Multi-Vehicle (m:N) Operations in the NAS – NASA’s Research Plans

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The Advanced Air Mobility movement is occurring across the world with goals of enabling, affordable, efficient, accessible, and safe air transportation at a much larger scale than today’s operations, largely enabled by electrification and automation. Transformative and disruptive innovations are emerging that will support an ecosystem designed to transport goods and people to locations not traditionally served by air transportation. To realize the full vision of AAM, technology will be needed to allow a few operators to operate many vehicles (m:N). The benefits of m:N operations are described, along with the current state-of-the-art, barriers, need, and NASA’s plans to address some of the barriers, including a Multi-Vehicle (m:N) Working Group with goals of producing a community-developed operational approval roadmap for various domains.

I. Introduction

The Advanced Air Mobility movement is occurring across the world with goals of enabling affordable, efficient, accessible, and safe air transportation at a much larger scale than today’s operations [1, 2], largely enabled by electrification and automation. Transformative and disruptive innovations are emerging that will support an ecosystem designed to transport people and goods to locations not traditionally served by current air transportation. Emerging markets include air taxi, package delivery, commercial cargo, and public good applications, such as security patrols, fire response, and delivery of life-saving medicines during emergencies [3].

> “NASA’s vision for Advanced Air Mobility (AAM) Mission is to help emerging aviation markets to safely develop an air transportation system that moves people and cargo between places previously not served or underserved by aviation – local, regional, intraregional, urban – using revolutionary new aircraft that are only just now becoming possible. AAM includes NASA’s work on Urban Air Mobility, and will provide substantial benefit to U.S. industry and the public” [4].

The AAM ecosystem is expected to advance from current state-of-the-art operations to a ubiquitous capability, similar to automobiles today. Significant advancements expected during this evolution are categorized in the Urban Air Mobility (UAM) Maturity Levels, which attempt to identify key vehicle, airspace, and community integration

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challenges that will need to be met to realize the full potential of the UAM vision[‡]. Fully-automated or autonomous aircraft will have no need for a pilot or operator on-board or on the ground, improving vehicle productivity and economics. The likely scenario is that a remote supervisor will oversee the operation of multiple aircraft with strategic fleet management goals. Multi-vehicle operations will likely be realized in the UAM Maturity Level 5 (UML-5) time frame, when the "fully-automated" aircraft transformation is expected to be complete [5].

This paper builds the case for further research on multi-vehicle (m:N)[§] operations in the National Airspace (NAS) and contains a description of what is meant by multi-vehicle operations, why multi-vehicle operations is being pursued in industry, current state-of-the-art, and barriers to wide-spread implementation are described. This is followed by a summary of the workplans associated with a NASA Aeronautics Mission Directorate (ARMD) Technical Challenge that resides in the Revolutionary Aviation Mobility Sub-Project in the Transformational Tools and Technologies Project.

II. Multi-Vehicle (m:N) Operations Overview

Remotely piloted aircraft systems (RPAS) are becoming more and more prevalent in aerospace operations. This is true in a number of diverse domains: electrified vertical take-off and landing (eVTOL) air taxis, medical product delivery, infrastructure inspection, high altitude pseudo-satellites, search and rescue, autonomous cargo delivery, and several other applications. One aspect that all of these shares in common is the need for scalability to be viable and continue to grow. The Association of Uncrewed Vehicle Systems International (AUVSI)'s most recent economic report projects an economic impact of $82 billion by 2025 with more than 100,000 jobs created [6].

For many of these domains, to reach these levels and have the scalability needed, they will require a remote pilot to control multiple aircraft (1:N) or multiple pilots controlling multiple aircraft (m:N). In the latter case, the remote pilot in command (RPIC) may hand-off vehicles to other RPICs based on operational or contingency management issues. For example, a particular RPAS service provider might have RPICs for different phases of flight – en route/mission vs. take-off and recovery. This is analogous to DoD operations. Or an RPIC's workload might get too high due to contingencies (Temporary Flight Restrictions, aircraft failure) and would need to reduce the workload by handing off assets to another RPIC team member.

This is a new control paradigm that raises multiple issues in various areas. There are many issues that need to be addressed before m:N can become a routine operation. These include regulatory, technical, safety, community acceptance, and human factors. Human factors issues include displays, pilot workload, pilot situation awareness, just to name a few.

At this time, there are not clear requirements and standards that must be met for certification and operational approval and the development of those requires research. NASA plans to lead the community through development of a roadmap that defines the path to m:N operational approval with respect to different domains.

III. Potential Benefits of Employing m:N Operations

AAM's viability as a market largely depends on streamlining the certification process for new vehicle types, advances in battery technology, vehicle efficiency derived from new designs, vehicle performance and reliability, scalable air traffic control, operating and manufacturing costs and affordability, safety, noise, low emissions, infrastructure, and pilot availability or reduced training time [7]. Significant cost savings can be derived from reducing operating and pilot training and salary costs. In the nearer term, simplified vehicle operations are being pursued to augment the pilot, which could reduce pilot skill requirements, and, therefore, training time. This is likely not enough of an operations cost reduction to completely close the business case for AAM.

