Overview of NASA's Air Traffic Management - eXploration (ATM-X) Project

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Projected increases in new vehicle types, new missions, and the continual growth in traditional (e.g., airlines, general aviation) aviation will require changes to the current air traffic system, particularly to accommodate the desire of operators to be more involved in air traffic decisions. To address these challenges, the National Airspace System needs to undergo a transformation to a more scalable, flexible, user-focused system that addresses safety and security requirements and resiliency for current and new users. A system designed to integrate modular software services, provided by users, third parties and government for air traffic management functions, will be scalable and more easily allow modernization and for collaboration between users and service providers. ATM-X is responding to NASA's pivot towards integrating projected new, diverse entrants into the NAS, while also leveraging NASA's prior ATM achievements that continue to improve traditional airspace operations. This project is a two-phased approach to conduct research and focused evaluations to assess the feasibility of a service-based approach and to identify critical design considerations to enable airspace access for new entrants, integrated with current traditional operations. Phase 1 research will be conducted to determine what is needed to reach the ATM-X goals based on specific use-cases to enable large-scale, passenger-carrying Urban Air Mobility operations in a metroplex environment, and also to improve traditional operations in the Northeast Region leveraging mature NASA technologies. Some of these evaluations will be conducted in simulations and field activities. Phase 2 will build upon Phase 1 towards more defined, focused research and field demonstrations in real-world environments to integrate multiple elements of a scalable, service-based ATM-X concept.

I. Introduction

There is a need to integrate the proposed increase of new entrants and their diverse missions into the National Airspace System (NAS), manage the corresponding expected increase in traditional operations, and enable enhanced collaboration between users and the Federal Aviation Administration (FAA)[1]. Some new entrant operations (e.g., large Unmanned Aerial Systems (UAS) and commercial space) have been active in the airspace for several years but more recently there is a significant movement to enable the large scale use of small electric Vertical Take-Off and Landing aircraft (eVTOL) for rapid passenger movement in an urban environment[2]. The US airspace is already managing, on average, approximately 26,000 scheduled traditional commercial operations per day[3] and their delays cost the US approximately $26.6B in 2017.[4] The inclusion of new entrant operations will likely increase costs due to delays as more users access the airspace. To address these issues, NASA's Aeronautics Research Mission Directorate (ARMD) has defined a "pivot" to address these transportation challenges and recently approved the Air Traffic Management – eXploration (ATM-X) project to achieve the goals of equitable access to the airspace for all users, vehicles, and missions while also improving current operations.

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II. Project Description

ATM-X is one of four projects in NASA's Airspace Operations and Safety Program (AOSP) within ARMD. The ATM-X technical goals, to be realized over two phases, are to explore alternate methods to incorporate new technologies into the NAS using a software "service-oriented paradigm" based on Unmanned Aerial System (UAS) Traffic Management (UTM) principles.[5] UTM principles allow for system and management flexibility whenever possible and imposing structure when required and includes seamless airspace access for all users, scalability for new demand and users, collaboration through digital information exchange, resilience to disruptions and uncertainty, and increased availability and use of services. Individual software services allow greater flexibility for airspace management support and potential for faster modernization, as the new algorithms are not forced to be intertwined with larger, centralized software systems. Breaking out algorithms, such as airborne weather routing, into a modular software service allows the algorithms to be developed and updated by third-parties with less modification to the larger system using a software service-oriented paradigm. This service-oriented paradigm is currently being developed and used by the UTM project to manage small UAS operations; an example of a field-tested capability for ATM-X research and a model for managing flight vehicles in field demonstrations.

With a large set of challenges to enable access by the new entrant market, as well as to continue to improve traditional operations, Phase 1 of ATM-X (FY18-FY20) will focus on two use-cases supported by four sub-projects. The "Urban Air Mobility (UAM) Operations" use-case will address passenger-carrying eVTOL urban operations by performing research to understand how to develop verifiably-safe and secure airspace and vertiport management technologies to enable missions at a user-specified tempo in low altitude, controlled airspace. The second use-case, "Northeast Region Operations", will focus on improved collaboration, dynamic airspace access and planning, and integrated scheduling in the US Northeast Region for traditional NAS users.

