Sim to Flight: Evaluating Flight Path Management Automation in High Density Urban Environments

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Combined simulation and flight testing enable the study of single- and multi-aircraft performance of onboard automation systems for dynamic flight path management (FPM). The National Aeronautics and Space Administration (NASA) is investigating system performance and functional capabilities of such automation for immersion into complex, high density, future operations such as Urban Air Mobility (UAM). This paper provides an overview of a series of interdependent sim-to-flight research activities involving large-scale batch simulations, human-in-the-loop verification, and flight-test validation of a research prototype FPM automation system. Together, they significantly contributed to a functional assessment of FPM automation functionality in a live-virtual-constructive (LVC) operating environment characterized by two live aircraft and hundreds of virtual aircraft interacting in a modeled complex urban airspace. Initial simulation and flight test results, future work, and conclusions are presented.

I. Nomenclature

AAM = Advanced Air Mobility
AFCM = Automated Flight and Contingency Management
AOP = Autonomous Operations Planner
CPA = Closest Point of Approach
DFW = Dallas/Fort Worth
FPM = Flight Path Management
EUTL = Efficient Universal Trajectory Language
eVTOL = Electric Vertical Takeoff and Landing
HITL = Human-in-the-Loop
IAS = Integration of Automated Systems
LOS = Loss of Separation
LVC = Live-Virtual-Constructive
NAS = National Airspace System
NASA = National Aeronautics and Space Administration
OPV = Optionally Piloted Vehicle
PBGA = Pattern-Based Genetic Algorithm
RTA = Required Time of Arrival

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SARA = Sikorsky Autonomy Research Aircraft
TPUBs = Trajectory Prediction Uncertainty Bounds
TTFLOS = Time-to-first LOS
UAM = Urban Air Mobility
UML = UAM Maturity Level

II. Introduction

The National Aeronautics and Space Administration (NASA) Advanced Air Mobility (AAM) initiative supports the development of advanced air transportation [1] for novel air vehicles between local, regional, intraregional, and urban areas by means of passenger, private recreational and cargo transport services [2]. Urban Air Mobility (UAM), perhaps the most challenging application of AAM, presents a transformative complement to modern commercial air transport within the National Airspace System (NAS) by which increasingly complex operations are desired in underserved, low-altitude airspace in metropolitan regions. UAM introduces complexity unlike those encountered in modern commercial air transport. UAM envisions the immersion of operations of novel electric vertical takeoff and landing (eVTOL) aircraft at much closer traffic proximity and at significantly greater density and operational tempos in urban and suburban low-altitude airspace. Safety and efficiency of increasingly complex AAM operational environments are expected to require extensive use of automation, ranging from controlling revolutionary new aircraft to managing flights dynamically in higher tempo airspace operations [3].

UAM is anticipated to evolve through a series of progressive technology maturity levels. The UAM Maturity Level (UML) scale [4] is primarily characterized by operational complexity, operations density, and automation and autonomy systems dependence. Specifically, UAM Maturity Level 4 (UML-4) is classified as "*medium-density and medium-complexity operations with collaborative and automated systems*," and is unlikely to be realizable using current operating modes that rely primarily on human decision-making [5]. Traditional human-centric approaches to air traffic management functions, which ensure the safe, orderly, and expeditious flow of traffic, will be extremely challenging at UML-4 complexities. Dynamic path planning automation is one element of a new paradigm of operations that empowers operators with the authority to automate some functions typically performed by humans, such as traffic deconfliction [6]. Such automation may be a critical enabler of envisioned UML-4 operations and is therefore a primary driving requirement behind NASA simulation and flight test activities.

The Flight Path Management (FPM) research team, under the Automated Flight and Contingency Management (AFCM) Subproject of the NASA AAM Project, seeks to explore concepts and related airborne technologies enabling largely automated dynamic path planning in UML-4 operational environments [3]. At the start of the research effort, the AAM Project established an overall strategy to investigate FPM for UML-4 operations: develop a reference automation technology and associated UAM simulation test environment, conduct constructive "batch" and Human-in-the-Loop (HITL) simulations at UML-4 complexity to assess and mature FPM performance, and validate key finding through flight testing. For UML-4, the reference automation technology leverages existing prototypes from decades of advanced research in aircraft autonomous operations. Constructive simulations would enable researchers to investigate multi-aircraft performance and behaviors at UML-4 scale operations, with the human role being largely automated. HITL simulations would investigate how pilots interact with the automation technology and the role of human decision-making in envisioned future UML-4 operations. Flight testing would investigate performance of the FPM functions and confirm certain simulation findings through replication in a limited flight environment. To duplicate UML-4 operations affordably in flight, live-virtual-constructive (LVC) testing was employed. Trained test pilots using representative automation technology addressed real-world encounters between two live test aircraft, while simulated traffic, airspace constraints, and arrival constraints completed the LVC representation of the complex operating environment of UML-4. By the conclusion of the AAM Project, significant progress was made across FPM batch simulation and HITL research activities [7], and the flight test was completed just prior to this publication. The flight test was conducted under the joint National Campaign subproject of AAM in support of its Integration of Automated Systems (IAS) flight test series [8]. The flight test containing FPM research (among other research) is identified as IAS-1.

This paper provides an overview of the AFCM Subproject's applied FPM research accomplished to-date for the UAM use case at UML-4. Covered in this work is a cohesive and interdependent set of tests which culminate in the achievement of the overarching FPM research goals. The progression of FPM research discussed in this paper begins with an initial performance study of a reference onboard FPM automation system, proceeds through two batch simulations and a HITL evaluation that matured the technology, and ends with preliminary observations from the just-completed flight test. In Section III, background is provided regarding the reference FPM automation system, the operational environment, and key objectives of each activity. Section IV describes the test scenario that unified all of

the simulation and flight activities. In Section V, two batch simulation activities and a HITL assessment are discussed, with an emphasis on similarities and differences between simulation scenario configurations and performance indicators, and their impact to eventual flight testing. Section VI summarizes the flight test methodology, systems integration, test conductance methodologies and initial flight test observations, and insights gleaned between simulation and flight. Scenario design, integration and flight test configuration are further detailed in a companion reference [8]. Additionally, details regarding the development of the FPM reference technology used in the flight test are covered in companion reference [9]. Section VII discusses future work and recommendations. Section VIII presents conclusive thoughts regarding all accomplished FPM research activities. All of the FPM research activities presented here represent an integrated accomplishment.