One solution that has gained the interest of many AAM manufacturers and operators due to its ability to produce a profitable, viable market is to move the pilot out of the vehicle and replace them with a remote supervisor or fleet manager that manages several aircraft at one time. This mode of operating, called multi-vehicle operations or m:N, is projected to result in cost savings for the customer and operator and enables the system to scale more easily in an environment where there is shortage of properly trained pilots. The cost savings and scalability benefits will ultimately make AAM more accessible to the general public. An argument can also be made that m:N operations enables the

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[‡] AAM includes rural and urban applications, such as cargo transport, passenger carrying taxi and regional air transportation, small UAS package delivery, etc. Urban Air Mobility (UAM) is a subset of Advanced Air Mobility (AAM), which exhibits particularly challenging characteristics with a high benefit.

[§] m represents the number of ground operators or managers and N represents the number of aircraft. The ratio, m:N, is meant to represent that ratio of ground operators to aircraft. For example, 2 operators could manage 10 aircraft, represented by the ratio, 2:10.

deployment of several to many aircraft for public good missions, such as wild fire fighting, without a standing army of pilots either on the vehicle or on the ground and allows operations to occur more seamlessly and coordinated.

The below sub-sections go into more detail about the scalability benefits, the business case, and potential benefits for autonomous systems certification and specialization of human roles.

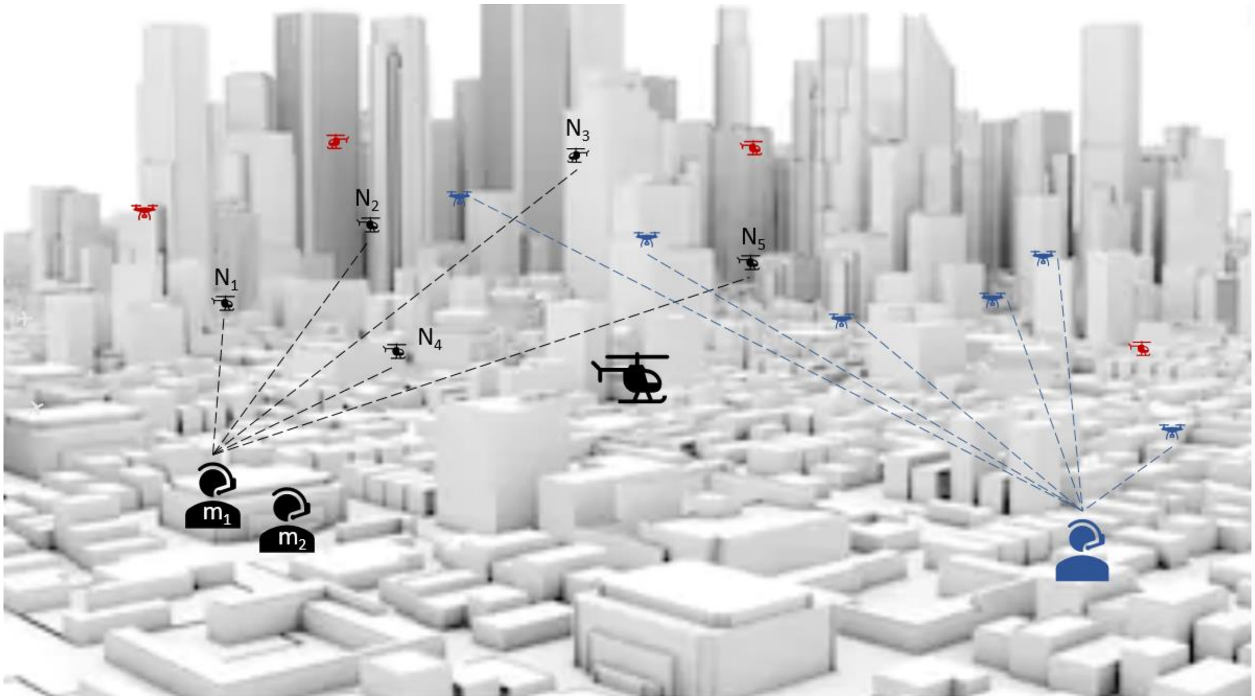

Fig. 1 Diagram of heterogeneous m:N operations.

A. Enabling scalability

The future state for AAM, as defined by the UML scale, assumes maturation of autonomous capabilities such as autonomous execution of complex functions, trusted autonomy performance, and autonomous contingency management [5]. Such capabilities allow the human's interaction with an increasingly autonomous vehicle to shift from continual provision of explicit commands to less frequent provision of intent and/or supervision. Stated in other words, the metaphorical *distance* between the human and the vehicle increases as the vehicle becomes more autonomous. m:N operations capitalize on this increased distance (and decreased workload) by adding additional vehicles to the humans' purview.

Given that the same number operations can feasibly require fewer skilled operators in an m:N implementation than in a traditionally piloted implementation, m;N operations can scale more quickly when skilled labor is limited. Similarly, the same number of operators can accommodate more operations in an m:N implementation than in current operational models. The economic analyses, such as the ones performed by Uber [2], Crown [8], and Booz Allen Hamilton [9], indicate an increased number of aircraft operations per day. That assumption along with the steady-to-decreasing pilot training pipeline suggest that simplified vehicle operations in the near-term and multi-vehicle operations such as m:N in the far-term are optimal solutions to enabling a scalable market [3].

