agents within the system (e.g. pilots and controllers) can be reassessed and redefined based on the capabilities and demonstrated assurance properties of automated systems performing specific, safety-critical functions. This is expected to result in reduced requirements for highly specialized training of human agents (e.g. learning and practicing procedures specific to esoteric failure modes). However, at this level, general oversight from human agents is still expected to be an important part assuring the safety and resilience of the system. Whether on- or off-board, pilots dedicated to the oversight of individual vehicles are still required at this level. The fourth level, "highly-integrated automated networks" is reached when dedicated, real-time human involvement is no longer required for the safe operation of the system. Operational performance or efficiency may be improved by informed human oversight and intervention, but it is no longer needed from the perspective of assuring safety in real-time, even in novel situations. Finally, at the "system-wide optimization" level, no continuous human monitoring, let alone interventions, in the system are expected for either safety or efficiency.

Briefly recapping, figure 1 shows how the UML scale aggregates combinations of the three attributes and associated levels into six, overall system maturity levels. It is recognized that while the scale consists of only six levels for general ease of describing overall system operating capabilities, operations may evolve in some attributes faster than others for a variety of reasons and motivations. For example, operations in areas with persistently clear visibility may reach UML-4 levels of traffic density without achieving the UML-4 level of operational complexity (i.e. operations in IMC are not required). Also, cities at lower altitudes may reach UML-4 traffic levels faster since the higher density maximizes vehicle performance, which may be a key factor in expanding operations profitably. Similarly, for economic reasons, several developers are planning to move rapidly to remote, off-board piloting, a capability consistent with UML-4 or higher automation reliance ahead of achieving other UML-4 attributes. While the aggregated maturity levels as described so far may seem rather arbitrary, the six groupings are heavily influenced by likely regulatory and policy changes required to advance between levels. As described in the next section, these regulatory considerations are expected to reinforce the presented groupings. The following section describes how operations may advance through the levels and describes some of the associated technology requirements and associated federal and/or local regulation and policy considerations.

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IV. Realization of Maturity Levels

The realization of the progression through the 6 UML levels will require a number of advances in the aircraft, airspace system, and community integration technologies, including the interfaces between these system elements. This section steps through each of the 6 UML levels, and describes the most significant attributes of each level, and details the key characteristics of the given level from the perspective of the aircraft segment, airspace system segment, and community integration. It should be remembered that this is one potential realization of the UML levels primarily for passenger-carrying UAM use cases.

A. UML-1

UML-1 is unique from the other five levels in that it precedes rather than describes a commercial operating capability. From the perspective of the TRL scale, UML-1 is the only maturity level with a corresponding TRL less than 9. Because UML-1 is pre-operational, the attributes of traffic density, operational complexity, and automation reliance are not appropriate for its definition. Rather, UML-1 is characterized from the perspective of aircraft development with the nominal indication of reaching UML-1 being, as explained below in more detail, the existence of a late-stage aircraft type certification project.

1. Aircraft

UML-1 is defined by aircraft development projects nearing completion of the type certification process. A clear indication of a mature certification project is the issuance of a FAA Type Inspection Authorization (TIA) [3] or its international equivalent. As described in [3], to be eligible for a TIA, the FAA and a vehicle developer must jointly agree on a completed project specific certification plan (PSCP) which defines the analysis and tests (ground and flight) that will be used to show compliance with the applicable type certification regulations. The vehicle developer must then perform, and the FAA review and accept, that the developers in-house testing as defined in the PSCP has been successfully completed. At this point, the FAA finds the design ready for FAA pilots to perform the flight tests required for certification and a TIA is issued. After the issuance of the TIA, the completion of the certification process may still be a year or more in the future.

The development of a complete PSCP involves, 1) establishing a certification basis for the aircraft (e.g. Code of Federal Regulations (CFR) 14 Part 21.17) along with 2) defining the standards, analysis and testing that will be used as methods of compliance for the certification requirements. It should be recognized that even for conventionally piloted UAM aircraft (i.e. pilot on-board), which are nominally expected to be electric vertical takeoff and landing (eVTOL) configurations, many key requirements and corresponding methods of compliance must be developed for novel eVTOL configurations before a PSCP can be developed, let alone executed.

