Urban Air Mobility (UAM) Airspace Research Roadmap –

Systems Engineering Approach to Managing Airspace Evolution Towards UML-4

Annie Cheng[1], Kevin Witzberger[2], Nipa Phojanamongkolkij[3] , Ian Levitt[4]

NASA Ames Research Center, Moffett Field, CA, 94035, USA

NASA Langley Research Center, Hampton, VA, 23681, USA

Abstract:

The paper describes how the Urban Air Mobility (UAM) Airspace Research Roadmap (herein referred to as the Roadmap) is applied by the NASA Air Traffic Management – eXploration (ATM-X) UAM Subproject as a System Engineering artifact to managing the evolution of UAM airspace operations during its Research & Development (R&D) lifecycle. A description of the Roadmap can be found in [2] which presents an Enterprise view of the research necessary to develop airspace for UAM operations towards UML-4, laid out by when the capability needs to be matured (i.e., UML). This paper follows from that Enterprise view but focuses specifically on the part of the Roadmap that the UAM Subproject will work on. The UAM Subproject will focus on airspace research on new technologies and new airspace constructs for UAM operations to enable increased demand by the end of FY25 and validate an integrated system that enables NAS operations by the end of FY30.

1. Introduction

Advanced Air Mobility (AAM) encompasses a range of innovative aviation technologies (small drones, electric aircraft, automated air traffic management, etc.) that are transforming aviation's role in everyday life, including the movement of goods and people. The concept of Urban Air Mobility (UAM) is composed of certain AAM concepts that have the potential to provide commercial services to the public over densely populated cities and the urban

[1] Lead Systems Engineer for ATM-X Urban Air Mobility (UAM) Subproject, NASA Ames Research Center, Aeronautics Projects Office.
[2] Subproject Manager for ATM-X Urban Air Mobility (UAM) Subproject, NASA Ames Research Center, Aviation Systems Division.
[3] Lead Model-Based System Engineer for ATM-X Urban Air Mobility (UAM) Subproject, NASA Langley Research Center, Systems Engineering and Engineering Methods, Engineering Directorate.
[4] Principle Engineer for ATM-X Urban Air Mobility (UAM) Subproject, NASA Langley Research Center, Crew Systems & Aviation Operations, Research Directorate.

periphery, including flying between local, regional, intra-regional, and urban locations using revolutionary new electric Vertical Takeoff and Landing (eVTOL) aircraft that are only just now becoming possible. The improvement of UAM envisages a future in which advanced technologies and new operational procedures enable practical, cost-effective air transport as an integrated mode of movement of people and goods in metropolitan areas.

NASA Aeronautics Research Mission Directorate (ARMD) AAM vision is to “enable, safe, sustainable, affordable, and accessible aviation for transformational local and interregional missions”. To fulfill that vision, NASA defined an AAM Critical Commitment (CC) to describe NASA’s anticipated contributions to support the AAM ecosystem. The AAM CC is to “deliver aircraft, airspace, and infrastructure system and architecture requirements to enable sustainable and scalable medium density advanced air mobility operations based on validated operational concepts, simulations, analyses, and results from the National Campaign demonstrations”, as shown in Table 1 below. The AAM CC describes the high-level UAM ecosystem, in which vehicle, airspace, and community play an important part. The Roadmap focuses on the airspace perspective of the CC, and particularly on the initial and intermediate states, i.e., UAM Maturity Level (UML)-1 to UML-4.

Figure 1. AAM Mission Critical Commitment

The UAM Maturity Level (UML) scale [1] developed by NASA provides insight into UAM operational, technical, and regulatory progression in the National Airspace System (NAS). The UML scale is a useful framework for understanding and evaluating the evolution of the NAS as it pertains to UAM, where the UMLs themselves are periods of change that build up to significant “step-functions” in operational capabilities. While the existing definition of the UML scale provides an extensive and well-defined treatment of the progression of UAM from a vehicle operations perspective, it is limited in its treatment of the UAM airspace system. This progression of the NAS through the UMLs from an airspace system perspective is detailed in [2] and summarized in Table 1. UAM Maturity Level (UML) Definitions below. At the time of this publication, these definitions are referenced from Roadmap v1.0 in [2], and some definitions will likely evolve and be updated in the next iteration of the Roadmap.