The use of m:N operations is not yet a guarantee of market scalability. The potential success of m:N cannot be realized without commiserate airspace and regulatory maturation, realization of advanced vehicle autonomy, and public acceptance. However, adherence to an m:N architecture means that the infrastructure is in place to readily scale the number of operations as these related capabilities progress.

B. Cost Savings from m:N Operations

Cost and convenience are the most important motivators impacting mode choice amongst potential UAM customers [9]. Crown predicts a profitable last-mile parcel delivery market of ~500M UAS deliveries at a price point near $4.20 per delivery by 2030, assuming an m:N ratio of 1:100. They also predict air metro services could be profitable by 2028 with ~750M passenger trips at a price of ~$30 per trip across 15 major metro areas, assuming an m:N ratio of 1:2 [8]. Uber's economic analysis indicated that the customer cost for a 45 mile pool VTOL trip would be $50 in the near-term and $21 in the far-term. Their far-term assumptions included an m:N ratio of 1:8 [2].

There are various market studies available, such as those referenced above; however, previous studies cite only one m:N ratio and do not provide insight into the sensitivity of the operating cost to that ratio. To gain some clarity into the effect of m:N ratios on operating cost, the U.S. Department of Transportation's Volpe Center aided NASA in building a model to evaluate a range of m:N ratios, with details of the model and initial results presented below.

When investigating the cost of operating in an m:N scenario, there exists a fundamental cost tradeoff between replacing a pilot via automation and increased onboard avionics for remote operations. To gain a better understanding of this tradeoff, this study measured the cost implications of various AAM automation scenarios. Using passenger air taxis as the reference use case, a static lifecycle cost model was developed to analyze a range of m:N ratios based on automation maturity and deployment levels[**]. The primary purpose of the cost model is to estimate total costs (on both an annual and per passenger-mile basis) while accounting for the key operating and manufacturing costs, given a set of usage inputs. These costs are estimated for both a baseline scenario of no automation (human piloted AAM) and six different m:N ratio scenarios described in Table 1. These ratios were selected based on ratios that are discussed in the community and to provide a good range of operational scenarios and associated automation/autonomy levels. The scenario costs are then compared against the baseline to generate cost curves by m:N ratio. In addition, the cost and usage inputs can be calculated parametrically to provide ranges for the estimated cost curves to help bound the analysis. The inputs are presented in **Table 2**.

Table 1 Cost Model Scenarios and AAM m:N Ratios

Model Scenarios	
Baseline Scenario	Human-Piloted Aircraft (m:N ratio of 1.8:1)
Scenario 1	Unpiloted AAM with 1 Remote Pilot Technical Operator per Aircraft (1:1)
Scenario 2	Unpiloted AAM with 1 Remote Pilot Technical Operator to 2 aircraft (1:2)
Scenario 3	Unpiloted AAM with 1 Remote Pilot Technical Operator to 10 aircraft (1:10)
Scenario 4	Unpiloted AAM with 3 Specialized Technical Operators to 50 aircraft (3:50)
Scenario 5	Unpiloted AAM with 3 Specialized Technical Operators to 300 aircraft (3:300)

Each scenario assumes a fleet of 100 aircraft (N), while the labor required (m) changes conditional on the scenario. Under the Baseline scenario, the number of pilots required is 150 (1.5 per aircraft) [2], in addition to 30 dispatchers (author's estimate), yielding an m:N ratio of 1.8:1. This labor to aircraft ratio is then evaluated over 5 scenarios of increasing levels of automation, requiring either remote pilot technical operators or specialized technical operators depending on the scenario and automation maturity level. For Scenarios 1-3, technical operators will have some remote piloting duties, especially for contingencies, and will be responsible for one or more aircraft. In the most advanced stage of automation, Scenarios 4 and 5 assume specialized technical operators will control large fleets of automated AAM aircraft. These specialized operator roles are discussed more in Section D. Labor-based operating costs are then calculated by taking the product of labor required by the annual cost reported in Table 2. Additionally, it was assumed that labor costs increased above the base rate for the remote pilots and specialized operators as the technical complexity of controlling additional aircraft increases in Scenarios 2-5[††].

The other key cost input are aircraft manufacturing costs, estimated by the base cost of manufacturing an AAM aircraft plus the additional costs of advanced avionics for remote piloting and other increased manufacturing costs associated with automation, which are provided in Table 2. Similar to the dynamics included for the remote piloting and specialized technical operators, the additional annual manufacturing costs are assumed to increase as a function of increasing levels of m:N ratios[‡‡].

[**] The mode is considered 'static' as it only represents each scenario in a given point in time. Demand for AAM travel is also exogenously determined, with assumptions on load factors and passenger miles being used as inputs for usage.

[††] This increase in labor cost as the m:N ratio decreases (as a control becomes responsible for additional aircraft is expressed as a simple dynamic function: $LC_i + (1 - \text{m:N ratio}) * LC_i$, where LC_i is the labor cost for either the remote pilot or specialized technical operator.

[‡‡] The additional manufacturing costs is defined by the dynamic function: ($100/m:N ratio).