III. Background

A. Urban Air Mobility Maturity Level 4

At UML-4, the aircraft operator employs "collaborative and responsible" automation to perform the separation function. Collaborative and responsible automation is defined in [4] as "automation assured to perform specified functions such that human monitoring and mitigation of potential failures of those functions is not necessary." Prior research [4] defines UML-4 as medium density, corresponding to hundreds of simultaneous aircraft aloft over a metropolitan area. Therefore, UML-4 implies an extremely high level of traffic density compared to current operations. A significant challenge of UML-4 is defining adequate separation standards necessary to safely and reliably achieve desired traffic densities at acceptable risk. Unlike modern commercial transport operations, UAM aircraft in UML-4 are expected to operate at significantly lower altitudes, in broader diversity of aircraft performance and speed ranges, with shorter flight durations, and under strict battery-energy constraints. Greater reliance on automation and air traffic management services will likely be needed to support higher operational tempos and under conditions in which current-day operating modes will be significantly challenged and may possibly be comparatively unsustainable. Ultimately, UAM viability at UML-4 and above will depend on achieving many technical and regulatory breakthroughs, including possibly introducing a new operating mode that automates traffic separation under exceedingly challenging and diverse constraints. Onboard automation responsible for executing the FPM function of each participating aircraft is one approach under study toward achieving future UML-4 operations.

B. FPM Automation Function

The FPM automation system proposed in this research would be designed to perform the function of *dynamic path planning*. As described in [3], the purpose of dynamic path planning automation is to ensure that a safe and operationally acceptable flight path is available to the users and the flight path execution system throughout the flight. FPM automation achieves these goals by constructing and maintaining a flight path with five principal qualities: feasibility, deconfliction, harmonization, flexibility, and optimality [3,10].

- A *feasible* path is one that conforms to the aircraft performance and range capabilities; complies with the airspace structure, rules, and constraints; avoids the terrain and charted obstacles; and meets the arrival constraints.
- A *deconflicted* path is one that avoids unsafe proximity to known aircraft, dynamic obstacles, inclement weather, and other emergent airspace hazards.
- A *harmonized* path is one that follows cooperative rules and procedures to ensure that the use of the airspace is coordinated with other airspace users.
- A *flexible* path is one that provides adequate maneuverability to ensure future flight path changes, if needed, are available and feasible.
- An *optimal* path is one that best achieves the operator's business objectives for the specific flight.

The FPM automation system is responsible for creating a feasible flight path, then monitoring the flight path qualities, evaluating ongoing acceptability of the flight path and proposed changes, revising the flight path as needed to sustain the desired qualities, and coordinating the flight path with other airspace users and service providers in accordance with local airspace regulations and environmental factors. FPM-computed flight paths encompass mission objectives, pilot commands, aircraft performance, flight data from ownship and traffic aircraft, dynamic atmospheric conditions, terrain constraints, and dynamic changes to airspace and aerodrome configurations. These adaptive characteristics of FPM automation capability contribute to more efficient planning, decreased airspace buffer demands, enhanced responsiveness, and smaller separation criteria [10]. Widespread implementation of FPM

automation onboard or remotely serving participating aircraft is anticipated to contribute to increased efficiency and safety in higher density and greater complexity airspace environments.

For all approaches to implementing the FPM function, assessing technical feasibility is a necessary step of exploration. A set of foundational technical questions are considered throughout this work for an aircraft-centric implementation of FPM to meet the needs of UML-4 operations:

1. What conflict resolution success rate should FPM be required to achieve? FPM resolution failures must be mitigated by a separate tactical hazard avoidance system.
2. What separation standards will ensure adequate traffic flow for expected UML-4 traffic density?
3. At UML-4 traffic densities, will human operator attention and reaction time (and their variability) be adequate to allow humans to be in decision loops of the FPM function?
4. What is the minimum traffic separation (separation standard plus any necessary buffers) required by FPM to achieve acceptable conflict detection and conflict resolution performance?
5. Can FPM technology (automation plus associated air-to-air communications) adequately avoid triggering a domino effect? A conflict resolution that spawns new conflicts and causes a chain reaction is an example of domino effect.
6. How do FPM functions designed for unconstrained airspace perform in constrained airspace such as UAM corridors?

C. FPM Reference Automation

A reference-prototype FPM automation system developed at NASA Langley Research Center was adapted for this UAM research [11]. The Autonomous Operations Planner (AOP), originally conceived in the late 1990s and developed and matured over nearly two decades of commercial air traffic management research, was applied here to flexibly support FPM automation research objectives in simulation activities and flight testing. Adapted to eVTOL aircraft performance and UAM-scale operations, AOP was employed and evaluated across multiple virtual simulation activities (batch and HITL) in a representative UML-4 operational environment [7,10]. To further the technology maturity of the FPM automation concept, it was necessary to test the reference system (AOP) in flight to enable researchers to identify technical barriers, emergent behaviors, and operational challenges associate with the FPM function in operational environments. AOP served as the reference automation system for all FPM simulation and flight studies discussed here.

AOP capabilities deemed ready for flight testing align with the five principal automation concept qualities previously outlined. *Feasibility* was achieved via the AOP trajectory generation function which uses the ownship's performance model and operating limits while complying with airspace and time constraints and mission goals. *Deconfliction* was achieved via intent-based conflict detection and strategic conflict resolution algorithms, which in addition to traffic can consider 4D convective weather, 4D (i.e., 3D with time) restricted airspace, and dynamically changing time constraints. *Harmonization* was achieved via conflict resolution and subsequent conflict prevention functionality while adhering to cooperative airspace regulations, such as right-of-way rules. *Flexibility* was sustained through the capability of relaxing arrival time requirements, as necessary, based on other influencing factors of the airspace. Sudden changes to arrival schedules, such as an arrival advance or delay, can occur due to traffic behavior, environmental impacts, or user demand. Lastly, *optimality* was achieved by capabilities of the trajectory generation function to provide trajectory resolutions fitted to user-defined optimization criteria. For example, battery-energy-based optimization may be preferrable under specific circumstances as opposed to shortest-time paths.

A complementary capability within AOP that helps achieve separation is the Trajectory Prediction Uncertainty Bounds (TPUBs) algorithm [12]. Primarily, the TPUBs algorithm provides conflict detection for trajectories accounting for uncertainty about how the aircraft's actual four-dimensional path compares to the predicted trajectory (that is, comparing the actual path of the aircraft with the predicted path, both in spatial dimensions and in time). TPUBs is used by AOP conflict detection and the pattern-based genetic algorithm (PBGA) [13] for conflict resolution and optimization. In simulation, an initial "enabled" TPUBs configuration of ±150 ft. lateral, ±25 ft. vertical, and 2 seconds along-path is defined that is later revised and discussed.

IV. UML-4 Scenario Configuration

FPM simulation activities and IAS-1 flight testing were designed to represent virtual UML-4 operations in the Dallas/Fort Worth (DFW) metropolitan area, across roughly 1,800 square nautical miles. Fig. 1 illustrates the test environment. More than 150 simultaneous aircraft simultaneously operated within the airspace region, with routing distributed across 55 vertiport locations. "No fly" zones (shown in yellow) were established throughout the region to protect non-UAM commercial operations, which introduced polygons (including corridor constraints) in addition to

traffic constraints. All virtual aircraft were eVTOL aircraft representing either of two model specifications: 1) NASA Lift+Cruise Electric model with a speed range of 80 to 129 knots indicated airspeed and 2) NASA Quadrotor Electric model with a speed range of 60 to 109 knots indicated airspeed. Flight operations occurred below 3,000 ft. mean sea level and were subjected to unvarying homogenous winds. Scenarios were assigned one of two traffic demand levels: 1) peak demand associated with higher traffic density early in the simulation and 2) valley (lull demand) associated with constant traffic density throughout. The scenario environment described here was consistent across all simulation activities and flight testing discussed throughout this paper. Further information regarding the simulation environment and operations in UML-4 simulation can be found in [7].