Table 1. UAM Maturity Level (UML) Definitions

UML	Definition
UML-1: Pre-Operational	UML-1 represents the (current) pre-operational phase that precedes the first operational approval of commercial UAM eVTOL operations in the NAS. These will be largely experimental operations in the NAS, although there may be a period of non-experimental flights in the NAS using eVTOL that are certified while commercial operations are not yet approved. Existing infrastructure will be used to demonstrate UAM

	operations, and to collect field data that will advance UAM operations to the next stage. Traffic densities will be low, and interactions with existing ATC will be known and controlled through the appropriate safety management system (SMS) processes. These operations will primarily take place under Visual Meteorological Conditions (VMC), and as piloted operations under Visual Flight Rules (VFR) or Instrument Flight Rules (IFR).
UML-2: Initial	UML-2 represents initial commercial operations under existing regulations which utilize existing airspace constructs. These operations are expected to take place in carefully chosen early adopter markets where operational challenges can be eased with non-regulatory accommodations where possible. These operations will likely rely on commercial pilot certification and ratings, operating under VFR or IFR with Part 91 and Part 135 approvals. UAM operations will be designed to minimize interactions with existing Air Traffic Management (ATM) operations, with operational tempo expected to be on the order of 3-15 operations per vertiport per hour, and simultaneous operations in the tens (10-50) per metropolitan area [1]. Existing and new infrastructure will be leveraged by the UAM Operator, initially with low-complexity route networks. Vertiports are expected to be shared among UAM Operators in some cases, and in others private vertiports may be employed by a single UAM Operator. Assistive technology will be leveraged by the Pilot-In-Command (PIC) and the UAM Operator to safely increase operational tempo without increasing ATC workload to the extent possible, and the operational design will be to enable safe and efficient scaling of the operations. Technology maturation will be on a path towards, among other things, assisting humans in the safe and strategic management of airspace resources being utilized by UAM operations. Information exchanges may be established that permit cooperative behaviors that lead to overall system benefit. Eventually, the need to increase operational tempo will be limited by the capacity of existing NAS constraints. More significant regulatory changes will be required to further increase operational flexibility while maintaining safety. The same is true for increased UAM Vehicle autonomy, and a holistic approach to maturing regulations to permit both operational flexibility and alternate pilot configurations on the UAM Vehicle would be ideal
UML-3: Proliferation	UML-3 represents the proliferation of novel regulatory and airspace constructs (e.g., cooperative UAM corridors) and the supporting systems and services, designed to overcome the capacity constraints of UML-2. The UAM Operators will seek operational credit for systems and services that have matured in an assistive capacity during UML-2, and which will reduce the ATC workload otherwise required to maintain the increase in operational tempo. It is expected that the vertiports may service 20-30 operations per hour, with up to 100 simultaneous airborne UAM operations in a metropolitan area. In order to accommodate this new operational flexibility and responsibility for the UAM Operator, regulatory changes will need to be made. This may include the establishment of new airspace constructs (e.g., UAM Corridors), Letters of Agreement (LOA), and waivers to existing rules. Airspace systems and services will support complex strategic conflict management and provide early safety-critical functionality to assure separation provision between all UAM and non-UAM operations, including under updated VMC and IMC regulatory framework. This will permit greater complexity in the route and vertiport networks, potentially incorporating novel airspace constructs. Within this period, the UTM ecosystem will be mature and interoperate with the UAM airspace system. This increased operational flexibility also comes at a time of increased automation on the vehicle, supporting concepts such as Simplified Vehicle Operations (SVO) and Remote Pilot in Control (RPIC) [1]. The relationship between increased autonomy levels for the vehicle and increased responsibility of the UAM Operator is an important area of future research. The solutions put in place for UML-3 will be tailored to many of the specific regional conditions and operational use cases that proliferate across the NAS. Individual SMS processes and technologies will be employed for operational approval. These pathfinding use cases will eventually lead to a national strategy for integrating UAM operations in a streamlined manner to meet the growing national market demand.
UML-4: Integration	UML-4 represents the integration of UAM operations into the NAS under more complex meteorological conditions, with the support of more complex safety-critical systems, and with increased digital exchanges including with the ANSP. The airspace constructs that will have emerged are used routinely in conjunction with third party systems and services to ensure safe, efficient, and equitable access to the airspace for the UAM Operator. It is expected that the vertiports may service 40-60 operations per hour, with hundreds (100-500) of

