

Optimizing Urban Air Mobility Research Through Bi-Directional Integration Processes for Effective Verification and Validation

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Abstract— Urban Air Mobility (UAM), a subset of Advanced Air Mobility (AAM), aims to revolutionize metropolitan transportation. This paper explores an engineering process framework within National Aeronautics and Space Administration (NASA)’s Air Mobility Pathfinders (AMP) project, which is focused on the safe scaling and seamless integration of UAM operations within the National Airspace System (NAS). Progressing through three phases — Initial, Midterm, and Mature — the Federal Aviation Administration (FAA)’s UAM Concept of Operations (ConOps) describes a proposed path for the evolution of UAM operations, presenting multifaceted challenges in technology, regulation, and stakeholder engagement. With this ConOps as a basis, the AMP project is executing research, development, test, and evaluation activities aimed at delivering validated reference architectures for the Midterm phase. This paper illuminates the pivotal role of the systems engineering process in managing these technical efforts. Robust verification and validation methods, along with systematic bi-directional integration process, enhance the ability to conduct research into the design and evolution of safe, efficient, and reliable UAM systems. In this paper a systematic framework will be presented and shown to facilitate interactions between UAM stakeholders and to effectively manage the complex architecture of UAM operations in the NAS.

Keywords: *National Airspace System; NASA Air Mobility Pathfinders; System Engineering Processes; Urban Air Mobility/Advanced Air Mobility; Verification and Validation methods*

I. INTRODUCTION

Urban Air Mobility (UAM) is a subset of Advanced Air Mobility (AAM) that focuses on transporting people and goods over metropolitan areas and the urban periphery, supported by the introduction of a cooperative operating environment known as Extensible Traffic Management [1]. The Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), and industry are leading the initiative to advance the research needed to enable the integration of UAM operations within the existing United States National Airspace System (NAS). This research has driven rapid

advancements in new technology and operational procedures to support solutions that enable safe, efficient, and scalable UAM operations.

The FAA’s UAM Concept of Operations (ConOps) [1] communicates an evolutionary vision that guides the progression of UAM operations within the NAS. Hereafter in this paper, "UAM ConOps" will be used to refer to the FAA's UAM Concept of Operations. The FAA has characterized the progression of UAM operations by defining three phases: Initial, Midterm, and Mature. UAM operations increase in scale throughout the evolution, enabled by changes in governing regulations, infrastructure, and automation. Progressing through these phases presents complex operational challenges and barriers for the industry, regulatory bodies, and involved stakeholders. These challenges encompass a wide array of factors, from technological advancements and safety considerations to public acceptance and integration with existing air traffic.

Due to the complex interdependencies involved in integrating UAM within an evolving NAS, a systematic approach is needed to harmonize interactions and streamline a path to enable and evolve the interoperability of UAM operations and traditional air traffic. To proceed effectively, a comprehensive and inclusive perspective will be necessary, synthesizing and leveraging knowledge from research beyond one’s own project or efforts. Traceability between validated requirements and the underlying research will be essential to safely and efficiently moving UAM (and AAM) forward.

The NASA Air Mobility Pathfinders (AMP) project within the Airspace Operations and Safety Program (AOSP) is focused on identifying and validating a path to safely accelerate UAM operations at scale. The AMP project will develop and validate reference architectures and integrated requirements that advance the understanding of safe and scalable UAM operations through the Midterm phase, as defined by the UAM ConOps.

The AMP project is adopting rigorous verification and validation methodologies to systematically mature the reliability of the UAM system requirements and architectures it develops, with an aim to serve the community and foster trust among stakeholders and the public. This comprehensive framework will leverage systems engineering processes to identify what is known, what is developed, and what is needed as research continuously evolves [2].

This paper describes some of the systems engineering processes being initiated and evaluated by NASA's AMP project to optimize the effectiveness of the various research activities it performs. The efficiency of these processes depends on useful digital encodings of the latest engineering knowledge gained, and a metamodel defining relationships between the research activities and reference architectures. Bi-directional traceability between the reference architecture and test activities is what establishes the validation of the UAM system.

II. NASA AMP PROJECT OVERVIEW

The AMP project aims to expedite the advancement and incorporation of UAM concepts into the NAS. Its primary objective revolves around developing and showcasing vital functions while developing validated system architectures and requirements that benefit the broader UAM ecosystem. The project's objectives align closely with NASA's Aeronautics Research Mission Directorate (ARMD) strategic plan for advancing aviation research and innovation. By prioritizing safety, security, and scalability, the project seeks to contribute to NASA ARMD's primary goal of enabling a safe, efficient, and environmentally sustainable global aviation system. This strategic alignment aims to reinforce U.S. aeronautics leadership on a global scale while simultaneously serving the public good [3].