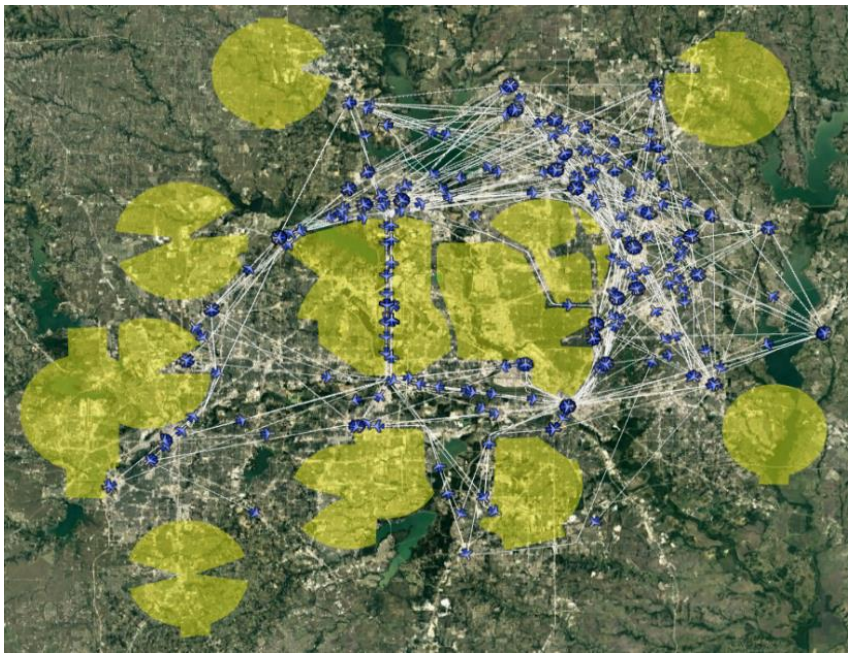


Fig 1: DFW metropolitan area virtual representative density of UML-4 operating environment (blue markers indicate traffic). Credit: NASA

Smaller eVTOL class aircraft with significantly more agile and responsive performance capabilities from that of conventional commercial transport vehicles are anticipated to operate under reduced separation in future UML-4 operations. While no industry standards are currently defined for UML-4 aircraft separation, placeholder separation minima of 1500 ft. lateral separation and 250 ft. vertical separation were initially chosen for study [7], a twelve-fold reduction from that of current terminal airspace lateral separation standards of 3 nmi. Upon further evaluation of initial simulation results, it was determined to increase the vertical separation criterion closer to 500 ft. for consistency with terminal area DO-365A Detect-and-Avoid (DAA) Well-Clear volumes.

V. Simulation

Two batch simulation activities observing FPM automation served as qualifying evaluations leading up to the IAS-1 flight test. Termed “FPM-1” and “FPM-2,” these activities were intended to better understand the performance characteristics of FPM automation distributed among all aircraft in a UML-4 operational environment. Secondary objectives of both simulation activities included determining whether design objectives and intrinsic functional capabilities of the system, under UAM-scale conditions (close proximity and short time scales), met acceptable performance before flight testing. Three underlying goals toward flight test preparation were considered across these FPM simulation activities:

1. Exercise desired FPM functions in UML-4 conditions and document the current state of AOP performance.
2. Verify that AOP functionality exhibits acceptable performance associated with anticipated flight test objectives, making upgrades and adjustments as necessary.
3. Verify test pilot acceptability of an engineering user interface (UI) that meets IAS-1 flight test procedural requirements.

Both simulation activities used AOP to collect and analyze data for baselining performance. FPM-1 batch simulation was focused on (not limited to) performance characteristic evaluation across all equipped with AOP. FPM-2 batch simulation explored upgraded simulation and scenario capabilities, smaller (yet more detailed) scope of FPM automation functional performance investigation, and refined UML-4 scenario definitions. Meanwhile, the HITL portion of FPM-2 was entirely focused on ensuring that a proposed user-interface would be adequate for the test pilots to interact with AOP in flight testing. Neither the user-interface prototype nor the HITL evaluation were intended or designed for generalizable end-user operational human factors evaluation. All simulation activities were collectively purposed to establish and confirm AOP's ability to meet mission and flight test objectives.

A. FPM-1: An Initial Performance Evaluation

An initial performance evaluation of onboard FPM automation using the AOP was conducted using gathered data from the FPM-1 batch simulation activity [7]. Objectives of this activity included understanding the impact of AOP performance on UAM operational safety and mission success, discovering hidden phenomena of AOP performance, and documenting a baseline performance evaluation for use in future research and development activities. A primary research challenge in the FPM-1 batch study was to provide reference performance metrics for automated en route operations in a UML-4 operational environment. To address this challenge, scenario definition and parameter tuning was focused on coverage of normal flight operations, which encompassed expected nominal UML-4 operations based on a broad and continuously developing definition at the time. Scenario coverage primarily concerned the feasibility, deconfliction, and harmonization objectives of the FPM.

The FPM-1 batch simulation activity across a 2x2x2x3x3 (72 total) test matrix, with 50,963 total flights, was performed and analyzed to understand the impacts of various deviations from nominal operational conditions, such as limited flight path deconfliction maneuver option and mid-flight schedule-change contingencies, on AOP performance. Dozens of scenario parameters were considered in FPM-1 experiment design and post-evaluation. A down-selected set of independent variables (IVs) included traffic demand levels, delays in required time of arrival (RTA), wind error, intent sharing, and conflict resolution type availability (previously called "maneuver availability"). Of the many metrics analyzed, loss of separation (LOS) between airborne aircraft and RTA conformance were two primary performance metrics shown to have been significantly impacted by the IVs. Notably, disabling traffic intent broadcast resulted in the most significant increase of LOS events across all scenarios, which suggested that traffic intent information is crucial to achieve desired deconfliction performance. Additionally, traffic demand level was found to significantly impact LOS occurrence and was more prominent for scenarios with "peak" traffic demand over scenarios with "lull" traffic demand. RTA delay, determined by time and magnitude of delay issued to an aircraft midflight, and resolution type availability, significantly impacted RTA conformance across all scenarios. It was observed that when "significant" RTA delays were issued, regardless of the en route phase during which they were triggered, flights tended to ignore the new RTA and stick to the original – indicating the infeasibility of the updated RTA delay. Similar behavior was noticed when resolution type restrictions were imposed, where for example, lateral resolution restrictions typically caused flights to arrive earlier, and were exacerbated during "peak" traffic periods with higher congestion. These findings from FPM-1 provided a solid baseline for comparisons with the follow-on FPM-2 batch simulation dataset and directly influenced IAS-1 flight test scenario design.

