Designing a Flight Test of a Flight Path Management System for Advanced Air Mobility Research

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The National Aeronautics and Space Administration (NASA) has completed a flight test to evaluate the performance of an onboard prototype automation system operating in future high density urban airspace. The test was part of a research investigation of the Urban Air Mobility (UAM) concept, with a focus on a future environment having hundreds of simultaneous operations over a metropolitan area. The complexity of this future UAM airspace may require automation capable of replanning an aircraft's path in the presence of traffic and other changing constraints. A live-virtual-constructive (LVC) approach was used to conduct the test. Prototype automation technology was integrated into one of the two live aircraft, which were combined with virtual traffic to create a mixed reality environment at the target airspace density. In-flight evaluation enabled verification of the automation's functions and discovery of any unexpected behaviors resulting from its operation in an actual flight environment. The in-flight evaluation also provided data for validation of air traffic simulations. This paper discusses the design, methodology, and challenges overcome to conduct a successful flight test. Remaining challenges, future work, and recommendations to improve the flight test capability are also discussed.

I. Introduction

Advanced Air Mobility (AAM) is a vision for future air transportation modes and markets based on transformative and disruptive new technology [1]. Emerging markets include the efficient movement of large numbers of people within complex urban and suburban environments. To realize this vison, the development of advanced flight automation tools may be essential. Specifically, advancements that enable the managing of flight paths via ground and onboard automation may be central to achieving safe and efficient operations as the number of AAM flight operations increases. Under the National Aeronautics and Space Administration (NASA) AAM Project's Automated Flight Contingency Management (AFCM) Subproject, the Flight Path Management (FPM) technical package seeks to

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support safe, efficient, and scalable operations by exploring the automation technology that strategically manages an aircraft's flight path in the complex AAM environment.

FPM is an element of a future concept of operations that provides strategic and dynamic flight path planning in the presence of other airspace users. *Strategic* planning retains intended mission goals when the route must be replanned, and *dynamic* planning occurs throughout the flight as often as necessary to adjust to changes in situation. Specifically, FPM provides strategic flight planning while accounting for various airspace hazards and restrictions, operational constraints such as an assigned arrival time slot, and other aircraft sharing the airspace.

NASA has developed a prototype flight path management system known as the Autonomous Operations Planner (AOP), which has a long history of use in flight path research [2-7]. In addition to strategic flight path planning, AOP can detect conflicts (i.e., predict Loss of Separation (LOS) with traffic aircraft) and avoid area hazards (e.g., convective weather, special use airspace). It uses flight intent shared from other aircraft to compute a new deconflicted four-dimensional (4D) trajectory in flight. Building on these capabilities, AOP can also respond to arrival time changes and replan its route to meet its required time of arrival (RTA).

Among the most complex operations of the AAM concept stem from intra-urban operations, known as Urban Air Mobility (UAM). To classify the high-density operations envisioned for UAM, the Urban Air Mobility Maturity Level (UML) is used [8]. While AOP was originally designed for commercial transport operations in Class A airspace, a modified version of AOP has been created to explore flight path management at UML-4 [9]. UML-4 is defined to have medium traffic levels and operational complexity, as well as dependence on collaborative and responsible automation [8]. This translates to a requirement of hundreds of aircraft flying over a metropolitan area with traffic densities that far exceed those of current operations by orders of magnitude. This modified version of AOP has been tested in batch and human-in-the-loop simulation activities in a UML-4 environment and is ready for the next phase of research [10, 11]. An opportunity to exercise AOP for UAM operations in a flight test environment with surrogate aircraft has been provided by the NASA AAM National Campaign Subproject through the Integration of Automated Systems (IAS) technical package.

This paper will describe the process of designing a flight test for Flight Path Management research at UML-4 and evaluate how effectively the design of the flight test allowed research to be successfully conducted. Along with an overview of the FPM concept and the history of AOP, a description of the flight test environment and corresponding challenges is provided. The test card and maneuver designs are outlined, and relevant connections to the core research elements are explored. Finally, the maneuver execution process is described, followed by analysis results and concluding remarks.