Companies working to reach UML-1 with uncrewed[*] UAM configurations face significantly more uncertainty than the developers of conventionally piloted aircraft given the still nascent regulatory framework covering operations of unmanned aircraft system (UAS) in the national airspace system in general and the dearth of even preliminary guidance for commercial, passenger carrying operations. Some companies seeking to initiate operations with uncrewed aircraft are currently working with local CAAs to conduct pilot programs that involve operating unoccupied, passenger-scale vehicles with the goal of gaining flight experience in relevant conditions to guide regulatory development and ultimately create a certification pathway for remotely-piloted, passenger carrying aircraft [4] [5].

2. *Airspace System*

For aircraft with on-board pilots, access to and operations in the national airspace system (NAS) is straightforward since the general operating rules detailed in Part 91 implicitly assume the presence of one or more pilots on-board. Uncrewed aircraft projects face significant airspace challenges even at UML-1 as the aircraft, even for developmental testing, let alone commercial operations, are generally impractical to test under the operating rules for small UAS (e.g. Part 107) and generally cannot operate under Part 91. Testing of passenger-scale, uncrewed aircraft must typically be conducted at approved test ranges with an FAA approved exemption from Part 107 that is granted on a case by case basis. Achieving UML-1 for uncrewed certification projects also entails working with the FAA, or other applicable CAA, to define how the operational aircraft would be operated in the NAS and then determining the resulting airworthiness requirements. Presently, there are generally no agreed upon requirements for conducting such operations and developing the needed requirements and standards involves a lengthy process and often, uncertain outcomes.

3. *Community Integration:*

While UML-1 does not nominal address community integration, it is likely that prototype aircraft, with appropriate approvals, will conduct demonstrations in potential early adopter markets for purposes of assessing community integration and acceptance of issues such as noise, suitability of local facilities (e.g. existing heliports), and integration into local airspace operations.

B. UML-2

UML-2 is characterized by low density traffic, low complexity operations, and reliance on assistive automation. It is expected to correlate to capabilities at the initiation of commercial passenger carrying UAM operations. Under current US aviation regulations, to initiate commercial operations there must be: 1) a type certified aircraft design; 2) aircraft produced in accordance with the type certificate and otherwise maintained in an airworthy condition, 3) pilots certified and rated in the aircraft to serve as pilot in command of commercial operations; and 4) an air carrier with the necessary operational approvals to conduct passenger-carrying operations. UML-2 operations are expected to be conducted in a limited number of "early adopter" localities having generally favorable weather and local political support for the introduction of UAM service.

1. *Aircraft*

Commercial operations nominally require aircraft having a standard airworthiness certificate. To be eligible, the design must complete the type certification process and individual aircraft must be produced in conformance with the type certificate and otherwise appropriately maintained in an airworthy condition. While conformance of individual aircraft to the type certificate is typical done under a certified manufacturing process (i.e. Production Certificate), it can also be done through a conformance inspection process. Since UML-2 may initially involve only a limited number of aircraft, low-volume production methods and conformance inspections could be used if a production certificate has not yet been issued.

The pilot certification process for crewed UAM aircraft will generally follow the requirements of CFR 14 Part 61 (Certification: Pilot, Flight Instructors, and Ground Instructors [6]) with the "powered-lift" category perhaps best representing the requirements for piloting an eVTOL aircraft. At least a commercial pilot license will be required to perform UML-2 operations. It should be noted that there are aspects of the commercial powered-lift rating that are incompatible with the projected capabilities of most eVTOL aircraft under development. For example, 61.129 requires several cross-country flights with duration and range that exceed the projected performance of essential all battery-electric eVTOL aircraft under development. It is also worth noting that at present, due to the lack of existing civil

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[*] We use uncrewed rather than unmanned to avoid potential confusion stemming from the passenger carrying use-case.

powered-lift aircraft, very few civilian power-lift ratings have ever been issued and there are almost no certified flight instructors rated in powered-lift aircraft.