	simultaneous airborne UAM operations in a metropolitan area. The route and vertiport networks will be highly complex and responsive to accurate weather and traffic predictions. The UAM Operator is responsible for cooperatively managing conflicts within the parameters of the airspace constructs and ultimate form of regulatory accommodations. They are supported by mature rules and requirements, some of which are achieved by consensus in industry and approved by the FAA. Performance standards will enable heterogeneous operations and vehicle types while allowing operational flexibility and adaptation, supported by increasingly autonomous technologies both airborne and terrestrial. UML-4 is an important step towards more complex and automated environment, but there is a lot of uncertainty on how that would be achieved. More research would need to be done by analyzing UML-2 and UML-3, to inform further requirements for UML-4.

2. UAM Subproject Research Focus

Because today's air traffic management system cannot scale to the expected demand levels of UML-4, NASA will develop and demonstrate community-informed, extensible UAM traffic management enabling low-to-medium density operations and deliver validated requirements to the FAA and Industry.

The UAM Subproject is one of several sub-projects operating under the broader Air Traffic Management -- eXploration (ATM-X) project at NASA. The Subproject's primary research goal is to evolve the airspace towards UML-4, and eventually enable future operations in the National Airspace System (NAS). To achieve that, the UAM Subproject identified research and technology development efforts needed to evolve the architecture to lower density operations while ensuring it is extensible to higher density operations. The Subproject also identified research and technology that is critical and expected to take a long time to complete, such as Communication Services and Systems, to develop initial requirements early on. The UAM Subproject will initially (FY21-FY25) focus on new airspace technologies and constructs that will be needed for UML-3, to satisfy the UAM Technical Challenge by FY25. Subsequently (FY26-FY30), the UAM Subproject will evolve the UAM airspace towards UML-4, to satisfy the AAM Mission Critical Commitment by FY30.

The portfolio of research and demonstration activities identified by the UAM Subproject are compiled to meet the five defined NASA ATM-X AAM objectives, described as follows:

1. **Low Volumes Airspace Operations.** The UAM Subproject will develop airspace concept technologies, ATC information requirements, and use-case analysis for selected urban environment to support low volume UAM operations within the current regulatory structure (i.e., no Provider of Services to UAM (PSU) nor new airspace constructs).

2. **UAM Separation Standards.** The UAM Subproject will develop and evaluate conflict management concepts, preliminary conflict management community-based rules (CBRs), and vehicle performance-based separation criteria to enable increasing levels of UAM operations. Based on the analysis and findings, the UAM Subproject will deliver industry-informed recommendations to the FAA on conflict management concepts.

3. **UAM Procedures.** The UAM Subproject will develop and design new collaborative airspace structures and perform analysis for early adopter cities to support medium volume UAM operations. The design will be informed by FAA and evaluated by the industry through planned demonstration activities.

4. **Develop Preliminary UAM CNS Architecture.** The UAM Subproject will develop preliminary UAM communications architecture and requirements across the UMLs.

5. **UAM Airspace Architectures and Services.** The UAM Subproject will collaborate with Industry and the FAA to evolve the notional UAM architecture towards a secure prototype airspace UML-4 architecture. The UAM Subproject will develop requirements, application programming interfaces, and software prototypes

for UAM services such as the Provider of Services for UAM (PSU), FAA-Industry Data Exchange Protocol (FIDXP), airspace structure definition service (ASDS), vertiport management service, and technologies supporting cooperative conflict management (e.g., demand-capacity balance and detect-and-avoid).