The project's system of interest is the UAM Midterm ecosystem as scoped by the UAM ConOps and other guiding documentation [4-6]. The research activities executed by the project will entail rigorous evaluation and validation of critical components of the system, elucidating detailed use cases, scenarios, architectures, and requirements.

The research activities that the AMP project executes should build upon the past many years of effort and collaboration among key stakeholders across the UAM ecosystem, which has led to the development and evaluation of a wide range of airspace services and automation prototypes tailored to various needs of UAM Midterm operations. Multiple efforts have considered the application of the Extensible Traffic Management concept to Vertical Take-Off and Landing use cases, while separately a variety of UAM vehicle platforms have been developed and evaluated. The architecture and

infrastructures that comprise a conceptual Info-Centric NAS are being proposed, while other research efforts have targeted focused and complex issues, such as the transition from Visual Meteorological Conditions to Instrument Meteorological Conditions and from crewed to uncrewed operations. Though much progress has been made to advance the safe, secure, and scalable integration of UAM operations into the NAS, research efforts have often been conducted by separate, but related projects with only partially aligned goals. As a result, inconsistent concepts and terms have been used to describe related aspects of research. Focused research has often been disconnected from higher-level requirements and program or directorate-level objectives, which can dilute the impact of specific research activities that have not been explicitly tied to broader goals. This uncoordinated approach, despite it being effective for research findings, has perpetuated some inefficiencies in the evolution of this work.

A holistic, integrative project management strategy, based on systems engineering methodology, is required to address these inefficiencies. As such, the AMP project aims to bring systematic coordination to connected technical research activities, and alignment with organizational goals. Through an approach along the lines of what is described in this paper, the AMP project aims not only to identify but also to systematically address the most relevant research and development needs necessary to safely accelerate UAM operations at scale.

The AMP project seeks to advance UAM operationalization within the current NAS through targeted exploration. Its objectives include crafting a comprehensive framework for safe and scalable UAM operations through collaboration with industry and governmental entities. Additionally, the project aims to develop and assess prototype systems with interoperable interfaces, robust infrastructure, and resilient security measures. These prototypes will evaluate the viability and extensibility of systems, emphasizing compatibility with Communication, Navigation, and Surveillance capabilities. Another key objective is to evaluate the operational suitability of UAM vehicles within the airspace integration paradigm, considering diverse vehicle types, airspace classifications, and community acceptance requirements. Lastly, the project commits to facilitating technology transfer by providing updated architectures for the NAS, essential tools for airspace integration, interoperability standards, and crucial information for assessing aircraft performance capabilities.

III. BI-DIRECTIONAL INTEGRATION PROCESS

Systems engineering is defined as a methodical, multidisciplinary approach for the design, realization, technical management, operation, and retirement of a system [7]. For research and development projects, implementing a systems engineering process provides value throughout the research and development lifecycle to ensure that the research meets goals, objectives, and stakeholder expectations. Given the complexity and interdependencies of the UAM system-of-systems, implementing a systems engineering process during the research phase is crucial to successful outcomes. A holistic approach is needed to synthesize the many research findings and to integrate the many interdependent elements of the UAM system. A knowledge base is needed to facilitate the flow of research learnings, which evolve and mature the system requirements.

Past efforts form the basis for the bi-directional integration process that will be described in the following paragraphs. To holistically manage complexity and interdependencies, the UAM Airspace Research Roadmap (ARR) was developed by NASA as an initial framework to help guide and manage the research being done to mature the UAM airspace system [3]. The UAM ARR organizes more than 300 requirements and assumptions across a wide swath of the UAM architecture as well as through multiple stages of UAM maturity. It provides a means to help guide research goals and develop test requirements and test architectures. The definitions from [3] lend themselves to define a schema to encode the requirements and associated information into System Modeling Language (SysML) [4], enabling the population of a digital engineering database. This has enabled NASA researchers to develop innovative front-end interfaces that have the potential to increase efficiency, enhance communication, and promote collaboration across the stakeholder community [8]. The enhanced traceability afforded by the digital engineering database facilitates a bi-directional process that both decomposes conceptual requirements into test requirements and synthesizes the research results back into the conceptual architecture, thereby updating the common knowledgebase for future testing.