The following lists the objectives of the four ATM-X sub-projects that will address those two use-cases; the sub-projects are described in more detail later in the document:

Initial Urban Air Mobility Operations Integration (UAM sub-project)	Conduct research and develop technologies for airspace and vertiport management towards enabling UAM missions at user-specified tempo
Increasing Diverse Operations (IDO)	Evaluate digitally-negotiated trajectory-based capabilities research that includes leveraging NASA's Airspace Technology Demonstration technologies in the Northeast Region with improved user collaboration to enable traditional operators' desire for flexibility and predictability
Integrated Demand Management (IDM)	Develop Integrated Demand Management concept using coordinated traffic flow management capabilities to better manage demand/capacity imbalance during adverse weather
Testbed	Develop a capability to simply and easily connect high-fidelity simulations to support NASA and community research

Table 1 ATM-X Subproject Descriptions

During Phase 1 research, the project will develop concepts and prototype technologies for improved data exchange and digital negotiation to enable traditional operators' desire for improved collaboration, throughput, flexibility and predictability and be extensible to allow new entrants' desire to access and operate in controlled airspace. The guiding principles of Phase 1 are "Explore, Build and Learn" to address these activities. There will be research in both UAM and traditional operations with appropriate prototype development and evaluations to learn what research and prototypes will be carried forward into Phase 2. To leverage the research of other projects, ATM-X will collaborate with NASA's AOSP System Wide Safety (SWS) Project to ensure the development of safe, secure, and efficient operations in both use-cases.

The second Phase for ATM-X (approximately from FY21-FY26) will build towards longer-term goals, and address challenges and activities informed by Phase 1 results and evaluations. Phase 2 will mature the technologies and the service-oriented ATM system for a possible field demonstration of capabilities for routine access for a wide range of vehicles and missions.

The relationship between the ATM-X sub-projects is illustrated in **Error! Reference source not found.**. Passenger carrying UAM operations are addressed in the Initial Urban Air Mobility Operations Integration sub-project and traditional operations in the Northeast Region are addressed by the Increasing Diverse Operations and Integrated Demand Management sub-projects. The arrows in this figure show representative work areas of these sub-projects that will be integrated and tested utilizing the Testbed. The Testbed will provide a realistic and flexible environment, allowing advanced concepts and the study of interaction across components, and will be critical in the development of a service-oriented ATM architecture.

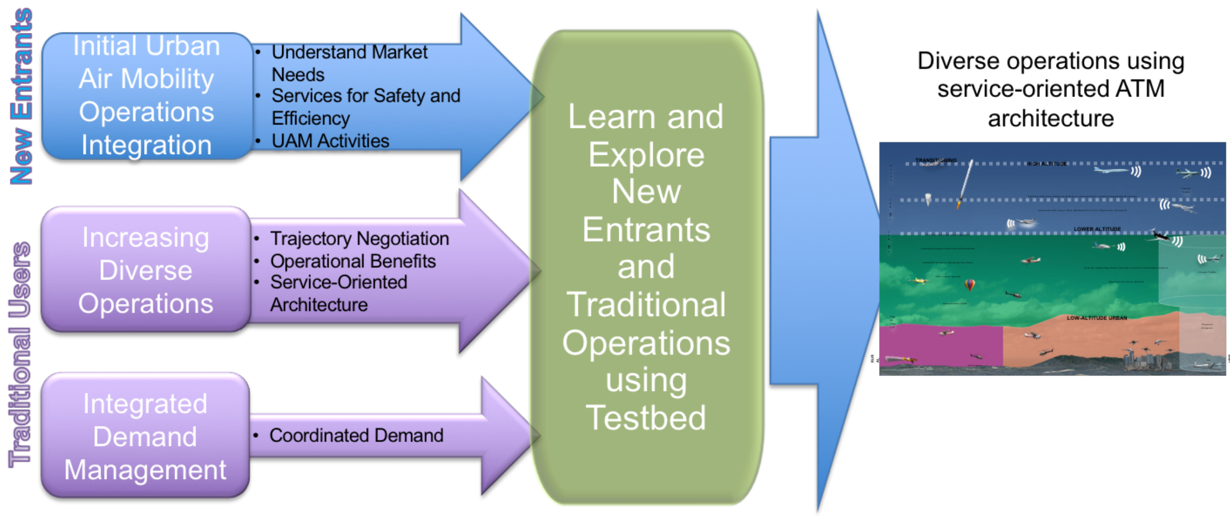

Fig. 1 Relationship of the Four Sub-Projects in Phase 1.