B. FPM-2: Extended Simulation in Preparation for Flight Testing

FPM-2 batch simulation was similarly conducted to assess AOP performance in representative UML-4 scenarios with a heavy emphasis on assessing operational readiness for IAS-1 flight testing. More specifically, FPM-2 objectives involved performing initial verification of AOP functions, informing the design and selection of candidate test scenarios capable of meeting flight test requirements, and integrating a newly designed engineering UI with AOP. The term "FPM engineering UI" reflects the decision to forego exhaustive human factors design and assessment in preparation for the flight test, though human factors expertise was leveraged in the design. Since FPM-1, several design and feature improvements were made to AOP for FPM-2 in preparation for IAS-1. A prominent change in FPM-2 was the addition of a speed-based degree of freedom for conflict resolution. This new feature provided AOP the capability of potentially resolving conflicts without changing the lateral path or altitude. In addition, FPM-2 introduced a vertical + lateral *hybrid-only* resolution availability test condition, where speed resolution was not permitted. It was desired in FPM-2 to test AOP performance in scenarios where only hybrid resolutions could be executed to further explore the impacts from disabling speed resolution capabilities.

Additional changes were made to the FPM-2 scenarios and simulations which improved performance. To prevent virtual UAMs from taking off and immediately entering a traffic conflict, AOP-equipped vehicles were configured to receive traffic state and intent data prior to takeoff. Progressive testing leading up to FPM-2 batch simulation indicated that several aircraft would encounter conflicts upon takeoff and not be able to proceed with the planned route, leading

toward the application of AOP's deconfliction capability as part of pre-flight planning in FPM-2. This was a fundamental change for all scenarios that significantly increased overall simulation performance. Other underlying improvements to FPM-2 simulation included: parallelized processing for AOP's core conflict resolution PBGA, changing the "freeze horizon" (the point along the active path that an aircraft must follow before beginning a strategic conflict-resolution maneuver) to be specified as a function of time rather than distance, and improvements to data collection and recording.

1. Test Scenario Configuration

Like FPM-1, FPM-2 scenarios were designed to represent UML-4 operations via appropriate AOP configuration and simulation environment variable conditions and support future flight test activities. The FPM-2 test matrix was a 2x2x2x4 (32 total) matrix composed of four IVs. There were two scenario conditions: RTA delay impact (two levels) and traffic demand (two levels), and two types of AOP restrictions: availability of traffic intent data (two levels) and availability of maneuver conflict resolution degrees of freedom (four levels). RTA delay impact levels of mild (20% of time-to-destination) and moderate (35% of time-to-destination) occurred only once per flight at random times between two minutes after takeoff and eight minutes before landing. Traffic demand levels were unchanged from FPM-1. Traffic intent sharing was either enabled with "full capability" (intent sharing and TPUBs) or disabled. Full resolution availability, which included lateral, vertical and speed degrees of freedom, was compared against three other configurations, as shown in Table 2. Additionally, changes from FPM-1 included making the wind error condition and TPUBs settings constant, as well as the inclusion of an additional maneuver option.

A special subset of data was collected across all four levels of scenario conditions where AOP was effectively disabled for the purpose of establishing a worst-case scenario to compare against. All 36 scenarios (32 plus the 4 special-case dataset) were repeated three times for a total of 108 total scenarios per simulation batch. In order to receive different samplings of the traffic data across all scenarios, the full 108 scenario batch data collection was repeated which resulted in a total of 216 scenarios. A total number of 127,224 flights were recorded and used for evaluation. Lastly, in simulation AOP was configured to assume zero wind vector values, while the simulated true winds were varied linearly as a function of altitude ranging between 3 ft/s (above ground level) to 10 ft/s (3,000 ft. altitude ceiling). Tables 1 and 2 show the full set of scenario conditions used in the FPM-2 experiment.

Table 1: Scenario Conditions

Scenario Conditions	RTA Delay Impact	Traffic Demand
A	Mild	Lull
B		Peak
C	Moderate to Significant	Lull
D		Peak

Table 2: AOP Performance Conditions

AOP Conditions	Intent Sharing	Resolution Type Availability
1	Full Capability	Full
2		Lateral + Vertical
3		Lateral + Speed
4		Vertical + Speed
5	No Traffic Intent	Full
6		Lateral + Vertical
7		Lateral + Speed
8		Vertical + Speed
9		None

2. Analysis

In total, six metrics were studied: LOS count, RTA conformance, slant-range distance at closest point of approach (CPA), lateral flight path deviation, time-to-first LOS (TTFLOS), and strategic conflict resolution execution count.

- *LOS count* is defined as the average total count of LOS events for each flight.
- *RTA conformance* is defined as the difference between each flight's arrival time (or estimated arrival time if still en route) and the last RTA update received, in seconds.
- *Slant-range distance at CPA* is defined as the slant distance between the ownship and conflicting aircraft at the actual CPA, in nautical miles.
- *Lateral flight path deviation* is defined as the total excess path length from the original plan, in nautical miles.

- *Time-to-first LOS* is defined as the time remaining before LOS at the start of each conflict detection cycle, in seconds.
- *Strategic conflict resolution execution count* is defined as the total count of conflicts resolution execution events for each flight.

Evaluation of AOP in FPM-2 had two key motivations. First, determination of which scenario and AOP conditions are the most impactful to AOP performance in accordance with FPM-2 metrics and either support or refute FPM-1 findings. Second, are performance expectations consistent between repeated simulation runs with the same configuration.

The first question was investigated by assessing the statistical significance of each IV on the metrics. A full factorial analysis of variance, using the standard least-squares method on a 4-degree regression analysis, was performed for each of the six key metrics to determine which IVs had significant impact (p-value ≤ 0.05). Since a "factorial to degree" approach was used with 4-degree interaction effects and four independent variables (wind error omitted), a total of 15 effects were observed per metric. Tables 3 through 8 only list the significant main and interaction effects impacting the mean values for each metric. Though this statistically indicates high dependence relationships, the relative significance of each effect was of enough interest to warrant a closer look. A logarithmic transform (LogWorth) was applied to each p-value score to provide a more intuitive scale of dependence on each effect. Higher LogWorth values generally indicate higher dependence relationships – a sort of inverse interpretation of the traditional p-value. It is immediately clear from these results that several effects, such as traffic intent and resolution type available, consistently significantly impacted key metrics.