Initial UML-2 flight operations will likely be performed under a Part 135 air carrier certificate with operational approval to conduct operations using visual flight rules (VFR) and following an appropriate hybrid of rules, under Parts 91 and 135, for airplane and helicopter operations. Given initial limitations on numbers of available aircraft and pilots, UML-2 operations are expected to be relatively low-volume raising minimal safety concerns relating to operational densities, even in proximity to the limited number of ports in use at this time.

Considering the automation reliance attribute, given that eVTOL UAM configurations are likely to be both unstable and over-actuated, at least in powered-lift flight, relatively sophisticated, high-authority flight control systems will likely be needed to assist pilots flying the aircraft in achieving the required levels of safety, performance, and robustness. Also, aircraft power and energy management systems will likely require relatively sophisticated automation. Beyond control and power management systems, it is not expected that higher levels of aircraft automation would be necessary for low density and complexity VFR operations, and the vehicles may have relatively minimal automation beyond these two basic control and management system in order to limit initial certification costs, risks, and delays. Because of these considerations, the automation reliance attribute of these early operations is expected to be consistent with the UML-2 definition (i.e. assistive).

For initial commercial operations of any uncrewed UAM aircraft, the challenges unique to uncrewed operations discussed under UML-1 must be resolved. Due to limited operational experience with uncrewed aircraft, initial commercial operations, even if passenger carrying, are likely to be similar to the development and publicity demonstration activities mentioned under UML-1, in that they will occur away from urban areas to minimize risks to uninvolved persons and property as well as other airspace users.

2. *Airspace System*

For crewed VFR operations, airspace design and operational integration requirements are relatively straightforward with only minimal modifications to current procedures being required to accommodate low-volume UAM operations. As carriage of passengers to/from busy commercial airports is expected to be primary use of early UAM air-taxis [7], addressing the efficient integration of UAM operations into the controlled airspace around major commercial airports is likely to be a consideration even at the UML-2 level. For example, NASA, as part of a partnership with Uber, has been conducting simulation studies to assess integration of UAM into the operations and procedures of the DFW airport [8].

For previously discussed reasons, airspace access and operations for uncrewed operations at UML-2 involves significant barriers with uncertain solution strategies. As described for under the aircraft category, initial airspace operations for uncrewed, UML-2 operations are likely to take place in relatively lightly used airspace, away from urban areas.

3. *Community Integration*

As mentioned earlier, initial commercial UAM operations are expected to occur in a small number of early adopter locations. These locations will be selected based on a combination of criteria including being supportive of UAM from the perspective of local integration, regulation, and political support. These communities will likely have experience with the integration of low-volume helicopter operations and early UAM operations should present similar challenges and requirements. For this reason, beyond choosing supportive initial locations, community integration at UML-2 is expected not to entail major challenges. Even so, these early adopter cities will likely want to introduce UAM into their localities with a controlled and deliberative build-up. For example, given the limited operational history of UAM vehicles with novel configurations and system, early operations are likely to occur on the periphery of urban areas with port locations and routes selected to offer emergency landing options avoiding congested areas and minimizing the risk to the uninvolved public. Similarly, initial operations will likely be restricted to less noise sensitive areas such as business districts and commercial airports.

C. **UML-3**

UML-3 is characterized by low average traffic density, medium complexity operations, and reliance on comprehensive safety automation. UML-3 is expected to be a transitional period where technologies required to support more advanced and scalable operations are introduced and operationally assessed, but with limited operational credit granted until significant operational data and validation of the new technologies has been obtained. As such, the defining characteristics of UML-3 are expected to be initial operational growth beyond UML-2 but with limited scalability and deployment outside of early adopter areas until regulatory changes allow operational credit for the integration of key technologies and capabilities. Key technologies introduced during UML-3 relate to scalability of human resources (e.g. pilots and controllers); scalability of airspace operations; establishing and meeting noise limits for community acceptance; and the ability to operate in IMC. Moving from UML-3 to 4 is expected to require significant revisions to regulations pertaining to the general operating rules of Part 91, potentially creating a third set of flight rules to VFR and IFR. Moving from 3 to 4 is also expected to involve significant updates to the roles and certification requirements of human agents such as defined in Parts 61 and 91 for pilots and similar regulations for controller (e.g. Part 65 and CFR 49 44506).