These past efforts suggest an abstract process, shown in Fig. 1, that will be leveraged and refined by the AMP project to help establish its systems engineering framework and approach. The diagram, depicting a 'bi-directional integration' process, or simply referred to as the 'integration process' for brevity, illustrates how various teams collaborate to manage and integrate multiple research activities. Procedural steps and interactions, facilitated by systems engineering teams, guide a systematic process to develop a mature set of artifacts and deliverables that align with the overall goals and objectives of

the project. The process incorporates both traditional systems engineering principles and dynamic methodologies. These methodologies are iterative and adoptive in nature and prioritize the gradual development and validation of foundational components. By adopting incremental stages, the approach facilitates responsive planning and enables swift adjustments to evolving demands.

Continuous stakeholder engagement is integral to this approach, ensuring that throughout the research and development lifecycle, diverse perspectives inform and shape research expectations. The process remains receptive to insights and information from across the UAM Community, allowing for ongoing evolution and validation of architectural artifacts based on learnings and findings.

As a result, this process provides the structure and organization needed to manage complex research efforts in an integrative manner, while remaining responsive to both evolving expectations from the community and evolving research performed by the project.

A. *Body of Knowledge*

The body of knowledge that the project references for decisions about its research portfolio is digitized and encoded into an engineering product which includes a reference architecture for the UAM system. This reference architecture is informed by a library of test architectures that have been verified and validated against requirements that are traceable to and from the reference. In addition to the SysML modeling, the data produced by these test architectures, the source documentation that scopes and informs the UAM system, and other deliverables that the project may choose to include, all comprise a knowledge-based digital platform that can increase efficiency and build over time.

A great many advantages are gained through modeling and digitizing this information. A dashboard is developed so that a user such as a program manager, a junior systems engineer, or a subject matter expert can extract views and information that are relevant to their portion of the project.

B. *Identify Reference Artifacts (Step 1)*

The integration process begins with extracting relevant artifacts from the latest reference architecture, focused on aspects of the UAM system that the project plans to validate. These artifacts guide the project's research activities, and include concept documentation, high level research requirements, and views of the reference architecture. Stakeholder expectations are elicited through numerous stakeholder engagement activities, including workshops and tabletop discussions, that inform the architecture and help to prioritize research. While there are many drivers and constraints on the prioritization of a research