III. Development Approach

The ATM-X project will conduct research towards the service-oriented paradigm by developing prototypes and focus on research capabilities that will significantly improve the safety, security, efficiency, and reliability of the future NAS. To address the safety aspects of the technologies, ATM-X will leverage the work in other AOSP activities including verification and validation of software systems in SWS and NASA's cybersecurity efforts.

In addition to the research focus of Phase 1, ATM-X will develop prototype services and a reference implementation of a service-oriented architecture design for technical evaluations that leverages recent work by the UTM project. Additionally, there will be opportunities to identify technologies for more mature development in Phase 2 and evaluate technologies collaboratively in this phase. To guide the development, the key principles of ATM-X are presented below, derived from the UTM principles described earlier. These ATM-X principles are traceable in the research and resultant technologies.

- Seamless access to the airspace for both on-demand and scheduled operations;
- Scalability to match future air traffic demand where and when it occurs;
- System and management flexibility whenever possible and imposing structure when required;
- Collaboration between all participants through secure, integrated information sharing;
- Resilience to uncertainty, degradation and disruptions; and
- Availability of user and third-party services.

The two use-cases are:

- UAM Operations: An extension to current passenger carrying helicopter operations, but with a higher tempo and a denser network, using radically different vehicles being proposed by a wide range of new and existing aviation companies. This use-case is part of the larger UAM concept. NASA defines UAM as a safe and efficient system for air passenger and cargo transportation within an urban area. It is inclusive of small package delivery and other urban UAS services and supports a mix of onboard/ground-piloted and increasingly autonomous operations[6]. These passenger carrying vehicles would conduct high-frequency, short-distance flights between fixed locations, through dense urban centers and can also provide short-distance movement of goods. Most vehicles will be electrically powered and carry two to six passengers, or equivalent cargo, on flights of 10-70 miles. A mature vision of these operations will generally be on-demand with limited planning and may not necessarily follow pre-approved routes. However, near-term implementations of these operations may employ schedules using fixed routes and some routine short-cuts.

- Northeast Region Operations: Research focused initially on enhancing the efficiency and robustness of traditional airspace operations in the complex, highly-controlled airspace in the northeast of the U.S. For years, the FAA and NASA have focused on developing, testing, and deploying new capabilities in less complex operational airspaces to enhance efficiency with reduced risk. However, these new capabilities have not migrated to this more complex area due to a mix of technological and procedural barriers. This research will address setting the stage for seamlessly and equitably integrating new vehicle types (increasingly diverse operations), such as large UAS, autonomous freighters, supersonic aircraft, and UAM into these operations. Through the RTCA NextGen Advisory Committee (NAC)[7], industry has identified this region as a critical choke-point. The ATM-X effort supports FAA technology development activities and priorities to improve traditional operations in the same geographic area.[8,9]

While the two use cases focus on different types of airspace users, both use cases will ultimately address setting the stage for seamlessly and equitably integrating newer non-traditional vehicle types (increasingly diverse operations), such as large UAS, autonomous freighters, and UAM vehicles into these operations.

IV. Sub-project Descriptions

Figure 1 depicted the four sub-projects in ATM-X. The UAM sub-project focuses on the emergent users for a representative future operation, and will conduct research, develop and evaluate technologies, and explore architectures for airspace and vertiport management to enable safe UAM missions at a user-specified tempo. The first use case will serve as a concept focus for this research.

IDM and IDO focuses on the needs of traditional airspace users along the lines of the second use case. IDM will develop a concept that utilizes state-of-the-art capacity, demand, and weather forecasts in a coordinated fashion across different traffic flow management capabilities to better manage demand/capacity imbalance under adverse weather conditions. IDO will build on IDM progress, along with evaluating how NASA's Airspace Technology Demonstration (ATD) capabilities and others can be applied, to evaluate digital negotiation using trajectory-based technologies in the Northeast Region. The research will investigate improved user collaboration to enable traditional operators' desire for flexibility and predictability. IDO will explore how to transition the existing system to a future service-based architecture.