Table 3: LOS Count

Source	LogWorth	P-Value
Traffic Intent	76.481	<.0001
Resolution Type Available	22.108	<.0001
Traffic Intent * Resolution Type Available	20.574	<.0001
RTA Delay Impact	7.741	<.0001
Demand * Traffic Intent	5.595	<.0001
Demand	5.172	<.0001
RTA Delay Impact * Traffic Intent	4.897	<.0001

Table 4: RTA Conformance

Source	LogWorth	P-Value
Resolution Type Available	6.044	<.0001
RTA Delay Impact	6.034	<.0001
RTA Delay Impact * Resolution Type Available	5.408	<.0001

Table 5: Slant-Range Distance at CPA

Source	LogWorth	P-Value
Traffic Intent	110.27	<.0001
Traffic Intent * Resolution Type Available	12.939	<.0001
Resolution Type Available	11.611	<.0001
RTA Delay Impact * Traffic Intent	1.523	0.0300

Table 6: Lateral Flight Path Deviation

Source	LogWorth	P-Value
RTA Delay Impact	10.388	<.0001
Resolution Type Available	7.615	<.0001
RTA Delay Impact * Resolution Type Available	2.820	0.0015

Table 7: Time to First LOS

Source	LogWorth	P-Value
Traffic Intent	177.766	<.0001
Traffic Intent * Resolution Type Available	15.093	<.0001
Resolution Type Available	14.755	<.0001
Demand * Traffic Intent	7.156	<.0001
RTA Delay Impact * Traffic Intent	6.062	<.0001
Demand	5.634	<.0001
RTA Delay Impact	4.693	<.0001
Demand * RTA Delay Impact * Traffic Intent	2.437	0.0037
Demand * Traffic Intent * Resolution Type Available	2.188	0.0065
Demand * Resolution Type Available	1.866	0.0136
Demand * RTA Delay Impact	1.77	0.0170

Table 8: Strategic Conflict Resolution Execution Count

Source	LogWorth	P-Value
Traffic Intent	12.893	<.0001
Demand	5.173	<.0001
Demand * RTA Delay Impact * Traffic Intent	2.488	0.0033
RTA Delay Impact	1.417	0.0383

The second FPM-2 motivation presented in the evaluation statement above was investigated by analyzing data from a larger set of repeat runs. In addition to the FPM-2 batch simulation runs, variation analysis was performed on 12 repetitions of a single scenario configuration. Referring to Tables 1 and 2, the selected scenario using AOP configuration 'B' and scenario configuration '1' was deemed to be most closely related to the flight test. Across all runs, demand tables and original flight routes were held constant. For all 737 flights per scenario, at least 12 instances of each flight existed within an aggregate variance data set. All flights began the scenario with the same original flight plan. More than 12 instances often occurred due to the number of accepted flight path trajectory resolutions across a given flight. Variation was measured across the aggregate dataset for each grouping of flights, where groups were distinguished using their designated callsign identifiers (constant across runs). Standard deviations for each of the six

previously described metrics were computed per callsign and selectively evaluated. In addition, total counts of differences within each flight group and for each metric were tallied.

As expected, minimal variance between runs for the same scenario configuration was confirmed. It was determined that most flight groups had zero change across all six metrics and just under a third of all flights had only one difference across the combined six data metrics. Less than two percent of outliers had significant differences, where at least five or more occurrences were counted across multiple data metrics. Overall, this gave reassurance that the number of runs conducted for each element of the test matrix garnered a sufficient amount of data to be reliable. Variability analyses also gave closure to an unexplored area of FPM-1. Multiple runs ensured that one-off anomalies and instances of unusual performance were not behavioral characteristics of AOP. Rather, they were indicators that the simulation environment, scenario conditions, or other configuration elements needed refinement and tuning.

3. Discussion

Findings from FPM-2 further support a crucial key finding from FPM-1: traffic intent data plays a prominent role in AOP performance across multiple scenario configurations. Out of the AOP test conditions, it was found that traffic intent, RTA delay impact, and resolution type availability main effects were consistently among the top significant contributors to AOP performance across all metrics. Traffic intent was most impactful to the measured TTFLOS (i.e., proximity to the ownship at periodic intervals during conflict) and slant-range distance at CPA metrics for flights that encountered traffic conflicts. This behavior is highly plausible given that a lack of traffic intent can cause conflicts to be redetected shortly after successful execution of a strategic conflict resolution, potentially forcing tactical override (i.e., a state data-based conflict resolution with a relatively shorter time horizon) or tactical resolution by an independent hazard avoidance system to occur (this threshold is set within AOP configuration settings at a 30-second TTFLOS time). Furthermore, slant-range CPA is closely coupled with shrinking TTFLOS as ownship and intruder conflict pairs continue to converge. In addition to traffic intent, resolution type availability influenced all metrics except for strategic conflict resolution execution count. However, it is understandable for resolution type to exhibit little impact on strategic conflict resolution count since this metric is a count of total resolution executions across all types. RTA delay impact also had significance impact across all metrics, with lateral flight path deviation being impacted the most. In cases where the ownship was ahead or behind the RTA by 30 seconds (a parameterized threshold), PBGA would attempt to generate resolutions, often of lateral or hybrid type, to close the RTA gap. Thereby, additional lateral path stretching would arise. Traffic demand was most impactful on metrics closely coupled with LOS, which is plausible to occur as a function of increased traffic density.

Several takeaways from FPM-2 simulation influenced AOP configurations supporting IAS-1 flight test objectives. Consistently experiencing performance degradation upon removing traffic intent availability and limiting resolution degrees of freedom from AOP in FPM-2 led to increased confidence that FPM performance would be unacceptable during IAS-1 if these two variables were limited. Therefore, it was decided they would not be explored in IAS-1 flight testing, but rather held as constants to represent a nominal AOP configuration; traffic intent sharing would be fully enabled, and all resolution degrees of freedom would be made available. Significant RTA delays were considered important to study in flight test maneuvers as a result of findings from both FPM-1 and FPM-2 studies.

Additionally, several scenario conditions were significant across FPM-2 results which influenced research interests in flight testing. The peak demand level, in addition to an even greater maximum stressor traffic demand case, was important to study to better understand scalability with respect to FPM performance. Also, several select scenarios from FPM-2 datasets were visually inspected to observe the effects of RTA delays that were issued during or around the time of ownship instances of traffic conflicts. Unique cases from simulation sparked further research interest around the phenomena of presenting AOP with simultaneous RTA delays and traffic conflicts in flight. Furthermore, upon visual inspection of flight route patterns for many scenarios, it was noticed that the presence of exclusive “No Fly” regions had an impact on the number of resolution executions per flight. Lastly, FPM-1 analyses revealed that the limited TPUBs condition did not yield any significant impact to AOP performance. For FPM-2 and the subsequent IAS flight test, it was determined that TPUBs calibration via real-world performance testing was required in order to better define significant thresholds for use within simulation.

The HITL portion of the FPM-2 activity was conducted to enable the IAS-1 flight test pilots to provide feedback on the design and usability of the newly developed FPM engineering UI in preparation for its ultimate use in flight. The final version used in IAS-1 is shown in Fig. 2. Feedback was collected using a pilot survey and freeform commentary during debriefing sessions. An important objective difference from conventional experimental displays was to tailor the FPM engineering UI to the test pilots’ collective preferences solely to produce a minimum-functionality prototype that would provide sufficient situation awareness and efficient control of AOP functions. Notable adjustments to the FPM engineering UI prior to IAS included a real-time indicator of onboard AOP state, indication of when new resolutions were available for preview and execution, a two-button press (select, then execute)

procedure for resolution confirmation and indicators for the type of constraint or hazard that AOP was attempting to provide resolution for, such as RTA changes, traffic conflicts, and area hazards. Future work should further investigate the usability of this interface with a broader range of end users.