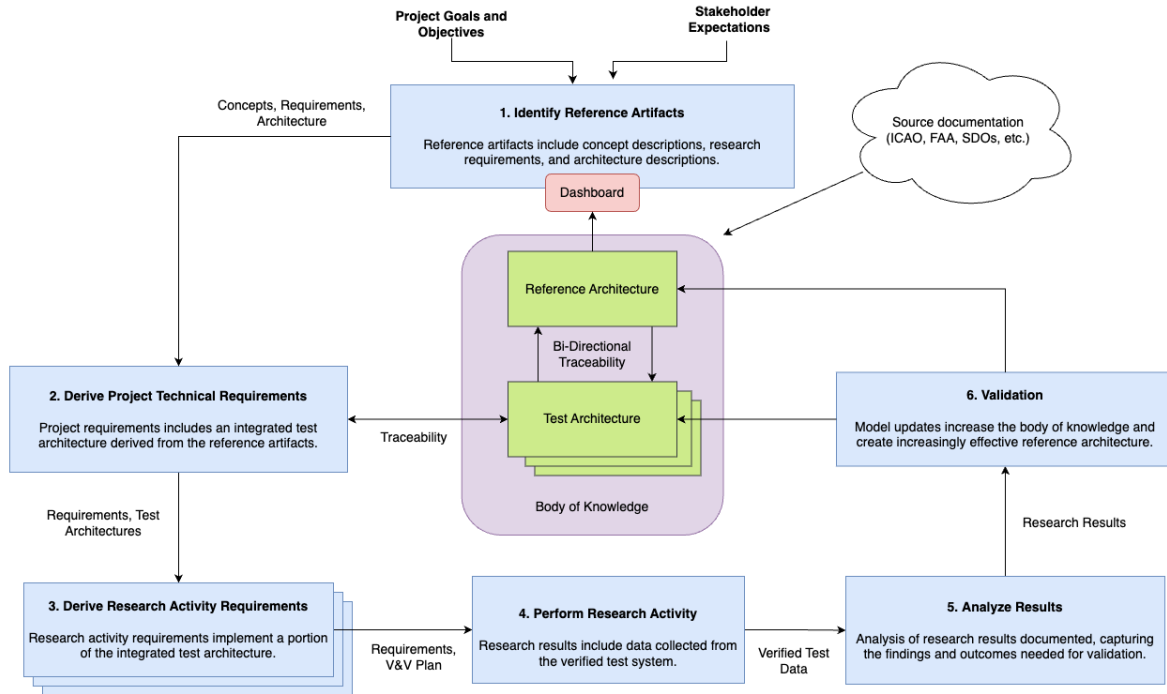


Figure1: Bi-Directional Integration Process

portfolio, the project goals and objectives are a primary driver for scoping the reference artifacts.

IV. BI-DIRECTIONAL INTEGRATION PROCESS IMPLEMENTATION

The integration process described in the previous section helps ensure traceability and coordinated validation across all technical research performed to achieve project objectives and meet stakeholder expectations. This process is expected to add structure and rigor to the planning, execution, and analysis of research project activities, and is in turn expected to lead to high impact and high quality project data and deliverables. A prototype of the digital engineering product has been developed and tested, based on years of prior project work [8].

The Strategic Conflict Management (SCM) simulation, dubbed “X4”, was conducted between July 2021 and June 2022 by NASA with the FAA and industry to evolve the Provider of Services for UAM that will be needed to ensure initial UAM operations can scale in the National Airspace System [9]. This activity broke ground on requirements around Demand-Capacity Balancing in a distributed and service-oriented architecture. That work helped to kickstart the integration process, and many of the reference artifacts that can be derived in Step 1 are traced to this work. A set of research requirements from the UAM ARR was identified and traced to the test

requirements that were developed and verified for the SCM simulation. The evaluation results are now being used to refine and validate the research requirements (Steps 5 and 6). This work has helped to establish a baseline for the application of the bi-directional integration process [10, 11].

The AMP project is now leveraging a follow-on research activity referred to as the Operational Integration Assessment (OIA), which began in January 2023 as a collaboration between NASA and the FAA Technical Center. The OIA is described as an evaluation that explores concepts, procedures, and prototype technologies to enable the safe integration and evolution of UAM operations in the NAS [12]. One of its key objectives is to assess airspace interoperability challenges associated with Midterm UAM operations in the NAS. At the time of writing, the research activity has not yet concluded.

The OIA has implemented the “front-end” process to exercise Steps 1 and 2 in the integration process shown in Fig. 1. The in-scope research requirements were initially identified from the UAM ARR (Step 1), and these Reference Artifacts were used to derive an initial set of test requirements (Step 2). The project is currently iterating between Steps 3 and 4 in a structured manner, and the expectation is that the test requirements will be verified on schedule, and the simulation results will produce reliable validation data for Steps 5 and 6.

This will lead to an update to the existing baseline models of both the reference architecture and the test architecture.

The bi-directional traceability of the test results from these two activities to the higher-level reference architecture artifacts is expected to facilitate a contribution towards a comprehensive understanding of the UAM system and demonstrate how this process can lead to increase efficiencies in how the project achieves its strategic goals and objectives. It is hoped that the results of this approach will illuminate an efficient path to developing a reference architecture for UAM, which is validated through requirements and experimental data, and is able to mature through many years of research.

V. CONCLUSIONS AND NEXT STEPS

In this paper, an engineering framework for UAM research has been explored, with a specific focus on optimizing NASA's AMP project. The challenges presented by the UAM ConOps demand a systematic and rigorous approach, addressing technological, regulatory, and stakeholder engagement aspects. The pivotal role of systems engineering processes is not in any doubt, and the authors believe that a process aligned with the ideas described by this paper in managing technical efforts and validating reference architectures would form a basis for developing the UAM reference architectures and recommended requirements.

Through the application of robust verification and validation methodologies, coupled with a systematic integration process, our proposed bi-directional process supports UAM system efficiency, safety, and reliability as it evolves through different phases. The harmonization of interactions between UAM and traditional air traffic elements within this systematic framework not only enhances the overall efficiency of the integration of UAM operations into the NAS but also fosters trust among stakeholders and the public.

In essence, this paper advocates for an optimized process for the validation of reference architectures, offering valuable insights into ongoing efforts to seamlessly integrate UAM operations within the NAS. As AMP progresses through its developmental phases, this systematic validation will be instrumental towards achieving the envisioned revolution in metropolitan transportation that the UAM system is envisioned to achieve.

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