Testbed will develop a capability to simply and easily connect high-fidelity human-in-the-loop (HITL) and automation-in-the-loop simulations and tests. Testbed will support the evaluation of trajectory-based automation and electronic negotiation, collaborative decision making, and connected service-based technologies. Testbed will also provide connectivity between operational FAA, conceptual NASA and other proposed systems.

A. Initial Urban Air Mobility Operations Sub-Project

NASA has conducted research addressing a wide range of air traffic management challenges for traditional aircraft since the 1980s. The concepts, technologies, and procedures developed through these efforts have benefited the flying public and the aviation community in the form of more efficient and predictable operations. Recently, NASA has increased focus on developing technologies and standards for new types of aircraft and missions being pursued by the broader aviation community. One notable example is NASA's ongoing effort as part of RTCA Special Committee-228 to develop minimum operational performance standards (MOPS) for detect and avoid (DAA) capabilities for large UAS. As part of this endeavor, NASA helped develop standards for separation, alerting, guidance, surveillance, and displays for DAA systems that the FAA will use to develop technical standards and regulations. NASA has also developed and demonstrated UTM capabilities for low-altitude small UAS (sUAS) operations.

More recently, there has been an increased interest in UAM. Significant industry investments have been made toward developing an ecosystem for UAM that includes manufacturers of eVTOL aircraft and builders of vertiports and other infrastructure on the ground. To conduct UAM operations in a safe, secure, and efficient way in the presence of existing airspace users, tools and methods for airspace integration are needed. Many of the technologies and procedures that have been developed to integrate new entrants, such as large and small UAS into the airspace with existing traditional aviation could be applicable to UAM operations and will be leveraged in this sub-project.

The Initial UAM Operations Integration sub-project is focused on the low altitude (e.g., below about 2,000 ft) airspace integration aspect of UAM, both to enable early entrants in the airspace and to identify, develop, and evaluate the services, procedures, and tools necessary to support high-demand, mature operations. This sub-project will collaborate closely with other NASA projects to address safety and security issues. Other aspects of UAM, such as vehicle development, battery technology development, ground infrastructure construction, and legal considerations are also important but will be addressed by other NASA projects and external organizations. This sub-project will work with an ARMD level UAM coordination team and support their activities with partners.

Phase 1 research will focus on airspace management and safe, secure, and efficient operations into, out of, and within an urban area. The project will support evaluations and field demonstrations of a wide range of technologies, requirements, and procedures, including but not limited to:

- Safe mission planning and operations
- Noise constraint management
- Secure data exchange system architecture
- Communications, navigation, and surveillance
- Separation assurance
- Dynamic scheduling, sequencing, and spacing
- Congestion management
- Interoperability with other vehicles - large UAS, sUAS, and traditional aircraft operations

In addition, a collaborative concept of operations in which the roles, responsibilities, and interactions of pilots, vehicle automation systems, air traffic control, existing airspace users, safety and security systems, and airspace management automation systems will also be defined. The concept of operations serves as a framework for NASA research and development efforts, lab simulations, and live flight demonstrations planned in this first phase. It also provides a benchmark that the UAM community can use to determine technology development priorities, requirements for infrastructure improvements, and achievable airspace capacities. Table 1 shows some of the UAM airspace management technologies that will be evaluated with partners in Phase 1. FY2018 will provide an initial capability that will be matured through evaluations in subsequent years.

FY2018	Initial weather and obstacle aware separation, scheduling, sequencing, and spacing algorithms
FY2019	Safe mission planning and operations, weather and obstacle-aware software services and operational procedures
FY2020	Separation and scheduling, sequencing, and spacing software services

Table 1 Representative UAM activities for Fiscal Year (FY) 2018 - 2020

B. Increasing Diverse Operations (IDO) Sub-Project

NASA has nearly three decades of experience working with the FAA and airspace users in conducting research, technologies and concepts to improve traditional user operations. This sub-project leverages prior developments by NASA and the FAA to continue to push the state-of-the-art in airspace management. To achieve long-term goals, IDO will define an overarching concept/architecture of a service-based system and develop supporting service technologies to enable safe and secure increasingly diverse operations in dense, controlled airspace. These diverse operations will span a range of vehicle performance and design, mission type, and equipage levels.