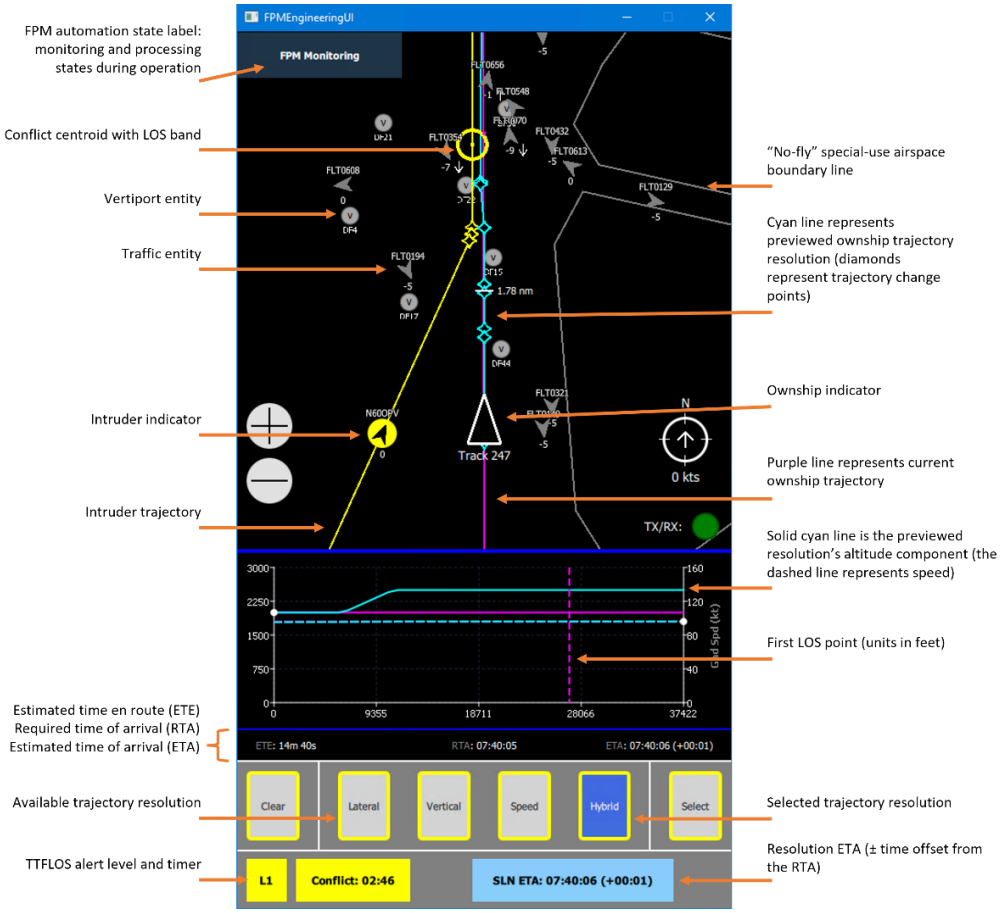


Fig. 2: FPM Engineering User-Interface. Credit: NASA

VI. Flight Testing

A. Background and Objectives

Flight testing was used to evaluate the concept and technology in a real-world operating environment. Four research objectives were defined for the test: function verification, concept and technology advancement, discovery, and simulation validation. The goal of *function verification* is to verify that the reference FPM automation system performed as expected in an actual flight environment. *Concept and technology advancement* has the goal of providing data to reduce known unknowns involving the technology (such as identifying performance limits) and the system (such as domino effect). The data are used to inform future concept and technology advancements and to establish quantified performance benchmarks for use in developing future FPM performance requirements. *Discovery* has the goal of revealing and characterizing unknown unknowns. It identifies emergent behaviors that result from execution in the actual flight environment. *Simulation Validation* has the goal of generating flight test data to validate current AAM simulation models. Future validation efforts will increase confidence in simulation results for traffic levels that cannot be tested in flight.

Building a representation of UML-4 operations in an actual flight environment presented several challenges. The test required at least 150 traffic aircraft to be operating in the airspace at any point in time. The urban airspace required a basis in projected traffic demand between plausible origin and destination locations as well as realistic regions that prohibit UAM operations. Rules for operation within the airspace were also required. The LVC approach was used. Two actual piloted aircraft, air/ground data links, and a ground station data relay made up the live element, while the

UML-4 operating environment, consisting of a future Dallas/Fort Worth airspace simulation populated by many virtual aircraft, made up the virtual/constructive element. One of the test aircraft hosted the representative FPM technology, which was to be operated by research pilots. The virtual traffic information was created by executing airspace simulations with FPM operations and recording state and intent information for playback during the flight test. Details of the test design and implementation are presented in [8].



Fig. 3: Transposed DFW FPM operational environment over test area. Credit: NASA

The IAS-1 flight test was performed in partnership with NASA Armstrong Flight Research Center and Lockheed Martin Sikorsky Aircraft. Test execution was managed by the National Campaign Subproject of the AAM Project. Flight operations were based at Sikorsky Memorial Airport, in Stratford CT, and all flight maneuvers took place over Long Island Sound from October 16 through October 26, 2023, see Fig. 3. Serving as surrogates of future UAM vehicle concepts, the Sikorsky Autonomy Research Aircraft (SARA) S-76B helicopter was equipped with NASA Langley's reference FPM automation, AOP, and the Sikorsky Optionally Piloted Vehicle (OPV) S-70 helicopter was employed to create strategic encounters with SARA for AOP to resolve under simulated UML-4 traffic densities, airspace constraints, and arrival time requirements. The FPM research team provided test requirements, operational test scenarios, the FPM automation prototype, and documentation facilitating the integration, testing, and operation of the functional system.

A total of eight distinct test groups were created to meet specific FPM research objectives of the flight test. Each group was focused on one or more topics of the broader research scope. The full set of maneuvers consisted of varying encounter geometries, altitude changes, AOP parameters, intruder vehicle conditions, execution instructions and operational procedures. Test groups and their respective maneuvers were specifically designed to study the following: *conflict detection, conflict resolution, RTA change compliance, RTA change compliance with traffic conflicts, time parameter variation, traffic intent change impact, corridor stressor conditions* and *high traffic density stressor conditions.* Including all test groups, an aggregate sum of 52 candidate maneuver test points were designed and generated. More information describing scenario design and generation and of operations can be found in a companion paper [8].