Table 2 Lifecycle Cost Model Inputs

Operational and Lifecycle Inputs			
Input	**Baseline**	**Parametric Range**	**Source and Notes**
Annual Miles per Aircraft	200,000 miles	+/- 50,000 miles	Uber (2016) [2], value reduced from 400,000 to 200,000 annual miles, author's estimation.
Passengers per Aircraft (Load Factor)	1.75 passengers	+/- 0.5 passengers	Antcliff, K. R., Moore, M. D., and Goodrich, K. H. (2016) [10], Uber (2016) [2]
Useful Service life of Aircraft	15 Years	+/- 5 Years	Uber (2016) [2]
Labor[§§] and Operating Cost Inputs			
Input	**Baseline**	**Parametric Range**	**Source and Notes**
Base Pilot Labor Cost	$50,000	+/- $15,000	Syed et al. (2017) [11], Uber (2016) [2]
Dispatcher Labor Cost	$60,000	N/A, only used in baseline scenario[***]	BLS: Occupation code 43-5030 [12]
Remote Pilot Technical Operator Base Labor Cost (Scenarios 1-3, increases as m:N ratio decreases)	$50,000	Dynamic labor cost based on m:N ratio	Assumed same cost as pilot, author's estimation.
Specialized Technical Operator Base Labor Cost (Scenarios 4-5, increases as m:N ratio decreases)	$100,000	Dynamic labor cost based on m:N ratio	BLS: Occupation code 53-2021 [12]
Manufacturing Cost Inputs			
Input	**Baseline**	**Parametric Range**	**Source and Notes**
AAM Aircraft Manufacturing Cost	$975,000 ($65,000 annually)	+/- $500,000	Syed et al. (2017) [11], Uber (2016) [2]
Avionics Manufacturing Costs	$52,500 ($3,500 annually)	N/A	Moore et al. (2013) [13], Uber (2016) [2]
Additional Annual Manufacturing Cost for Automation (Hardware, Software, sensors, etc.)	$100/(m:N ratio)	Dynamic cost based on m:N ratio	Additive manufacturing costs associated with automation, intended to capture additional hardware, software and sensors needed for advanced avionics. Author's estimation.
Notes: Additional costs were estimated for the Baseline scenario to provide an estimate of total baseline costs and costs per passenger mile, including annual maintenance, energy and ownership costs. The model assumes these costs remain constant between scenarios, and for brevity are not reported here.			

The calculation of total annual costs is the summation of the total annual labor and manufacturing costs under each scenario, and the total cost per passenger mile is estimated by simply dividing the total cost by usage measured in total annual miles per passenger[†††]. Fig. 2 presents the estimation of the cost savings per passenger mile by scenario using the median values. When compared against the baseline, there is a steady decrease in costs per passenger mile between Scenarios 1 to 3 due to cost savings attributed to removing pilots from onboard operations. These cost savings begin to level out around 19% cost savings by Scenario 3 as diminishing marginal returns set in from smaller m:N ratios.

[§§] Labor costs are assumed to be annual salary rates, and do not account for additional compensation in the form of benefits, health insurance or pensions.

[***] Dispatcher role assumed to be rolled into ground operator duties in Scenarios 1-5.

[†††] Total annual costs is explain by the following formula: $TC_j = TL_j + TM_j$, where TL and TM are total labor and manufacturing costs for Scenario j. As mentioned in the note in Table 2, additional lifecycle costs of maintenance, energy and ownership costs are included, but do not vary between scenarios.

The cost savings are estimated to decrease by Scenario 5 as higher manufacturing costs begin to overtake the labor cost savings from automation. These trends hold when you examine the upper and lower bounds of the inputs presented in Table 2.

The estimated cost curve shows that there is potential for significant cost savings between the Baseline and Scenario 1, moving from a human piloted (1.8:1) to automated (1:1) AAM environment. These cost savings increase as the m:N ratio gets smaller and less human involvement is needed per AAM aircraft; however, the model predicts these savings will diminish at the lowest ratio estimated (3:300). While the results from the cost model are encouraging, they are meant to be illustrative rather than definitive. A number of caveats exist with the analysis and need to be considered, including:

- The analysis attempted to cover all relevant lifecycle costs where data existed and in areas where they could differ between scenarios. Several cost areas remain unknown or impossible to calculate at this time, such as economies of scale for production and competition between manufacturers that would directly affect the price of AAM aircraft.
- Demand was assumed to be exogenously determined; however, increased competition between AAM providers at different m:N ratios will have impacts on consumer demand and prices. Moreover, advances in automation for other modes of transportation, such as vehicle travel, would likely see similar reductions in cost per passenger mile and any cross-modal competition would need to be measured.
- The m:N ratios developed for the scenarios are intended to cover plausible ranges of future automation levels and technical skills required; however, these should not be viewed as exhaustive. A review of assumptions made for both usage and cost inputs (including the dynamic cost elements) should be conducted when additional information or data becomes available.
- Additional second order cost accounting in terms of travel time savings, safety benefits, ground and communication infrastructure, and environmental benefits were not considered in this analysis, and are important areas for future research.

NASA will continue to use this model to examine the economic impact of m:N operations by changing inputs and updating the model as more is learned about human roles and other factors. The results presented here are an initial look at the variability of cost savings as m:N ratios increase.