To successfully evolve the UAM airspace, it requires close collaboration with the FAA and industry. The UAM Subproject will coordinate closely with the FAA, maintain strong partnership with the AAM Mission and National Campaign, participate in American Society for Testing and Materials (ASTM) and other standard development organizations, and identify candidate technical transfer products for the FAA and standard bodies. The research and technology developed will be tested and validated during planned demonstration activities with the FAA and the industry, including National Campaign (NC) Simulations, and UAM UML-3 Demonstration with FAA's William J. Hughes Technical Center (WJHTC) and Industry.

Milestones and deliverables for tracking completion of the UAM Subproject research and demonstration activities are mapped to these five objectives, as part of the process of contributing to the stakeholder goals, and this information is used in the Roadmap in reporting Subproject's progress, as described in later sections. The requirements developed and verified through these activities are expected to satisfy a portion of the airspace requirements for each UML.

3. Roadmap Overview, Decomposition, and Application for the UAM Subproject

The Roadmap described in [1] presents an Enterprise view of the research necessary to develop airspace for UAM operations towards UML-4, laid out by when the capability needs to be matured (i.e., UML). It defines the plan for how the UAM airspace system will evolve, synchronized with the UML definitions for aircraft and infrastructure. The breadth and complexity of research that underpins this evolution requires organization, a common language, and a unifying approach. Thus, the Roadmap is developed to meet the need for tracing and maturing system engineering artifacts which cover multiple complex dimensions in scope and time.

The Roadmap utilizes a top-down approach, starting with the definition of UMLs that relates to the evolution of airspace, then decomposing the UAM airspace system into a non-exhaustive list of operational research *elements*. Each research element is further decomposed into constituent *components*. This structure enables traceability of requirements to the concept of operations associated with each UML to support verification through planned research and development activities. With this structure, broad Systems Engineering (SE) process can be applied to improve alignment of cross-functional systems and technologies to the NASA mission and goals and to provide a tool that enables collaboration with other NASA projects, the FAA, and industry.

The UAM Subproject developed these *elements* and *components* with input from multiple stakeholders as well as leveraging terminology and definitions from references such as the FAA's ConOps [4] and other publications. The initial list of research *elements* and *components* is shown in Table 1 is expected to change and expand during the lifecycle of the Roadmap. These *elements* and *components* describe what will be needed to evolve the airspace from the Enterprise perspective, not limited to UAM Subproject's research. Identifying these relationships will be important to make sure those *components* evolve together, from current to future state, even if the *component* is not part of the UAM Subproject's planned research.

The UAM Subproject leverages the Enterprise view by focusing specifically on the subset of the Roadmap that the UAM Subproject will work on directly to satisfy the stakeholder objectives. It utilizes the Roadmap as an established framework for managing change and tracking the UAM Subproject's progression in fulfilment of the Subproject's stakeholder objectives by documenting the set of artifacts and requirements for the UAM Airspace for each UML. The *elements* and *components* that are not part of the UAM Subproject's planned research are grayed out from Table 2 below.

Table 2. UAM Subproject Elements and Components from the Roadmap

	Elements	Components
AIRSPACE	**Airspace Management Systems and Services Architecture**	• Provider of Services to UAM (PSU) • Supplemental Data and Services Provider (SDSP) • Discovery Services • FAA-Industry Data Exchange Protocol (FIDXP) • UAS Service Supplier (USS)
	Airspace and Procedure Design	• Airspace Management • Airspace Construct • Approach & Departure Procedures • En Route Procedures • Contingency Procedures
	Airspace System Regulations and Policies	• Community Based Rules (CBR) • FAA regulations (FAR) / Code of Federal Regulation (CFR) • Policies and Guidance • Safety Management System (SMS) / Safety Risk Management (SRM) • System Certification and Qualification
	Communication Services and Systems	• Voice Services • Telemetry Services • Command Services • Contingency Communications • Vehicle-to-Vehicle Services • Pre-/Post-Flight Wireless Services
	Navigation Services and Systems	• Ground-based positioning services • Satellite-based positioning services
	Separation Services and Standards	• Strategic Conflict Management Services • Separation Provision Services • Collision Avoidance Systems • Roles & Responsibilities • Separation Minima
	Surveillance Services and Systems	• Non-Cooperative • Cooperative