B. Systems Integration

In preparation for the IAS-1 flight test, some modifications and improvements were made to AOP based on findings from the FPM-1 and FPM-2 batch and HITL simulation activities. Significant notable changes, as described in [9], included disabling the tactical conflict resolution functions (outside the focus of the FPM portion of IAS-1), updating PBGA optimization criteria to battery-energy-based prioritization (simulating an eVTOL objective), and reconfiguring various AOP parameters (such as time horizon settings) in support of flight test objectives. Significant yet less noticeable changes included implementing internal support for sending Efficient Universal Trajectory Language (EUTL) [14] flight path intent information through a middleware gateway, and transmission of real-time

AOP system state information (monitoring, processing, idle, etc.). TPUBs were also redefined following a series of earlier development, discussed further in a companion paper [9]. Final calibrated TPUBs settings of ±150 ft. lateral, ±25 ft. vertical, and 3 seconds along-path were held constant throughout all flight test maneuver groups.

Flight test systems included AOP, the FPM engineering UI and an FPM ground station UI. AOP was installed onto a dedicated mid-range 4-core processor integrated alongside SARA's MATRIX™ technology platform. AOP forwarded conflict data, resolution options, aircraft state, and AOP status heartbeat to the engineering UI hosted on a portable touchscreen tablet situated by the test pilot's knee. The engineering UI provided a graphical display of the simulated UML-4 LVC operating environment to the pilot. An FPM ground station provided a graphical display of the FPM perspective of the flight operation to FPM researchers and NC personnel.

Additional systems enabling SARA/OPV integration and IAS-1 flight test procedures were developed and managed by the AFRC team. These systems included a "Middleware" software layer, an IAS pilot display, and three IAS ground displays dedicated to the Middleware engineers and flight test conductor. The Middleware software passed data between various FPM, IAS, and Sikorsky systems, enabling AOP to transmit data messages to both the FPM engineering and ground station UIs [8]. The IAS pilot display supported test scenario initial positioning and enabled pilots to signal test run initiation. The IAS ground displays collectively provided situational awareness to the AFRC team of Middleware layer performance and flight test maneuver setup [8].

C. Results

At the time of this publication, the IAS-1 flight test was only recently completed. Analysis continues, and a planned future paper will present detailed results. In this paper, high-level observations are presented.

In total, 34 test points were successfully collected throughout the IAS-1 flight test series. Test points collected span across eight distinct maneuver groups, with each focusing on tailored research questions that support overarching flight test objectives [8]. All maneuvers performed in flight were closely monitored by several FPM subject matter experts. Initial observations of in-flight performance, across all flown maneuvers, show that the AOP automation onboard the SARA vehicle overall performed as expected in a real-world flight environment. Designed conflicts with the OPV intruder aircraft and triggered events such as updated OPV route intent and mid-run RTA change updates were successfully detected and deconflicted as expected. Furthermore, observations of maneuvers were found to be extremely consistent with findings from pre-flight testing conducted in NASA LaRC's software integration lab several weeks prior to flight. Additionally, it was observed during the flight test, across all test points, that hardware and computing performance capability did not bottleneck the performance of the AOP system. Lastly, from the perspective of operational procedures and flight safety, separation requirements of 1500 ft. laterally and 450 ft. vertically were always satisfied: no LOS occurred between the SARA and OPV aircraft.

Preliminary results from the data show that a combined total of 41 traffic conflicts and RTA non-compliance events were detected by the SARA AOP automation system across all 34 test points. Of the total detections, 38 events have been observed between ownship and the OPV intruder aircraft. It was expected across the collected test points to encounter 31 traffic conflict events with OPV and 7 ownship RTA change events, detected by AOP as non-compliances with the latest RTA. Three conflicts were also observed between ownship and background traffic within the virtual environment, however; no known impacts from these conflicts on intended operations have currently been discovered. Upon initial inspection, all conflict detections appear to be valid. Combined, all maneuver test points yielded a total of 308 conflict resolution cycles and offered a total of 478 unique generated trajectory resolutions to the pilot operators. For all performed flight maneuvers involving traffic conflicts without RTA changes, initial evaluation shows that AOP's conflict resolution function successfully deconflicted with identified traffic hazards on all accounts. At the time of this publication, no accounts of missed detection by the AOP automation system have been identified.

An important initial area of focus is the evaluation of *nominal* maneuvers, which represent all test points where pilots operating AOP were instructed to execute resolutions for the first detected conflict (including RTA non-conformance) at their discretion. The term "nominal" is intended to represent expected day-to-day usage of AOP in a future anticipated UML-4 operational environment. A total of 11 test points involved operations where pilots were instructed not to execute resolutions computed by AOP to resolve RTA non-conformance and traffic conflicts. Removing these from the total count, to consider executed resolution cases only, produced a total of 100 conflict resolution cycles and 158 total unique resolutions. This resulted in an average of just over 3 resolution cycles and over 6 trajectory resolutions per maneuver. Furthermore, in all nominal maneuver cases involving a resolution execution, the conflict resolution function successfully generated conflict resolutions in the first conflict resolution cycle. On average, the first set of resolutions was provided 8.8 seconds after the time of initial conflict detection, with total computation times ranging between 3.5 and 12.1 seconds.

Nearly all test points revealed successful conflict prevention. However, one anomalous case of a repeat conflict has been documented. This single instance occurred during a maneuver which involved the OPV intruder vehicle overtaking SARA while merging at the entry point to a DFW corridor pathway. In this scenario, AOP onboard SARA successfully resolved the original expected conflict encountered with the OPV aircraft during its overtake of SARA prior to corridor entry. The conflict was resolved around two minutes TTFLOS. However, toward the end of the run SARA encountered a second conflict with OPV with a predicted LOS at the destination vertiport where both vehicles were planned to sequentially land. The pilot crew was instructed not to execute resolutions for additional conflicts for all runs and since flight test operations did not involve takeoff and landing flight phases. The conflict was ultimately ignored, and the run was ended shortly prior to both vehicles reaching the destination. Upon internal review, it was found that the repeat conflict with OPV was first detected at the conflict detection horizon point (3 minutes ahead). Three consecutive conflict resolution cycles were invoked prior to the end of the run, each providing only a speed degree of freedom resolution. Low-level inspection of the OPV EUTL plan near the point of its expected touchdown revealed that the aircraft would have only reduced a part its speed at the predicted point of conflict. Even such a minor difference in the deceleration curve during landing would have allowed enough time for the trailing SARA ownship vehicle to catch up and create a conflict. This phenomenon is thought to occur primarily due to an "accordion effect" at the destination, where two or more vehicles are commanded to reduced speed at the same location instead of at the same time. This theory is coupled with the known added complexity of additional smaller airspace volume constraints imposed on the vehicles during the landing phase. It is also a known behavior of AOP to optimize trajectory resolutions relatively close to the margins of separation, resulting in increased sensitivity for in-trail operations, especially in overtake maneuvers. Further investigation of the phenomena is ongoing.