New entrants (such as supersonic, space launch and re-entry, high-altitude long endurance, UAS, and UAM vehicles) are expected to introduce the greatest diversity to operations as their demand for entering controlled airspace increases. However, it is just as important to ensure that the future airspace systems continue to accommodate traditional users while providing appropriate levels of safety and security. During Phase 1, IDO will define a service-based airspace system that improves efficiency and predictability for traditional users but also prepares the system for increased diversity from new entrants. IDO will evaluate the applicability of NASA's ATD capabilities and others that are built on principles of information sharing and time-based scheduling. These capabilities can be integrated or coordinated to evaluate improvements to gate-to-gate operations incorporating user priorities of traditional airspace users. NASA's ATD project encompasses a collection of critical technology development and demonstration activities that addresses near-term, domain trajectory-based operations and provides benefits to traditional air transportation system stakeholders.[10]

IDO will develop a concept of operations and accompanying system architecture that evaluates the integration of ATD and other capabilities for a future service-oriented airspace system. This concept of operations will be evaluated in a HITL simulation using Northeast Region scenarios. The scenarios will be developed with FAA and airline partners where recent discussions have included dynamic scheduling of metroplex operations in the New York area and integration of arrival scheduling with pre-departure scheduling and en-route routing.

This sub-project seeks to improve operations by exploring the enhancement of software airspace management services described by the concept of operations. For example, existing time-based scheduling services may be enhanced to subscribe to a repository of flight trajectories and constraints to increase coordination. Controller tools may be enhanced to provide better awareness of FAA and user coordinated strategic flight trajectories and ensure that control actions dynamically respond to and reinforce, rather than compromise, the strategic plan. A digital negotiation service may be developed to standardize and speed up routine trajectory negotiations currently performed manually and often in an inconsistent manner.

Table 2 shows representative IDO activities and a series of evaluations based on a partner informed Northeast Region scenario. The culminating event is a collaborative high-fidelity simulation utilizing the Testbed.

FY2018	Northeast Region simulation scenario identification and definition
FY2019	Development of prototype services and procedures for evaluation
FY2020	High fidelity simulations in Testbed with external partners to evaluate services

Table 2 Representative IDO activities for FY (Fiscal Year) 2018 - 2020

C. Integrated Demand Management (IDM) Sub-Project

IDM was previously a subproject in the recently-completed Shadow Mode Assessment using Realistic Technologies (SMART-NAS) for Safe Trajectory Based Operations[11] project and continues in ATM-X. This sub-project explores operational integration of near- to mid-term NextGen traffic management capabilities to improve NAS performance when the capacity of critical airspace resources is inadequate to meet demand using current systems.

Because of the interactions between multiple flights across multiple airspace constraints, successful trajectory-based operations involve coordinated traffic flow management of constraints, as well as trajectories, to provide a continuous, robust solution for a collection of flights. However, in today's air traffic operations, a number of different, uncoordinated and locally-focused systems are involved in managing these interactions, resulting in inefficiencies in flight trajectories as well as inadequate demand / capacity balance.

In order to alleviate this problem in the near- to mid-term NextGen timeframe, IDM leverages two main traffic flow management capabilities in the National Airspace System, namely the FAA's Traffic Flow Management System (TFMS) and Time Based Flow Management (TBFM). In the IDM concept, TFMS tools are used to pre-condition traffic into the more tactical TBFM system, enabling TBFM to better manage delivery to the capacity-constrained destination. IDM is focused on coordinating the management strategies employed by the TFMS. TFMS strategically manages aircraft at the origin airports when the demand is expected to exceed capacity at their destination. TBFM tactically manages demand of the actual flow of aircraft near the destination airport. Currently, TFMS and TBFM work largely independently causing additional delay and inefficiencies in operations.