II. Flight Path Management Concept Overview

Under current flight operations, an aircraft's flight path is typically managed by air traffic controllers, flight planners, dispatchers, and pilots in a collaborative effort. This means that flight paths are generally a product of human-based decision-making, often enhanced by various planning tools, situation awareness information, and procedures. While these methods have led to the safe and efficient airspace system of today, current methods of managing flight paths will undoubtably prove insufficient in a future AAM environment. AAM complexities such as higher traffic densities, smaller separation standards, higher quantity of flight operations, and complicated traffic interactions are expected to overload the capabilities of conventional Visual Flight Rules and Instrument Flight Rules [12]. To address the higher demand of the future AAM operational airspace, NASA Langley Research Center has developed a prototype FPM automation system [13]. Langley has used the system in simulations to conduct extensive research to further refine the FPM concept [10, 11].

A. FPM Automation

FPM automation performs the functions of dynamic path planning [12] to continually deconflict a subject aircraft's flight path from traffic and other hazards, while adhering to aircraft and airspace constraints and achieving mission objectives such as schedule conformance and flight optimization goals. These automation functions are separate from those that establish or revise mission objectives, react to sudden tactical hazards (e.g., Detect and Avoid), or conform to an established flight path [14].

The goal of FPM automation is to provide a safe and operationally acceptable flight path throughout the flight. The objectives of an FPM automation system are to maintain the following five flight path qualities:

- Feasible: 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.
- Deconflicted: Avoids unsafe proximity to known aircraft, dynamic obstacles, inclement weather, and other emergent hazards.

- Harmonized: Follows cooperative rules and procedures to ensure that the use of the airspace is coordinated with other airspace users.
- Flexible: Provides adequate maneuverability to ensure future flight path changes, if needed, are available and feasible.
- Optimal: Best achieves the operator's business objectives for the specific flight.

To achieve its objectives, an FPM automation system conducts five primary tasks to manage a flight path, which are:

- *Creating* the flight path
- *Monitoring* the flight path and the factors which may impact it
- *Evaluating* ongoing acceptability of the flight path and proposed changes
- *Revising* the flight path, as needed, to sustain the desired qualities
- *Coordinating* the flight path with other airspace users and service providers

B. Autonomous Operations Planner

To conduct FPM research during the IAS Flight Test (referred to as IAS-1), the NASA Langley research team selected the AOP to act as the prototype FPM technology. AOP was developed as a research tool to investigate advanced onboard functionality to enable an aircraft to self-separate from other known aircraft, weather hazards, and special-use airspace (SUA) while still conforming to traffic management constraints such as an RTA or a requirement to meet an altitude at an arrival fix. By performing these separation functions using a technology located on the flight deck, the load on ground-based air traffic monitoring can be reduced, especially in the context of the complex airspaces expected for AAM operations [12]. While AOP is designed for research and not actual operations where safety critical certification is required, it approximates the functionality anticipated to enable UML-4 operations and supports research in refining and maturing those requirements [8]. AOP serves as a reference technology to investigate functional requirements and prototype algorithms rather than achieve high levels of system assurance.

AOP has been developed for more than two decades using batch studies and human-in-the-loop (HITL) simulations. To be selected as the FPM reference technology in the AFCM Subproject, AOP was modified for UAM-focused research. Before AOP was evaluated in flight, a series of test activities were performed on the UAM version of AOP to ensure FPM research objectives could be achieved, any technical challenges were identified and solved, and any unexpected artifacts from previous versions of AOP were discovered. These two studies are known as "FPM-1" and "FPM-2", and details can be found in Reference [10] and a companion paper, which can be found in Reference [11]. Additional details on AOP functionality and performance during the IAS-1 flight test can be found in the companion paper "An Experimental System for Strategic Flight Path Management in Advanced Air Mobility" [9].

III. Designing an FPM Flight Test Environment

The FPM portion of IAS-1 sought to evaluate the functionality and performance of FPM automation using a reference prototype system, identify technical barriers of the FPM automation concept, and discover emergent systemic behaviors and operational challenges associated with using the FPM technology. To maximize the efficacy of the flight test opportunity, a relevant flight test environment consistent with UML-4 operations needed to be designed. This section of the paper describes how the flight test environment was designed to conduct relevant FPM research for a future operational environment while flying within the current operational environment.