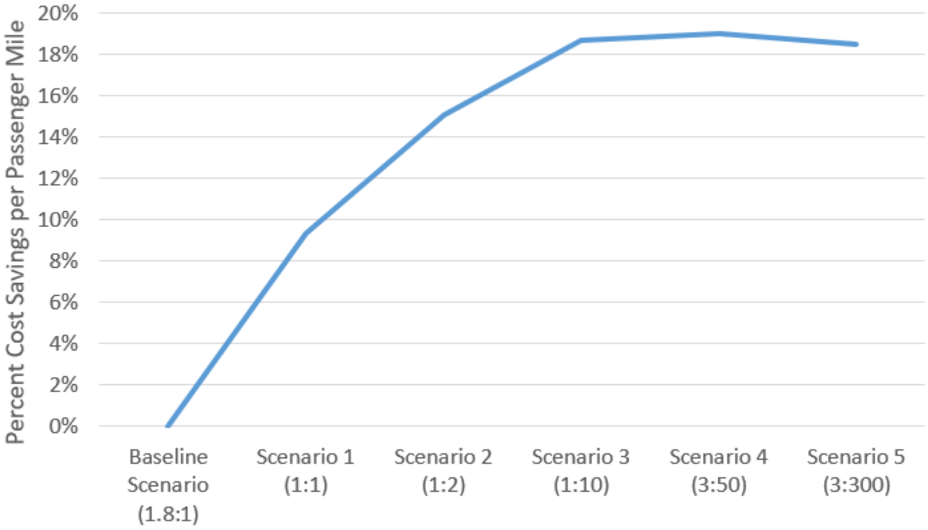

Fig. 2 Estimated percent cost savings per passenger mile in various m:N scenarios

C. Faster Path to Flight

Many AAM industry participants ultimately seek to operate near full autonomy with little to no human input to their highly autonomous vehicle fleets. Any operation in this mode will require significant regulatory change, and flight data collection even for the purposes of constructing a compelling safety case requires exception. An m:N implementation approximating the same operation desired with full autonomy could provide a faster path to flight due to the presence of humans in the total system that can be used to adhere to the existing or minimally-altered regulatory framework. Flight from the m:N version of operations could be used for data collection enabling future increasingly autonomous operational variants.

D. Increased Specialization in Human Roles

Interaction with an aircraft is not restricted on-board personnel or a single pilot in an m:N implementation. Specifically, the m off-board humans can collectively interact with the N autonomous aircraft such that no one person must execute all human-tasked functions. Responsibilities designated to the human can be split amongst m people if desired, leaving room for increased utilization of specialized role as was once standard for manned flights. For example, the m humans interacting with a flight could include communications, vehicle health, and weather specialists working together as opposed to one person who needs to be capable of all functions. This distribution of roles can enable utilization of highly specialized personnel but does require increase communication and coordination among the team [14]. This specialization of roles could lead to easier, faster, and more effective training.

Note: While the implicit hope is that an autonomy-driven transportation system will eventually be safer than a human-centric one, no such assurances can be made at this time [15]. A highly autonomous implementation such as m:N may reduce human error during operation but is also likely to introduce new sources of error (e.g. unexpected emergent behavior, inadequate design due to insufficient requirements) [16].

IV. State of the Art in Commercial Remotely Piloted and Multi-Vehicle Operations

Only UAS package delivery missions are being operated remotely at this time. Given the restrictive U.S. regulatory environment, many companies are operating in other countries. For example, Wing is piloting food delivery in Canberra Australia [17], Zipline is delivering medical supplies in Rwanda [18], and DHL is delivering packages in Germany [19], and many more examples can be readily found in a quick internet search.

The FAA is beginning to consider the multi-UAS human factors considerations of operating multiple UAS at once for small UAS package delivery. Operational approval programs, such as the FAA's BEYOND program, a follow-on to the UAS Integration Pilot Program (IPP), and the Partnership for Safety Plan (PSP) Program have begun investigating multi-UAS operations desired by industry. The first multi-UAS operations ever approved were the Intel ® light shows [20]. The BEYOND Program is investigating operations, such as home-health safety and package delivery. Package delivery, as well as disaster preparedness and agriculture are other applications that are being investigated for safe ratio of pilots to UAS [21]. The BEYOND Program has opened up some limited opportunities for last-mile delivery. For example, Flirtey is partnering with the Reno Emergency Management Services Agency to aide in "river rescue and fire-related emergency operations;" FedEx, 901 Drones, Asylon, and others partnered with the Memphis-Shelby County Airport Authority to support "aircraft inspections, security surveillance, FOD detection, and aircraft parts delivery;" and, the North Carolina Department of Transportation (NCDOT) is partnering with Skydio, Parazero, Sensfly, and others to "promote efficient inspection and mapping operations" [22].

The FAA UAS Integration Office is partnering with the FAA's Center of Excellence for UAS Research, Alliance for System Safety of UAS through Research Excellence (ASSURE) to assess required aptitude and human factors differences for pilots controlling multiple UAS versus technicians monitoring automated UAS in order to define preliminary training and certification insights [21].

NASA's UAS in the NAS Project that completed in 2020 and made strives in development and validation of Detect and Avoid (DAA) and Command and Control (C2) technologies [23, 24]. The Department of Defense is demonstrating and continually improving their multi-vehicle control and remotely piloted operations, through approaches, such as manned-unmanned teaming, or MUM-T [25, 26].