1. Aircraft:

At UML-3, aircraft are expected to have demonstrated performance, safety and noise properties consistent with operations from ports integrated into densely populated areas. From a safety perspective, this capability requires demonstration of an overall operational safety record consistent with public acceptance of routine overhead operations combined with (or resulting from) design features that assure continued safe flight and landing following any first critical failure, such as the loss of a motor or a propulsion-system power buss. The requirements of this fly-away capability is expected to be similar to the requirements for Category A helicopter operations, or ICAO Performance Class 1 [9] [10] as adopted to eVTOL configurations and systems. Once vehicle performance, safety, and noise characteristics acceptable to a community have been demonstrated, the locality may consider approval of initial ports within highly developed areas. For UAM to provide meaningful time-savings relative to surface alternatives, the ability to locate ports near or within population centers is an important advance beyond UML-2.

Aircraft automation at UML-3 is expected to introduce and operationally validate automation capable of planning, executing, and monitoring UAM flights while reliably detecting and mitigating a comprehensive range of common flight hazards and emergencies. The comprehensive range of hazards and emergencies is likely to encompass many hazards typically included in pilot training curriculums and aircraft related emergencies as covered in an aircraft flight manual. However, this automated flight and contingency management capability is likely to be incomplete relative to novel hazards and initially, relatively unproven, and it is expected to be certified and introduced as automation that aids pilot awareness and decision making as well as providing a backstop against pilot lapses. As such, pilot training requirements aren't expected to be significantly changed by this automation during UML-3. Rather, its primary role is helping to assure safety by mitigating the pilot as a potential single-point failure while also providing operational data essential to informing the development of regulations and standards for which operational credit can be granted in UML-4. In addition to safety and operational decision support, an important aspect of the UML-3 phase, will be assessing and validating on-vehicle sensors appropriate for future IMC operations. This is discussed in more detail in the following airspace system discussion.

2. Airspace System

Even though the number of aircraft simultaneously aloft during the UML-3 phase is likely to be relatively limited over a given area (e.g. <100), the density of aircraft operations through and around a few key ports could locally be high [7]. Efficient, high-tempo management of port takeoff and landing slots will be of vital importance for safety, passenger experience, minimization of in-flight delays, and maximization of system throughput. Scheduling of port slots and associated in-flight routing and scheduling to avoid conflicts between aircraft is likely to be done collaboratively between aircraft fleet operators, port mangers, and UAM transportation network providers (i.e. companies that facilitate the booking of service between travelers and fleet operators). Third-party, "Providers of Services to UAM" (PSU) are expected to be central to this negotiation and scheduling process and will use concepts from the UAS Traffic Management (UTM) system [11] to implement the processes. Prior to takeoff, through a combination of timing and routing, flights will be strategically deconflicted [12]. In-flight updates from PSUs will help detect and resolve potential conflicts as well as assisting pilots in locating and avoiding neighboring traffic. As flights are expected to be conducted under VFR at UML-3, ultimate responsibility to "see and avoid" other traffic remains with the aircraft pilots and PSUs at this stage provide supporting services. During UML-3 this process is expected to be developed, refined, and validated such that reliance on PSU capabilities is sufficiently trusted to become a core capability for enabling operations in IMC in UML-4. Interaction with traditional air traffic control (ATC) in controller-managed airspace classes used by UAM operations during UML-3 (e.g. class B, C, D) will still need to comply with current regulatory requirements. For example, entry into class B airspace will still require a clearance from ATC. However, to minimize additional workload on controllers and pilots, much of the routine communication is expected to be handled transparently through digital connectivity between aircraft, PSUs and the broader NAS. Standard voice communication will still need to be available in controller-managed airspace for non-routine interactions.