For each *component*, the requirements and capability level identified by the UAM Subproject are captured. These requirements will be added and updated based on NASA research and development and as part of the Roadmap's iteration and revision cycles. The classification of requirements is as follows:

- **Shall** is used to indicate a binding requirement, and will be verified
- **Will** is used to indicate a statement of fact, or an assumption taken for granted, and are binding in that an expectation of certainty is established
- **Should** is used to indicate a desired goal at the boundary of existing research, is non-binding, and is used to guide evaluation activities. As the research matures, these can be revised to become requirements.
- **To Be Resolved (TBR)** is used to indicate a lack of known requirements where further research and development is needed

To facilitate the management, communication, and status of requirements, Subproject uses a Model-Based System Engineering (MBSE) approach and the Systems Modeling Language (SysML) as the modeling standards to capture all System Engineering artifacts. As the AAM Mission Integration Office (AMIO) also uses MBSE methodology to assess progress towards AAM critical commitment by tracing completion of NASA objectives from collaborating NASA projects, this approach will allow for better alignment and traceability to meet ARMD's AAM vision. MBSE enables the Subproject to manage a very large and highly complex set of system concepts with clearly defined dependencies among Subproject milestones, requirements, and Roadmap *elements* and *components*.

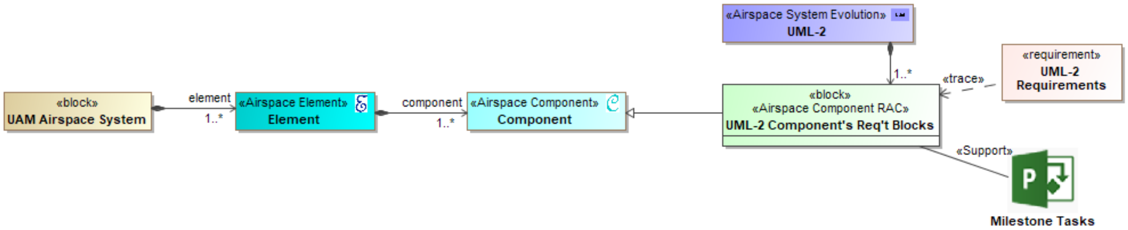

Figure 2. Roadmap's meta-model showing the structure and hierarchy behind the MBSE model

Figure 2 above shows structure and hierarchy behind the UAM Airspace Roadmap MBSE model. It is composed of multiple *elements* (1-to-many), each *element* is comprised of multiple *components* (1-to-many), and each *component* has multiple "requirement blocks" that are tied to specific UMLs (1-to-many). Each "requirement block" is traced to a single requirement, as well as the milestone task(s) that it supports. This structure is needed to make sure requirements for each UML are clearly defined and associated with milestones, and vice versa, to support the tracking of UAM subproject's progress described in in the next section. Details on the MBSE approach are further described in [3].

4. Roadmap as Continuous System Engineering Process

Throughout the lifecycle of the UAM Subproject's airspace research & development, the Roadmap will be continuously updated and matured to deliver a validated set of requirements and a framework for UAM airspace architectures. The Roadmap provides a mechanism for continuous application of the System Engineering "V" model.