New eVTOL air taxi aircraft have been demonstrated in flight, but all with pilots on-board. To date, there is no standards committee that is directly addressing the needs for m:N operations standards and regulatory changes. There is some movement in the small UAS world that could help set the stage for passenger-carrying and larger autonomous aircraft, but it is still in early stages in the U.S. To that end, NASA has established a government-industry co-led working group on m:N operations that is discussed more in Section VII.

V. Urgent Need from U.S. Industry

There is an urgent need from U.S. industry for this technology to not only create viable business plans, but to compete globally. Several emerging markets are fully enabled by m:N operations, such as air metro taxi service, package delivery, and regional cargo transportation. Many of the companies developing products or services in these application areas are relying on the immediate or eventual adoption of m:N operations. The current state of operations is described in the next section. An m:N Working Group was established with joint NASA/industry leadership in the spring of 2021. Many companies with varying interests and applications for m:N operations participate in that working group.

Global AAM competitiveness is another aspect that should be considered. Many U.S.-based companies are going overseas to test their operations due to heavier regulations in the U.S. This will limit near-term operations in the U.S. and grow the market earlier and faster in other countries. The U.S. also faces strong competition from China, Germany, and South Korea [27]. Foreign industries also have the advantage of getting past regulatory hurdles quicker in other countries. Foreign companies are also progressing quickly through the vehicle manufacturing process, generating stiff competition for U.S. companies.

VI. Significant Barriers to m:N Operations in the NAS

There are still significant barriers to implementing m:N operations in the NAS. These can be divided into four general categories: technical/operational, safety and security, social acceptance, and regulatory. This list does not include all of the barriers associated with ubiquitous AAM operations, merely a representation of barriers specific to m:N that appear in published sources and that were produced in Multi-Vehicle (m:N) Working Group discussions. The list below is by no means a complete list, but it meant to be representative of the numerous challenges that need to be overcome to fully implement m:N operations.

A. Technical/Operational

Technical and/or operational barriers to m:N implementation are listed below.

- Autonomous flight technology
    - Autonomous route development and navigation despite loss of signal or poor conditions
    - Ability to integrate with Air Traffic Control (ATC) systems and modify scheduled flight paths in real-time
    - Development of emergency systems and protocols to minimize risk in situation of crisis or vehicle failures [8]
    - Development of acceptable methods for excessive data/compute power required for perception and decision making
- Human Autonomy Teaming considerations
    - Calibrated trust of autonomous systems
    - Verified processes to identify conflicts that cannot be resolved by automated systems and processes to facilitate emergency rapid hand-off to human operators on standby [8]
    - Safe and effective workload management
- Detect and Avoid (DAA) systems that can reliably detect non-cooperative objects and avoid them
- GPS-denied technology [8]
- Cybersecurity
- Air traffic management
    - Communication with Air Traffic Control (ATC)
    - Information sharing between aircraft
    - Large numbers of aircraft (automated sector hand-offs)
    - UTM/airspace design/corridors (airspace design)
    - Heterogeneous autonomous operations

B. Safety and Security

Safety and security barriers to m:N implementation include:

- Privacy concerns related to DAA/SAA systems [8]
- “When it comes to UAS last-mile delivery, consumers are specifically concerned about safety (e.g., Vehicles malfunctioning and damaging people and property)” [8]
- Safe utilization of learning-based tools, especially given limited opportunity for flight data and limited range of in-flight experiences
- Effective handling of contingency situations (e.g., lost link)

- Cyber attacks
- Resilience against cascading software bugs (software assurance)

C. Societal Acceptance

"Consumers distrust autonomous technology and are not aware of safety systems in place" [8]. According to a study performed by Booz Allen Hamilton, passengers are more afraid to fly on an aircraft that is remotely piloted or automated than an aircraft with a pilot onboard [9]. In another study, the results indicated a similar conclusion, in that the potential customer would be less likely to use an air taxi with no pilot on-board versus an air taxi with a pilot on-board, leading to the conclusion that "trust in UAM automation and remote pilots or operators will likely affect public acceptance of UAM" [28].

D. Regulatory Challenges

Regulatory challenges in the AAM realm abound, as the industry looks to push the envelope in vehicle design and operation. The Crown UAM Market Study states,

"Today, the regulatory environment does not permit the types of operations that scalable UAM would entail:

- Last-mile delivery is heavily restricted and permitted only through the use of waivers and pilot programs
- Air metro and air taxi regimes are permitted only as traditional manned helicopter services, which leave out critical components of their businesses cases (e.g., autonomy, eVTOL design)" [8]

The Booz Allen Hamilton UAM Market Study lists the following specific regulatory barriers for remotely piloted and autonomous UAM:

- Beyond visual line of sight (BVLOS) – currently only with lengthy waiver process to 14 CFR Part 107.31
- Operations over people, streets, etc – currently only with lengthy waiver process to 14 CFR 107.39
- Passenger or patient transportation in UAM either within visual line of sight or beyond – airworthiness potentially addressed in 14 CFR Part 23
- Flight in instrument conditions (not addressed in FAA Reauthorization Act of 2018)
- Airworthiness certification of remotely piloted and autonomous aircraft
- Training and knowledge requirements for pilots and operators (FAA Reauthorization Act of 2018 Section 349 whereby Congress tasks the FAA with creating an aeronautical knowledge test for certain recreational UAS operators)
- There are also state and local laws affecting remotely piloted or autonomous aircraft. [9]