The IDM concept also provides a framework to take advantage of many of the past and current NASA ATM research, which developed powerful, integrated operations / tools for managing trajectory constraints, leveraging existing systems, and adding new automation tools / methods where needed. These solutions are complementary, with each focused on a specific portion of the complete flight trajectory. They represent crucial building blocks towards a gate-to-gate management solution. IDM provides an integrated solution across the domains to enable improved system performance.

The IDM team conducted HITL evaluations of its concepts focused on arrivals to the Newark Liberty Airport (EWR)[12]. Results show the concept achieved the target throughput while minimizing the expected cost associated with overall delays in arrival traffic. Future work based on these results will evaluate the concept for the LaGuardia (LGA) airport with combined EWR and LGA operations and multiple constraints. These evaluations will comprise a combination of fast-time and HITL simulations. As a result of this research and testing, a description of the IDM concept and procedures plus tool specifications will be delivered to the FAA.

Table 3 shows representative IDM activities. This shows a series of increasingly complex simulations to evaluate the evolving IDM concept for multiple airports and constraints.

FY2018	Initial report on IDM concept, procedures and tools requirements based on HITL results and stakeholders' feedback
FY2019	Conduct HITL experiment to evaluate IDM concept in convective weather for two or more airports
FY2020	Conduct HITL to evaluate final IDM concept for multiple constraints / airports

Table 3 Representative IDM activities for FY (Fiscal Year) 2018 - 2020

D. Testbed Sub-Project

The Testbed was formerly known as the SMART-NAS Testbed in the SMART-NAS for Safe Trajectory Based Operations Project.[13] Testbed will be capable of integrating FAA operational systems with prototype technologies or services and allow new concepts to be evaluated in a realistic environment. The Testbed's role is as an accelerator of concepts and technology development, with a use-case-driven development approach to support NASA research as well as collaborations.

The Testbed development was motivated by a survey of simulation capabilities that highlighted significant needs and limitations of existing in simulation systems. These limitations include:

- Tools and systems are rarely integrated across different ATM domains

- NASA, the FAA and ATM Industry lack an integrated development, test, and evaluation platform for enabling collaboration across disparate government and industry-developed ATM systems
- Simulation preparation and execution is time-consuming, resource intensive, error-prone and limited by the capabilities of individual facilities
- Simulations are traditionally comprised of individual brick-and-mortar labs or co-located facilities
- Live flight assets and enterprise level hardware and software are not accessible for many efforts seeking to advance ATM technology
- Many future concepts are untestable with current systems as documented in the National Research Council Autonomy Report, 2014[14]

During Phase 1, the Testbed and other NASA teams will develop core capabilities, such as:

- Back-end, Big-Data analytics tools to generate realistic simulation scenarios using NASA's ATM Sherlock data warehouse[15]
- Cloud technologies to securely, reliably, and cost-effectively connect distributed, NASA and non-NASA, real and simulated NAS infrastructure and flight assets
- Low-maintenance mechanisms to integrate a wide array of simulation assets without customized one-to-one solutions
- Ability to create an on-demand, shadow-mode NAS, high-fidelity evaluation from live traffic, weather data, and airspace information
- Ability to evaluate collaborative flight management concepts and technologies over an entire flight profile
- In-time system-wide safety analytics and key performance indicators to visualize simulation and operational performance
- Ability to assess the impact of new vehicle designs on NAS operations

The Testbed core capabilities will be developed through a series of two software builds. Build 1 follows the prototype development begun under the SMART-NAS project and focuses on the development of the primary scenario building, cloud-based connectivity and component communications for use by internal NASA stakeholders. Build 2 matures these technologies and develops the required interfaces to connect external stakeholders, thus supporting the Testbed objectives. Towards the end of Phase 1, ATM-X will provide a plan that includes community involvement in both the development, support and distribution of Testbed. Representative Phase 1 work is shown in Table 4.