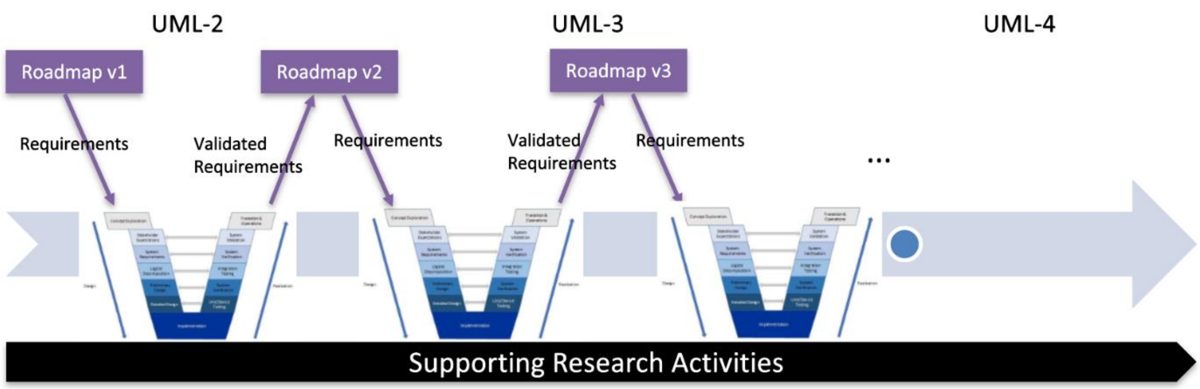

Figure 3. Roadmap as part of the Continuous System Engineering Process

The Roadmap is the key driver for the Subproject's SE process and executes the left side of the "V" model through system definition and decomposition. This approach formalizes the planning step that has to occur before each activity. Information from the Roadmap, defined by the UAM stakeholders, will affect how the research would be done, and what questions the research would be able to answer. As the initial requirements are gathered from the UAM stakeholders, including FAA and industry, these become candidate requirements that reflect the current state of understanding of the UAM airspace evolution and will be further explored. These candidate requirements will drive each research activity in different ways, appropriate to the task, for example:

- Some activities will draw requirements from multiple elements of the Roadmap, with focus on validating requirements for a particular element. For example, R&D on UAM cooperative conflict management for UML-3 will be informed by the requirements from the "Airspace Procedures and Design" and

“Communication Services and Systems” *elements* of the Roadmap, while the completed work will validate requirements in the “Separation Service and Standards” *element*. It may also result the refinement or validation of requirements in “Airspace Procedures and Design” and “Communication Services and Systems”.

- Other activities may involve prototype technology development and testing (e.g., prototype PSU, FAA-Industry Data Exchange Protocol, detect-and-avoid solutions). These initial candidate requirements from the Roadmap will be key input to the initial design, architecture, and functional decomposition for the prototype system-in-test.

At the start of key milestone activities, the UAM Subproject identifies the set of Roadmap candidate requirements to be validated as part of that milestone. The Roadmap, supported by MBSE, will be the "source of truth" for the different R&D activities throughout this UAM airspace evolution, and enables the UAM Subproject teams to achieve what they need to do while knowing how it might affect other components. The Roadmap SE process supporting the left side of the “V” model is shown in Figure 4 below.

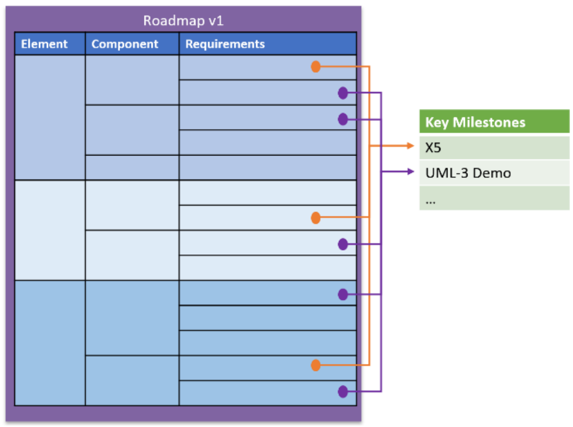

Figure 4. Roadmap candidate requirements will be used to guide milestone activities

As these requirements are being updated and refined, lower-level requirements may be identified and they will be captured in the MBSE model, with traceability to the appropriate requirements in the Roadmap. Through the development of these requirements, it is expected that the UAM Subproject will only be satisfying a subset of the Roadmap elements. Requirements that cannot be defined (i.e., TBRs) indicate where potential additional areas of research might need to be satisfied elsewhere. Using these common requirements classifications and terminologies, the Roadmap becomes a valuable tool not only for communicating the UAM Subproject’s current and planned states of research, but also for assessing gaps in the NASA research portfolio and in the ecosystem stakeholder’s development efforts.