Post-flight analysis also provided some initial insights regarding the foundational technical questions considered in the overall study. Insights include:

1. What conflict resolution success rate should FPM be required to achieve?

   Ultimate operational approval will likely require extremely high target levels of safety. An inner tactical layer of protection is expected, so strategic conflict resolution may be responsible for a lower level of assurance than the overall system requires. System-level design research is required to determine the allocation of responsibility between the strategic and tactical layers. Early FPM research defined full conflict resolution success as a 99% successful strategic deconfliction rate. Not counting one maneuver that elicited a known AOP defect [9], initial flight test results indicate all test points involving a traffic conflict were resolved by the onboard FPM automation system's strategic deconfliction capabilities; 100% conflict resolution was achieved by this safeguard layer.

2. What separation standards will ensure adequate traffic flow for expected UML-4 traffic density?

   Establishing standards for minimum separation in UML-4 operations will involve extensive research using large-scale validated traffic simulations. For this research, small separation minima were assumed necessary to accommodate anticipated UML-4 traffic densities. Assumed standards of 1500 ft lateral separation and 450 ft vertical separation were used in the simulations and the flight test. Results indicate existing FPM automation and flight guidance technology are easily capable of supporting safe flight operations using these minima. It should be noted that separation standards are determined based on many factors, and this research only considered feasibility based on capabilities of FPM automation and aircraft guidance systems. Failure scenarios were not investigated. The research also assumed a 4D guidance capability would be used. A 4D guidance approach may not be adopted in the future. This topic warrants further investigation.

3. At UML-4 traffic densities, will human operator attention and reaction time (and their variability) be adequate to allow humans to be in decision loops of the FPM function?

   Initial results indicate human operators residing on the aircraft have enough time to be in the path replanning decision loop. Research to date has not investigated the ability of remote human operators to be in the decision loop. Pilots were instructed to select a resolution advisory from the first computation cycle if possible (20-seconds default unless explicitly configured), but to use more time if necessary. Observations across a variety of flight test maneuvers revealed several instances where conflict resolutions were executed after the automation started a subsequent conflict resolution cycle. Initial analysis of quality of the computed resolutions indicates the later resolutions are acceptable. The default conflict detection horizon of three minutes may therefore be larger than necessary for safety. Nevertheless, longer detection horizons may allow more time for decision-making. Maneuvers involving increased time parameter conditions were observed to be more aligned with the natural tempo of operations conducted by the pilot crew. During debriefing sessions, research pilots directly stated a desire for longer resolution cycles, mentioning that most resolution sets

required more time to evaluate adequately. It should be noted that the research pilots were focused on FPM as their primary function during test runs. Results may have been different if the FPM task had been added to their typical task load. Human Operators' results in this study are with respect to the FPM engineering UI.

4. What is the minimum traffic separation (separation standard plus any necessary buffers) required by FPM to achieve acceptable conflict detection and conflict resolution performance?

   Results indicate excellent conflict resolution performance was achieved. However, research to date has provided only an initial exploration of sizing for separation minima and buffers. TPUBs were sized based on the trajectory conformance capabilities of the two test aircraft. Trajectory conformance precision for both aircraft was found to exceed expectations significantly. Low trajectory conformance was anticipated and was a factor in selecting the small separation minima used in the research. This foundational technical question can only be answered fully with an understanding of trajectory conformance precision required by the concept of operations. The future concept may not require aircraft to conform precisely with a 4D path. For example, aircraft may be expected to fly within conformance tolerances only for a specified time horizon, or aircraft may be expected to update their shared intent when they exceed conformance tolerances.

5. Can FPM technology (automation plus associated air-to-air communications) adequately avoid triggering a domino effect?

   Chain reaction conflicts representative of the domino effect phenomenon have not manifested in any FPM research activities discussed in this paper. Initial findings therefore suggest that the AOP conflict prevention function is effective at UML-4 traffic densities. Comprehensive testing in simulations, with each aircraft in the simulation having FPM capability, will be necessary to verify this initial conclusion. A flight test stressor scenario that increased traffic density was designed to reveal domino effect behaviors (such as secondary conflicts beyond the conflict prevention horizon), but none were found. The traffic generator's limitations in creating extremely high traffic densities narrowed the scope of the stressor scenario. As currently implemented, AOP's conflict prevention function is known to have adverse effects. Because AOP rejects any solution that would create a conflict, AOP may provide no solutions in some situations. This was not observed. Several approaches have been identified for reducing such adverse effects, including increasing the number of AOP's resolution patterns, modifying conflict prevention time horizons, and incorporating a relaxation strategy. Initial results indicate none of these are necessary for UML-4 traffic densities and operations using the assumed separation minima.

6. How do FPM functions designed for unconstrained airspace perform in constrained airspace such as UAM corridors?

   Research to date indicates dense traffic in highly constrained airspace, such as flow corridors, will require specialized FPM functionality. Observations from flight test data show that FPM functions are capable of handling corridor operations in a manner similar to how operations are handled in open airspace, but with a reduced number of resolution options. However, design and simulation of the test maneuvers in preparation for the flight test revealed current AOP functionality was not adequate for many traffic scenarios. Although some observed behaviors were caused by known AOP defects, further exploration in validated simulation will be required to gain a deeper understanding of functional needs to support corridor operations. Dynamic path planning may need to be combined with in-trail spacing functions. Of the maneuvers flown, one scenario partially demonstrated that aircraft containing an RTA at a destination within a corridor could merge at the corridor entrance and fly without conflicts to the destination. A corridor-constrained head-on scenario was also successful, while an in-trail corridor scenario was not.

VII. Future Work

Remaining future work encompasses further analysis of maneuver test points collected from the flight test and of human-operator feedback collected via pilot post-run questionnaires and debriefs. Expanded data analysis on flight test results will be used to validate simulation of the FPM reference implementation. Refinements to simulations will be performed as needed to support system validation. Extensive airspace-level research and technology development is desired to provide results for overarching concept questions defined in previous sections of this work. Discovery of flight test anomalies and "unknown unknown" performance behaviors and characteristics are to be discussed in future work. Furthermore, the FPM research team hopes to discover any unknown challenges or obscure phenomena interlaced in the perceptible complexities that are attributed to flight testing at UAM-like scale. Lastly, it is desired to couple pilot feedback from the past HITL simulation effort with pilot feedback data collected in the flight test to measure the impact of recent system implementations from the pilot perspective and to gain insight on quality

improvements to investigate in future flight testing. This includes future work to design an interface to specifically study human-machine teaming between pilots and AOP.

VIII. Conclusions

IAS-1 marks the first successful flight test of airborne automation for strategic flight path deconfliction between two live aircraft and concludes the AAM Project's National Campaign. A reference-prototype technology enabling the FPM automation system concept was developed, simulated and tested in flight. Across simulation and flight test activities, needs for further technology modifications were identified, developed and implemented to meet desired research objectives. Findings from two previous batch simulation activities verified that FPM automation system functionality exhibited a level of performance acceptable for meeting FPM flight test objectives. Initial observation and review of the data collected from the flight test reveal promising similarities to the overall behavior and performance characteristics demonstrated by the reference technology in simulation. Additionally, observations from the flight test have inspired future modifications to functions of the FPM automation reference-prototype.

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