FY2018	Establish connections to NASA ATM tools and initial connections to partner systems
FY2019	Support NASA and partner activities and system evaluations using a service-oriented system
FY2020	Expanded activities and system evaluations using improved connectivity, scalability, and usability to external stakeholder systems

Table 4 Representative Testbed activities for FY (Fiscal Year) 2018 - 2020

V. Summary

The ATM-X project is a two phased project to integrate new, diverse entrants into the NAS, while also leveraging NASA's prior ATM achievements that continue to improve traditional airspace operations. In the first phase, ATM-X will collaboratively develop ATM services and evaluate them in HITL simulations and field activities to inform the work for Phase 2. The evaluations are based on and in support of two partner defined use-cases for UAM and traditional Northeast Region operations and will adhere to principles of seamless access, and scalable, flexible, resilient, available, and collaborative operations. Phase 2 will further improve upon the relevant research and services identified and developed in Phase 1 for a possible demonstration of diverse operations.

To accomplish Phase 1, ATM-X is structured with four sub-projects: UAM sub-project, IDM, IDO and Testbed. The UAM sub-project will conduct research, develop and evaluate technologies, and explore architectures for airspace and vertiport management to enable safe UAM missions at user-specified tempo.

IDM and IDO initially focuses on the needs of traditional airspace users. IDM will develop a concept that utilizes state-of-the-art capacity, demand, and weather forecasts in a coordinated fashion across different traffic flow management capabilities to better manage demand/capacity imbalance under adverse weather conditions. IDO will build on IDM progress, along with evaluating how NASA's ATD capabilities and others can be applied, to evaluate digital negotiation using trajectory-based capabilities in the Northeast Region with improved user collaboration to enable operators' desire for flexibility and predictability.

Testbed will continue developing a capability to simply and easily connect high-fidelity HITL and automation-in-the-loop simulations, supporting the evaluation of electronic trajectory negotiation, collaborative decision making, and connected trajectory-based technologies. Testbed will also provide connectivity between operational FAA, conceptual NASA and other proposed systems.

References

[1] Eck, J., "The Future of the NAS." FAA, 2016
[2] Mueller, E., Kopardekar, P., and Goodrich, K., "Enabling Airspace Integration for High-Density On-Demand Mobility Operations," 17th AIAA Aviation Technology, Integration, and Operations Conference, 5-9 June, 2017.
[3] https://www.faa.gov/air_traffic/by_the_numbers/ [cited 14 April 2018]
[4] Airlines for America, "U.S. Airline Industry Review: Allocating Capital to Benefit Customers, Employees and Investors," April, 2018
[5] Kopardekar, P., et al., "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations," 16th AIAA Aviation Technology, Integration, and Operations Conference, 13 -17th, June, 2016
[6] https://www.nasa.gov/aero/nasa-embraces-urban-air-mobility [cited 14 April 2018]
[7] RTCA, "Priorities for Improving Operational Performance in the Northeast Corridor through CY2021," NextGen Advisory Committee, March, 2018
[8] Whitley, P., Bristol, T., and Bahrami, A., "NextGen Proirities – Joint Implementation Plan Update including the Northeast Corridor," FAA, October, 2017
[9] FAA, "Initial TBO and NEC," Presentation to NEC NIWG, December, 2017
[10] https://www.nasa.gov/aeroresearch/programs/atd/project-description [cited 25 Apr 2018]
[11] https://www.nasa.gov/aeroresearch/programs/aosp/smart-nas-project-description [cited 14 April 2018]
[12] Yoo, H., et al., "Integrated Demand Management: Minimizing Unanticipated Excessive Departure Delay while Ensuring Fairness from a Traffic Management Initiative," 17th AIAA Aviation Technology, Integration, and Operations Conference, 5-9 June 2017
[13] Palopo, K., et al., "Shadow Mode Assessment using Realistic Technologies for the National Airspace System (SMART NAS) Test Bed Development," 15th AIAA Aviation Technology, Integration, and Operations Conference, 22-26 June 2015
[14] Committee on Autonomy Research for Civil Aviation, "Autonomy Research For Civil Aviation: Toward A New Era Of Flight," National Academies Press, 2014
[15] Eshow, M. M., Lui, M., and Ranjan, S., "Architecture and Capabilities of a Data Warehouse for ATM Research," IEEE/AIAA 33rd Digital Avionics System Conference, Colorado Springs, CO., 5-9 October 2014