Implementation of the airspace management capabilities described above, combined with the desire to develop and validate aircraft navigation, separation services, and flight rules that can support high-throughput aircraft operations independent of external visibility suggests that fielding advanced communication, navigation, and surveillance capabilities (CNS) will occur in UML-3. Nominally, it is expected that the community will work to develop airspace equipage and procedures, including flight rules and flight procedures, enabling an alternative to present-day, instrument flight rules (IFR) and practices that are compatible with UAM operations and scalability in markets that regularly experience IMC [13]. In addition to CNS capabilities supporting the PSU-enabled resource and strategic deflection capabilities described above, technologies will be needed to support aircraft operations without reliance on human vision or sensors having insufficient penetration in visible moisture and other sources of obscuration to support safe and efficient flight operations from takeoff to touchdown in obstacle rich urban environments. Candidate CNS system solutions are expected to involve a fusion of air and ground sensors and processing that provide efficient operations in nominal operations and assure safety and resilience in off-nominal situations.

3. *Community*

As mentioned in the aircraft discussion, UML-3 is expected to involve greater integration of UAM operations and ground infrastructure into densely populated areas. Initially in UML-3, decisions regarding closer integration of UAM into the community is expected to involve local decision making, with different early adopter areas arriving at potentially different decisions and corresponding local regulations based on the needs, preferences, and other factors unique to a given locality. During the UML-3 phase, this diversity of experience is expected to provide a foundation of guidance for local integration and regulation of UAM systems as UAM expands beyond initial trial markets. Examples of local regulatory guidance include safety buffers and setbacks around ports; control of obstacles in the vicinity of departure and approach paths; and guidelines for individual aircraft noise as well as the aggregated noise exposure in high-noise areas such as near ports. It is expected that model regulations, standards, and recommended practices for localities will be developed during this period.

D. **UML-4**

UML 4 is characterized by medium total traffic levels, medium complexity operations, and reliance on collaborative and responsible automation. UML-4 is anticipated to be enabled following several key regulatory changes that significantly increase the reliability of UAM transportation and its scalability. These regulatory changes would extend UAM operations into IMC and reduce the specialized skills and associated training needed by human pilots and controllers as high-assurance automated systems are trusted to perform selected, safety-critical functions. At UML-4, UAM is expected to be practical in many US metropolitan areas, not just areas with predominately VMC weather. In addition, increasing economies of scale are expected to make UAM accessible and attractive to a significant percentage of the public for travel between high-density, origin-destination pairs (e.g. commercial airport to business district).

1. *Aircraft*

The primary difference between aircraft at UML 4 vs 3 is that the comprehensive flight and contingency management automation introduced in 3 has been refined and operationally validated such that CAAs fundamentally revise the expected roles and responsibilities of UAM pilots. Further, the certification and training requirements for pilots are updated to reflect the capabilities and reliability of this technology. While these revisions may take many forms, there are two general strategies being pursued by industry towards this relatively long-term goal. One strategy, often termed "Simplified Vehicle Operations" or SVO [14] involves retaining the pilot on-board while establishing a new category of pilot certificate specific to, and nominally limited to, UAM operations and aircraft with appropriate equipage. The intent is to increase the availability of pilots by making the process of obtaining a pilot certificate significantly faster and less expensive than today.

The other strategy is to leverage the on-aircraft automation capabilities to gain approval for locating the pilot off the vehicle. This approach, often referred to as remote supervisory operations (RSO) has the obvious advantage of removing the pilot and associated pilot's station from the vehicle's nominal payload which is quite significant for an aircraft for approximately four seats. A discussion of the comparative challenges and synergies between these two strategies is beyond the scope of this paper but has been described by several authors [15] [16].

Since a significant expansion of UAM operations into new metro areas and increased traffic within existing areas is expected to occur in UML-4, scalable, highly-automated manufacturing of aircraft is expected to become cost effective during UML-4, further increasing economies of scale to the industry and accessibility to the traveling public.