VII. NASA's Role in Enabling m:N Operations

NASA Aeronautics is tasked with support of US aviation competitiveness and is committed to AAM realization. As NASA is not a regulatory authority or industry operator in the AAM space, the agency is well-suited to consolidate public and industry interests, aid in maturing them, and assist in represent them to regulatory organizations. NASA-appropriate roles for furthering AAM operations today span each of the barrier categories:

Technical/Operational

- Develop technology beneficial for many airspace participants, especially when difficult or not cost effective for the aviation industry
- Provide data or infrastructure for data collection in support of barrier resolution
- Develop airspace-level technology for effective operations

Safety and Security

- Development of industry-enabling safety technology (e.g. verification and validation of learning-based algorithms; hardware safety features)
- Assess heterogeneous airspace operations

Social Acceptance

- Provide evidence aimed at increasing public acceptance of highly autonomous operations
- Investigate public good use cases that are not commercially viable

- Develop technology that improves public acceptance (e.g. noise reduction)

Regulatory Challenges

- Provide community coordination for identification and action on cross-community interests/concerns

To that end, NASA has a Mission Office for Advanced Air Mobility that coordinates the research and development being done across the projects and programs, addressing most of the roles described above [4].

To address some of the issues of AAM scalability, NASA has assembled a strategy in the form of a multi-year Technical Challenge (TC) investigating m:N operations of autonomous fleets. The body of work covered by the TC leverages several of the NASA-appropriate roles previously listed and seeks to enable scalable operations for AAM through development of an m:N operational approval roadmap supported by community coordination and critical tool and technique research. A summary of the TC content is provided in Fig. 3. A more detailed discussion of the TC work plan is provided subsequently.

m:N Operations of Autonomous Fleets

For efforts through FY27

Enable scalable operations for AAM through development of an m:N operational approval roadmap supported by community coordination and critical tool and technique research

Research areas

Human-Autonomy Teaming:
Develop tools and techniques to enable a small number of humans (m) to effectively manage many autonomous vehicles (N) across diverse use cases

Autonomous vehicle technology:
Develop **Sensing** and **Contingency Management** capabilities that enable vehicles to operate autonomously in UML 4+ scenarios with only high-level supervision from off-board humans

Exit criteria

- Delivery of an m:N **operational approval roadmap** informed by coordination of stakeholder community and progress on identified technology gaps
- Release of **tools and data** from complementary research activities:
  - Publicly available HAT tools based on effective teaming study series
  - Publicly available data sets for perception tasks for multi-sensor and distributed algorithm development
  - Intelligent contingency management toolbox

Fig. 3 Overview of the m:N technical challenge

Fig. 4 details the TC work plan by fiscal year. As seen in the top row of the figure, the TC is coordinated by the activities of the NASA-organized m:N Working Group. The goal of the group is identify and an take action on community-wide issues facing operationalization of m:N architectures. Working group participants consist of industry, government, and academic representatives interested in a wide range of m:N use cases, though particular emphasis is placed on the disparate needs of small UAS (sUAS) and UAM fleet applications. The group's planned activities include identification of barriers and gaps to m:N operation, followed by development of a Concept of Operations (ConOps) describing the most critical m:N fleet functions and roadmaps for making a safety case supporting regularity approval of functions. The final deliverable of the working group will be an operational approval roadmap for select m:N implementations considering both technical and regulatory needs. Participation in the working group and access to its deliverables is open to all interested in m:N operations [29].

The m:N Working Group is supported by a portfolio of NASA research activities as shown in the lower portion of Fig. 4. The activities are grouped into three subject areas: m:N human-in-the-loop (HITL) simulations vehicle autonomy, and human-autonomy teaming. The activities undertaken in each area are guided by the barriers and research needs identified by the m:N working group.