A. Initial Design

Early in IAS-1 planning, two decisions helped to create the desired future operational environment of UML-4: choosing flight test aircraft and defining a live-virtual-constructive (LVC) airspace operating environment. These decisions were used to develop a concept of test operations. This concept of test operations was specifically designed to define the high-level FPM use case for IAS-1, which provided a baseline for functional, performance, operational, and environmental requirements for data collection.

1. Flight Test Aircraft

To test the FPM technology, two research aircraft provided by Sikorsky Aircraft Company were utilized in IAS-1: the Sikorsky Autonomy Research Aircraft (SARA) S-76B helicopter and the Optionally Piloted Vehicle (OPV) S-70 Black Hawk, both pictured in Fig. 1. All flight operations involving SARA and OPV were piloted for safety and in an effort to represent the future UML-4 concept. In addition to the pilot in command, each aircraft's crew included a NASA research pilot onboard who operated the FPM and IAS systems.

(a) (b)

Fig. 1 SARA Ownship (a) and OPV Intruder (b)

Photo credit: Lockheed Martin Sikorsky Aircraft. Used with permission.

These vehicles served as surrogates for future eVTOL aircraft. Both aircraft had operational limitations that had to be considered in the design of the flight test. Limitations of the two aircraft include an indicated airspeed limit, an indicated airspeed minimum, and a ground speed limit. For this flight test, SARA was referred to as the *ownship* aircraft hosting AOP and the OPV aircraft was referred to as the *intruder* aircraft which had the role of creating the planned encounters with ownship.

2. Airspace Operating Environment

The two flight test aircraft operated in a mixed-reality, medium-traffic-density airspace with a minimum of 150 simulated traffic aircraft flying routes defined by the simulated UML-4 operating environment of the FPM-2 activity [11]. This LVC approach was identified as a safe and cost-effective way to achieve the required traffic density levels to represent UML-4. The simulated UML-4 operating environment was based on studies conducted by NASA Ames Research Center and the Virginia Tech Air Transportation Systems Laboratory [15]. The region of airspace surrounding Dallas/Fort Worth Airport (DFW) was selected as the more challenging of the two cases documented in the reference. Unusable airspace, represented as “area hazards” to avoid, is significant, making up 11.6% of total airspace for the modeled DFW region. These restrictions, shown as yellow regions in Fig. 2, represent airspace heavily used by commercial traffic through DFW and other area airports.

Future demand was modeled, and vertiports were identified and located based on mapping the anticipated demand to the region. Routes between vertiports were designed to minimize path distance while avoiding restricted airspace, but were not restrictive (i.e., UAM flights were free to navigate in the open airspace). Corridors were added to allow for less circuitous paths between vertiports. Figure 2 illustrates the simulated UML-4 operating environment used for the study. This simulated operating environment was used for previous FPM batch studies and simulations to represent a UML-4 environment [10, 11].

All aircraft, including the flight test aircraft (SARA and OPV) and simulated background traffic, exchanged aircraft state information (current position, track, groundspeed, altitude, and vertical speed) and flight path intent information (full 4D trajectory to their destination). To facilitate communication of this information between the two flight test aircraft, SARA and the OPV aircraft were equipped with Automatic Dependent Surveillance—Broadcast (ADS-B) Out/In and a proprietary Sikorsky telemetry system. ADS-B was used to share state information between the two flight test aircraft, and the Sikorsky telemetry system was used as a proxy for future communication technologies to share intent and other information.