2. *Airspace System*

Similar to the increasing on reliance on automation on-board the aircraft, the primary airspace system advances from required for UML-4 are likely to be facilitated by regulatory and policy change allowing increased operational credit for technologies deployed in UML-3. These changes would be targeted at enabling the UAM airspace operations management capabilities implemented and validated in VMC to be utilized in IMC in UML-4. Readers should recognize that achieving this objective requires a number of complex, interrelated changes in the design, operation, and underlying regulation of the NAS. The complexity of the changes probably require that the capabilities be phased in progressively from less controlled and busy airspace (e.g. G, E) to more increasingly busy (D, C, B) over a period of years.

3. *Community*

At UML-4, UAM grows beyond the relatively limited number of early adopter cities and becomes practical in a wide range of locations. This expansion is enabled by the combination of being able to operate in low-visibility weather; ability to locate high-capacity vertiports in densely populated areas while assuring safety of neighbors; noise/annoyance levels that are familiar to, and acceptable to, communities; and increasing economies of scale that make the capability broadly accessible to community members. As mentioned previously, the experience gained from UML-3 provides a knowledge base and regulatory examples to help guide and standardize the process of developing UAM systems in new areas.

E. UML 5

UML 5 is characterized by high-density and complexity operations, relying on highly-integrated, automated networks. Compared to UML-4, the system has an order of magnitude more aircraft and ports, e.g. “thousands” vs “hundreds” and “hundreds” vs “tens”, respectively, in a given metro area. For comparison, the total number of aircraft (commercial and general aviation) aloft over the continental US during peak periods today is on the order of 5,000[#]. While the projected level of local air activity would be very high be current standards, it should be recognized that even at this scale, the number of aircraft will still be relatively limited compared to typical car and light truck fleets in the area. For example, at current vehicle ownership rates in the US (~0.8 cars/trucks per person), a metropolitan area with population of ~5 million residents (e.g. the Phoenix-Mesa AZ combined statistical area) has “millions” of ground vehicles vs a projected UAM fleet of “thousands”, or roughly 1 UAM aircraft for every 1,000 ground vehicles. That said, due to increased speed, load-factors, and utilization, the productivity of individual aircraft will be many times higher than individual cars. Using the eVTOL productivity estimates from [7] (i.e. six hours of utilization per day, an average load factor of 2.7 passengers per flight, & three 30 mile trips per hour) individual UAM aircraft have a projected productivity on the order of 1,460 passenger miles per day compared to typical ground vehicle utilization rates of 33 miles per day, mostly with a single occupant. Based on these projections, at UML-5, total passenger miles traveled by UAM aircraft in a metro area are expected to be on the order of 4-5% of the personal ground vehicle fleet. The motivation for this comparison is to highlight that at UML-5 traffic levels, which are very high by current aviation standards, high-productivity, fleet operations are essential for the system to provide significant levels of passenger carriage compared to the current ground transportation system.

1. *Aircraft*

At UML-5, the ratio of aircraft to vertiports remains roughly unchanged from UML-4 initially suggesting that terminal area traffic densities also remain similar. However, following development patterns of other transportation systems, new ports are likely to be place at, and expand the periphery, of the system. Traffic densities at the periphery are likely to be below average while increasing travel to, and density around existing, high-demand destinations, which were probably already operating at the throughput limits UML-4 technologies.

From an aircraft perspective, the pressure to operate, at least locally, at increasing traffic densities, combined with the expansion of the aircraft fleet and operations by an order of magnitude beyond UML-4 is expected to complete the transition to “fully-automated” aircraft by UML-5. Fully-automated indicates aircraft that nominally operate without the need for a dedicated pilot or operator on- or off-board. There may still be roles for remote supervisors at this stage, overseeing the operation of multiple aircraft, but given their divided attentions, they cannot be relied on to detect or mitigate time-critical safety concerns. Rather, their role is likely to focus on strategic decision making regarding fleet utilization and passenger management on the routes or operations they supervise. The introduction of aircraft without full-time oversight by a trained pilot or supervisory requires appropriate measures for monitoring, managing and assisting passengers and their effects throughout the conduct of a flight, including boarding and deplaning. While this task is relatively simply for an on-board pilot, it could be challenging during the transition to automated aircraft supported by a remote supervisor responsible for multiple aircraft. Ground crew at ports may be able to provide guidance and assistance while the aircraft is on the ground and the cabin accessible, but in-flight

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[#] https://www.faa.gov/air_traffic/by_the_numbers/

support will need to be provided for, including consideration of passengers experiencing serious medical impairments and the potential for malicious or mischievous acts in an otherwise unsupervised cabin.