The Roadmap also implements the right side of the “V” model, i.e., integration of parts and their validation. Through the Subproject’s planned R&D activities, the candidate requirements will be verified and validated. Upon successful validation, the candidate requirements will become recommended requirements – these recommended requirements will be a key output from the Roadmap. As most UAM Subproject’s milestones are concluded with a final report documented with the findings, these final reports will be analyzed to inform which candidate requirements on the Roadmap were validated, or if requirements need to be updated based on research findings, as shown on Figure 5 below. The updated requirements will feed into the next “V” in the UAM Subproject’s lifecycle and will continue to be refined in the next iteration of the Roadmap, as shown in Figure 3 above.

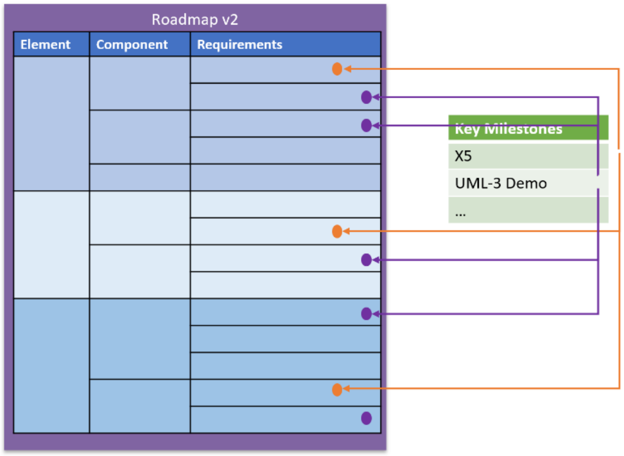

Figure 5. Completed milestones will be used to validate and update candidate requirements on the Roadmap

As the UAM Subproject progresses in terms of requirements identification and validation through the planned and completed milestones, there is a need to communicate the progression of the airspace R&D activities to key stakeholders. The Subproject tracks its progress of airspace R&D planned efforts in relation to the Roadmap and reports the progress periodically via the UAM Subproject Airspace Roadmap Progress Indicator (RPI). The RPI combines all the milestones from the Subproject's Integrated Master Schedule (IMS) and requirements captured in the Roadmap for UAM airspace *elements* and *components*.