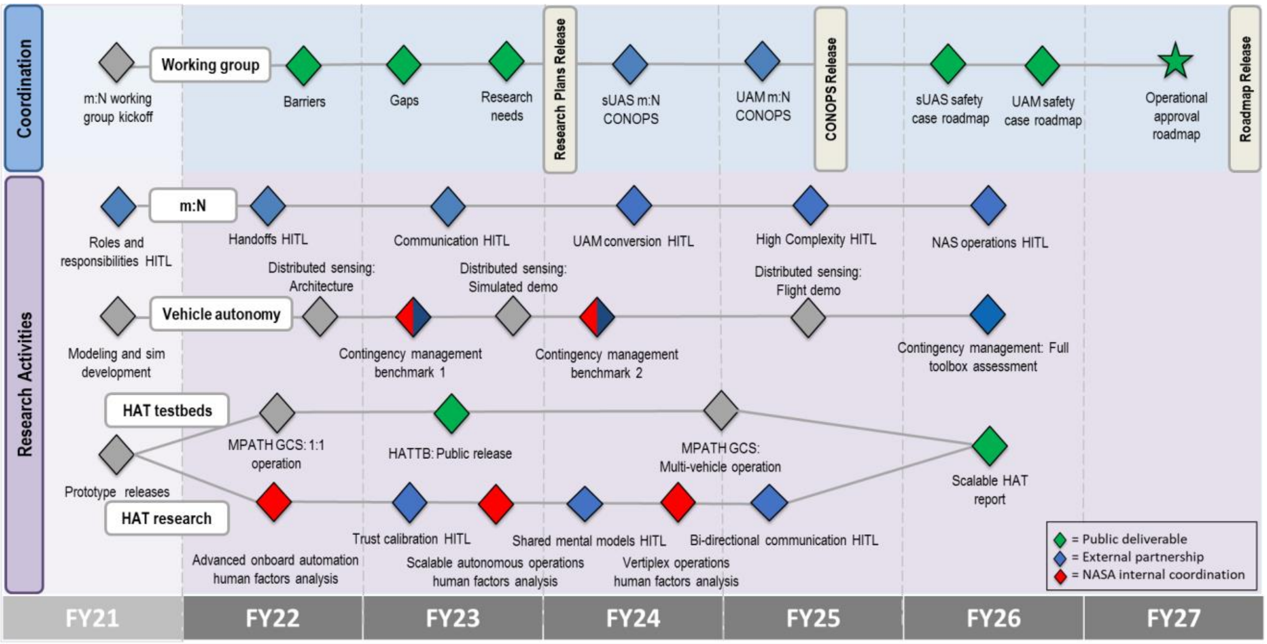

Fig. 4 Detailed m:N technical challenge work plan

A. Human-Autonomy Teaming (HAT)

Similar to the need for capable vehicle autonomy, an m:N implementation requires careful consideration of human behavior in this operating paradigm [30]. The TC splits activities in this area into foundational HAT research and testbed development. Research activities include a HITL series targeting foundational topics of concern such as human-autonomy trust and shared mental models [31]. A longitudinal human factors study will also be conducted in conjunction with flight activities in NASA's AAM Project as they progress from 1:1 visual line-of-sight operations to m:N BVLOS operations. Testbed development will include release of the Human-Autonomy Teaming Task Battery (HATTB), a freely available research tool to study HAT and m:N concepts. Testbed development will also include the *Measuring Performance for Autonomy Teaming with Humans Ground Control Station* (MPATH GCS), an m:N capable GCS being developed as part of the NASA Langley *Remote Operations for Autonomous Mission UAS Operations Center* (ROAM Operations Center).

B. m:N Human-in-the Loop (HITL) Simulations

The TC's HAT research consists of a series of HITLs designed to investigate community-driven concerns related to development of an m:N operational roadmap. The series began with an sUAS-focused study of possible human and autonomy roles and responsibilities in an m:N implementation [32] and will progress to include design of *plays* for responsibility handoff and appropriate airspace communication mechanisms [33]. Further HITLs will focus on study of m:N techniques in increasing demanding scenarios such as UAM applications and in high complexity airspace. The series will culminate with an m:N operation demonstrated in an environment representative of the NAS.

C. Vehicle Autonomy

As most m:N implementations will require highly autonomous vehicles, a portion of the TC's effort is devoted to advancing the state-of-the-art for on-board autonomous functionality. Contingency management and sensor-based perception techniques have been identified as key areas requiring further technology development [34, 35]. For contingency management, an increasingly comprehensive toolbox of intelligent algorithms is under development to autonomously handle both common and unforeseen off-nominal events [36]. Many of the algorithms utilize machine learning, and effectiveness of the tool suite will be assessed against a series of benchmark problems developed in coordination with other stakeholders [37]. For perception, techniques are being developed to address problems such as GPS-free Alternative Positioning, Navigation, and Timing (APNT), precision approach and landing, and airborne hazard detection and tracking [38, 39, 40, 41]. The algorithms in development focus on intelligent utilization of distributed information sources such as onboard sensors, offboard sensors, and service providers. The perception techniques will be evaluated in high-fidelity simulation and with flight demonstrations.

D. Community-Advancing Goals

Given the community-advancing goals of the TC, the supporting NASA teams are making public accessibility of their activities a priority. As mentioned, the working group participation is open with meeting material and deliverables posted on the group's website. The contingency management toolbox is pursing release to partners and the public. Sensor datasets used to develop and validate perception algorithms will be posted publicly [42, 43]. The HATTB research tool will be released as an app. Results will be documented in both traditional publications and in open forums as appropriate (e.g. Ref. [44]).

Success in establishing m:N as an permissible operational mode requires progress against the barriers to be applicable to a range of use cases, or equivalently stated, m:N progress must be *generalizable*. Developments that work for one industry is neither in line with NASA's role nor appropriate for regulatory change as the airspace remains a resource shared among many interests. Accordingly, many activities in the TC are conducted jointly with industry partners representing diverse applications. For example, the experimental design of the communication HITL was informed by three companies formally partnered with NASA each with different vehicle types and missions. Similarly, the working group involves participants from many use cases and will release content targeting both sUAS and UAM operations.

VIII. Conclusion

Multi-vehicle, or m:N, operations are a key enabler for the AAM market to achieve its full vision and potential. The benefits of m:N operations are many, but the barriers to implementation in the U.S. are also many – especially for passenger-carrying vehicles. The Multi-Vehicle (m:N) Working Group was formed as a first step in getting U.S. industry, academia, regulatory agencies, and NASA to collaborate and organize around the challenges of implementing this operational scheme in the U.S. NASA is investing in research on this topic with the ultimate goal of providing more citizens with access to AAM services and providing an invaluable capability to the nation that can be extended to many public good missions and even other non-aviation domains.

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