Aside from automation capabilities at UML-5, the primary advances of the basic aircraft are expected to focus on continued improvements in the areas of noise reduction, range, weather tolerance (e.g. flight into known icing), maintainability, and low-cost manufacturing.

2. Airspace system

Similar to aircraft advances, the primary differentiator between UML-4 and 5 airspace capabilities is driven by the order of magnitude increase in the scale of the system and the practical inability of human controllers to be relied for safety- and time-critical interventions at this scale of operation. Similar to the aircraft, human roles will likely be limited to strategic decision making, still done with the support of automation that affects the efficiency of the overall system operation. This may involve, for example, decisions to relating to how to prioritize the flow of traffic through the system in response to special occurrences like an impending storm system or special, high-demand events (e.g. football game or large concert).

As a key characteristic of UML-5 is the expansion of the port network into less densely populated areas of the service area, the level of traffic through some of these ports may be relatively low, perhaps fewer than 10 aircraft per hour an hour during non-peak periods. To be economically viable, such low traffic ports probably need to be unstaffed, with automation used to control access to the port and otherwise assure the surface is free from hazards that might otherwise disruption the operation. Since the vehicles themselves are expected to be uncrewed, a combination of on- and off-board automation, along with potential oversight from a remote supervisor, will need to assure that passengers are loaded and secured safely and that the vehicle is within weight and balance limits.

3. Community

Community integration considerations at UML-5 are expected to center on the integration of UAM facilities and operations closer to more noise sensitive, residential areas. By UML-5, communities and their residents should have direct experience with UAM operations and have first-hand understanding of the impacts of operations on surrounding properties and their residents. Similar to expansion or construction of roads today, there is likely to be on-going tension between residents wanting to have access to the high-speed connectivity afforded by UAM but without it being too close to their own backyards.

F. **UML6**

The attainment of UML-6 is characterized by “ubiquitous” UAM operations and facilities within a metro area. A more operationally tangible definition of UML-6 is when the build-out of UAM is essentially complete and further growth of the system corresponds to population growth within a metro area. There is obviously a high-degree of uncertainty as to what this mature system might look like as it is probably multiple decades and several generations of technology in the future. At UML-5 with hundreds of ports distributed across the area, most people will live within a few miles of a port. Since most trips will require ground trip segments, nominally by car, to get to/from these ports, the capability would primarily only be advantageous for longer trips, with cars still being the predominate mode choice for shorter trips. For UAM to gain increased utilization beyond UML-5, it is likely that it will need to operate door-to-door or nearly door to door (e.g. between neighborhood vertiports) for a significant number of potential trips, making it time advantageous compared to surface travel options for trips under ~ 20 miles. Practical and wide spread, door-to-door operation is likely to introduce several important and challenging advances beyond UML-5 as described below.

1. Aircraft

Door to door UAM requires the ability to take off and land at, or very near (i.e. short walk or commute, possibly by a light-electric vehicle) the true origin and destination. This could potentially be achieved using several definite approaches. Perhaps ideally, UML-6 aircraft would be able to operate from highly-constrained areas such as residential rooftops, driveways, neighborhood streets, and other potentially, ad-hoc landing areas. Such operations would face severe challenges associated with operating into relatively uncontrolled areas such as limited clearance from potential obstacles and hazards and a high potential for adverse interactions between lift-system downwash and loose or minimally secured items near the landing areas. Vehicle noise constraints for these sorts of operations would likely be well beyond UML-5 levels and present additional developmental challenges. Realizing such vehicles likely depends on technological advances beyond the continued evolution or refinement of UML-5 aircraft.