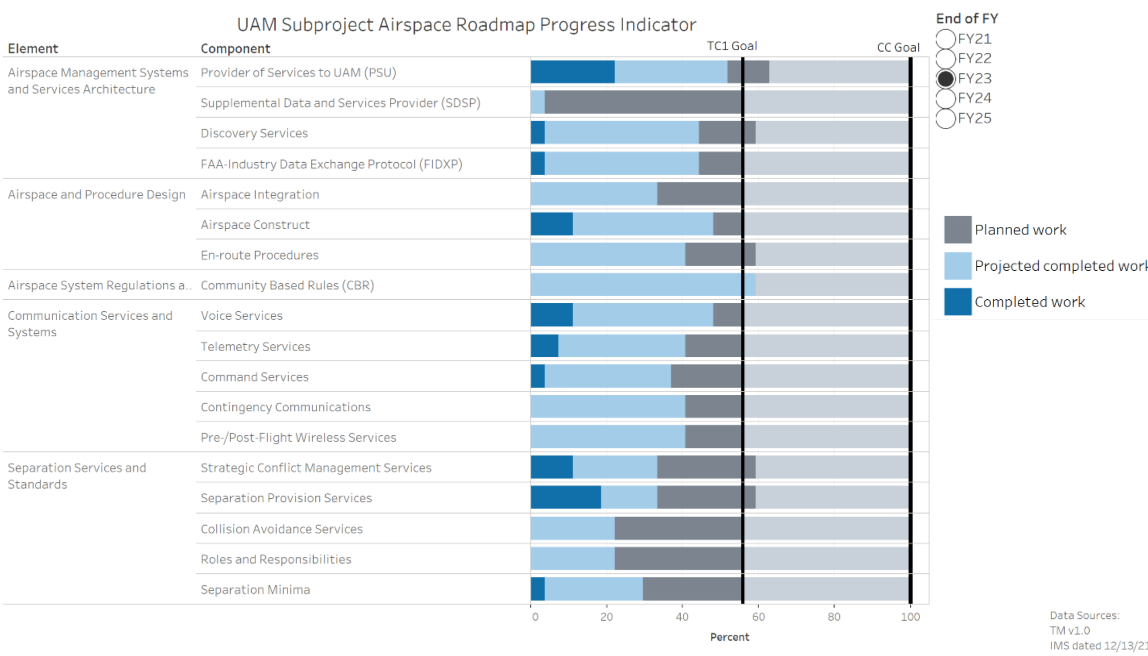

Figure 6. Example of UAM Subproject Airspace Roadmap Progress Indicator

The RPI will be used to enable periodic assessments that track the progression of NASA's UAM Airspace research towards UML-4. Figure 6 shows UAM Subproject's RPI and progress towards completing higher NASA goals, such as the ARMD Critical Commitment and Technical Challenge. These are indicated by the "CC Goal" and "TC1 Goal" lines, respectively, in the figure above. At the end of each FY, requirements that have been validated are marked as "Completed work" (shown in dark blue). The next FY's "Projected completed work", with requirements projected to be validated, are shown in light blue. Requirements that will be identified and/or validated in the future years are shown as Planned work (in grey). If the UAM Subproject completes all its planned work through FY25, then it will have completed approximately 55% of the airspace component of the UML-4 effort.

5. Conclusion

The SE approach to defining, managing, and tracking the Roadmap described in this paper is expected to be an initial plan for how the UAM Subproject will conduct its system engineering practices within its lifecycle over the next ten years. This SE approach includes a plan for how Roadmap is managed and updated by the UAM Subproject, and how results from the planned research and development work will inform the airspace evolution towards UML-4. By using MBSE to help manage the Roadmap, it provides a single, consolidated view for the various airspace research areas managed by the UAM Subproject, and enables the UAM Subproject to communicate its planned research and progress to its current stakeholders.

6. Next Steps

This SE approach described in this paper is a starting point and will continue to be refined based on internal and external input. Further refinement of the MBSE is expected as it is a key part of the SE process, and lessons learned in applying MBSE will be captured and shared with the wider community. The next steps for the Subproject will include synthesizing information from current major research efforts such as X4 into the Roadmap and implementing the left side of the “V” model for the upcoming research efforts and milestones.

Finally, views of the roadmap such as the UAM Roadmap Progress Indicator above will be refined, and the underlying roadmap model will become more comprehensive. For instance, requirements may be subjectively rated for maturity to enhance identification of research gaps, or the components may be traced to other lower-level requirements and source documentation.

References

[1] Kenneth H. Goodrich and Colin R. Theodore. "Description of the NASA Urban Air Mobility Maturity Level (UML) Scale," AIAA 2021-1627. AIAA Scitech 2021 Forum. January 2021.
[2] Levitt I., Phojanamongkolkij N., Witzberger K., Rios J., and Cheng A.. *UAM Airspace Research Roadmap*. National Aeronautics and Space Administration, NASA/TM-20210019876, 2021.
[3] Phojanamongkolkij, N., Levitt, I., Barnes, P. “Overview of Model-Based Systems Engineering Efforts to Evolve the Airspace Research System Roadmap”, 2022 AIAA Aviation Forum, June 2022 (To appear)
[4] Federal Aviation Administration, “NextGen Concept of Operations for Urban Air Mobility (UAM) v1.0”, June 2020