At this time, vehicle configurations with some degree of roadability probably provide a clearer or more plausible path to significant growth beyond UML-5 levels. Our working hypothesis is that such vehicles may be practical from the perspective of operating from neighborhood or other local vertiports and would require only limited, low-speed ground operations to satisfy the door-to-door transit requirement. The short/low-speed operating restrictions are intended to minimize the challenges of roadability that have historically vexed roadable aircraft [17]. Despite these simplifications, roadable UAM aircraft are still likely to require some level of reconfiguration between ground and air modes which introduces significant potential mechanical complexities, associated weight, and potential time delays associated with the conversion process. Alternatively, while less convenient for the user than a single vehicle, it may ultimately be more practical to achieve operations from neighborhood vertiports using a combination of inexpensive, limited-capability ground vehicles (e.g. electric scooters or carts) combined with single-mode UAM aircraft. Aircraft compatible with this sort of operation may be achievable based on continued refinement of UML-5 configurations.

Aircraft automation at UML-6 is expected to have advanced to where no human involvement, on- or off-board, is needed for the conduct of transportation oriented flights where the origin and destination are specified prior to flight, but offer the flexibility to change routing and landing destination while in-transit.

2. *Airspace system*

Compared to UML-5, UML-6 airspace operations involve a dramatic increase in the number of vertiports along with flight operations, with much of this increase involving shorter range flights as UAM operations are substituted for routine automobile trips. The management of the airspace system at UML-6, like individual aircraft, is expected to be fully automated with no requirement for real-time human involvement. Specific operational details UML-6 airspace operations are highly-speculative and will be informed by the experiences at the earlier maturity levels. Of particular importance to the development of UML-6 operations will be the underlying capabilities, performance, and demonstrated assurance properties of the supporting communication, navigation, and surveillance infrastructure.

The highly distributed network of ports at UML-6 and resulting highly variable pattern of trips is likely to require strategic awareness of desired traffic flows (e.g. planned flights) to or through key system bottlenecks to avoid unmanageable demand, delays, and/or diversions. Tactical traffic management challenges can be eased in part by technologies enabling reduced separation minima between vehicles. Reducing the protected space around vehicle proportionately reduces the number of conflicts needing mitigation, albeit reducing the time and space available to mitigate conflicts which do occur.

3. *Community*

At UML-6, communities may be fundamentally reshaped by UAM, similar to how automobiles encouraged suburbanization in the 1950s. Growth of UAM beyond UML-5 likely depends on the development communities designed, at least in part, around the new transportation capability provided by UAM. While highly speculative, the ability to routinely travel at higher speeds has generally contributed to more distributed living patterns and the availability of widely accessible UAM would like continue this pattern. The combination of tele-presence combined with UAM and other emerging forms of transportation such as self-driving cars that reduce the direct and indirect (e.g. time dedicated to the driving task) costs of travel is likely to encourage increased exurbanization, albeit, while retaining convenient access to urban centers, infrastructure, and other amenities. As eluded to in the vehicle section, the transition from UML-5 to 6 is motivated in large part by UAM being integrated into communities at the neighborhood level.

V. Summary

This paper presented and described a framework developed by NASA called the UAM maturity level (UML) scale. This scale is intended to identify significant phases expected during the evolution of a UAM transportations system from the current state of the art to a future state where UAM vehicles are an integral and ubiquitous part of an overall mobility system. The UML scale described in this paper was developed with a primary focus on the passenger-carrying UAM use case, but does have application to other missions. The UAM scale is composed of 6 levels that are differentiated by a combination of 3 main attributes, namely, traffic density, operational complexity, and reliance on automation. The realization of the progression through the 6 UML levels will require many advances in aircraft, airspace system, and community integration technologies. While no timeline for the progression through UML capabilities was presented, the paper described the key challenges, technological advanced, and capabilities envisioned of a projection of the introduction of UAM capabilities over time.

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