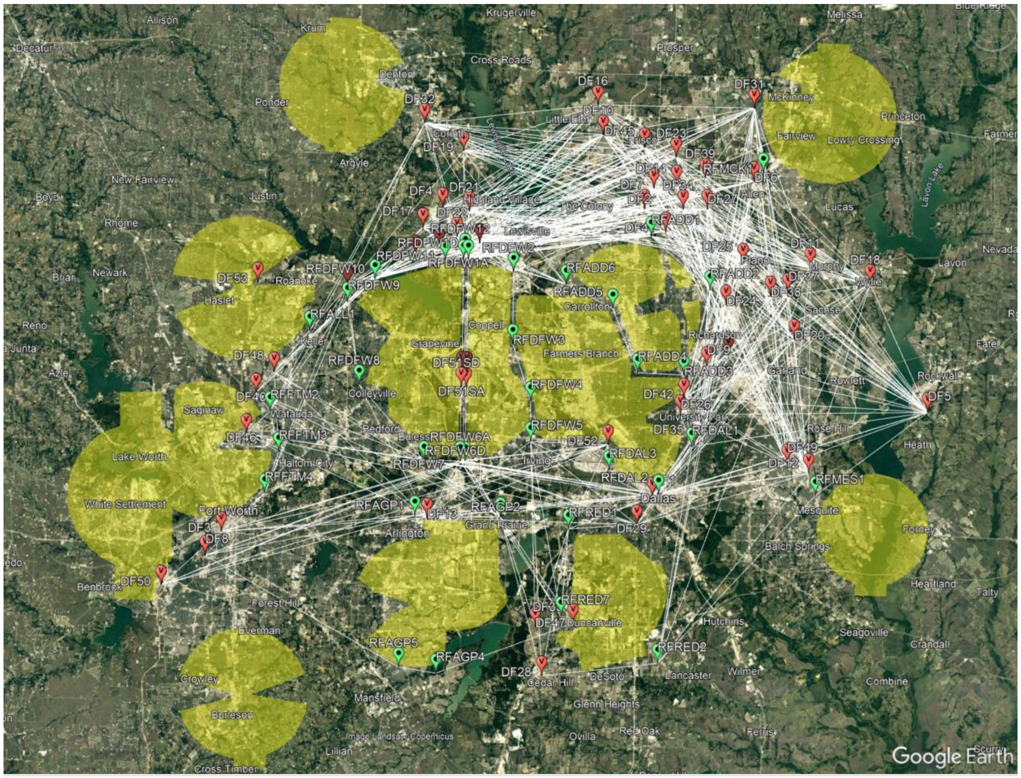

Fig. 2 Virtual UAM UML-4 Operating Environment

3. *Concept of Test Operations*

SARA was the only aircraft in the flight test equipped with AOP, including both the primary AOP engine and an engineering user interface, the “FPM Engineering UI,” for the research pilot to observe and invoke AOP functionality. The AOP software interfaced with SARA’s avionics to receive ownship information (e.g., aircraft state data) and with the Sikorsky telemetry system to obtain information originating off-board the aircraft (e.g., traffic aircraft state via ADS-B In and intent information). Additionally, SARA was equipped with Sikorsky’s Autonomous Mission Manager system (AMM), which provided 4D trajectory guidance to the aircraft based on 4D trajectory plans provided by the AOP software. The FPM engineering UI was located on a portable touchscreen tablet. It provided a graphical display of the current operational situation and served as a mechanism to preview, select, and execute AOP-generated trajectory change solutions. Additional information on the flight test systems and their interoperability can be found in the next section.

B. IAS-1 Test System

IAS-1 was a multi-center, multi-organization effort that required collaboration between several research teams and technical personnel, as well as integration of multiple sophisticated technologies. Significant integration efforts were needed to ensure that these complex technologies were harmoniously integrated to produce the functional test system required to successfully meet the planned research goals. The development and integration of the IAS-1 Test System occurred over the course of a year through a series of preparation flights. These initial flights allowed the NASA teams and Sikorsky to test system integration, identify and resolve technical issues, and solidify the operational methodology. As a result, the finalized IAS-1 test system was developed. The test system constituted three main elements represented by the predominant boxes in Fig. 3 – the ownship (SARA), the intruder (OPV), and the ground control station. Each element comprised of a set of research systems and technologies, which were interconnected by various data or communication links. The arrows in Fig. 3 show the interaction type between the various technologies and human operators.

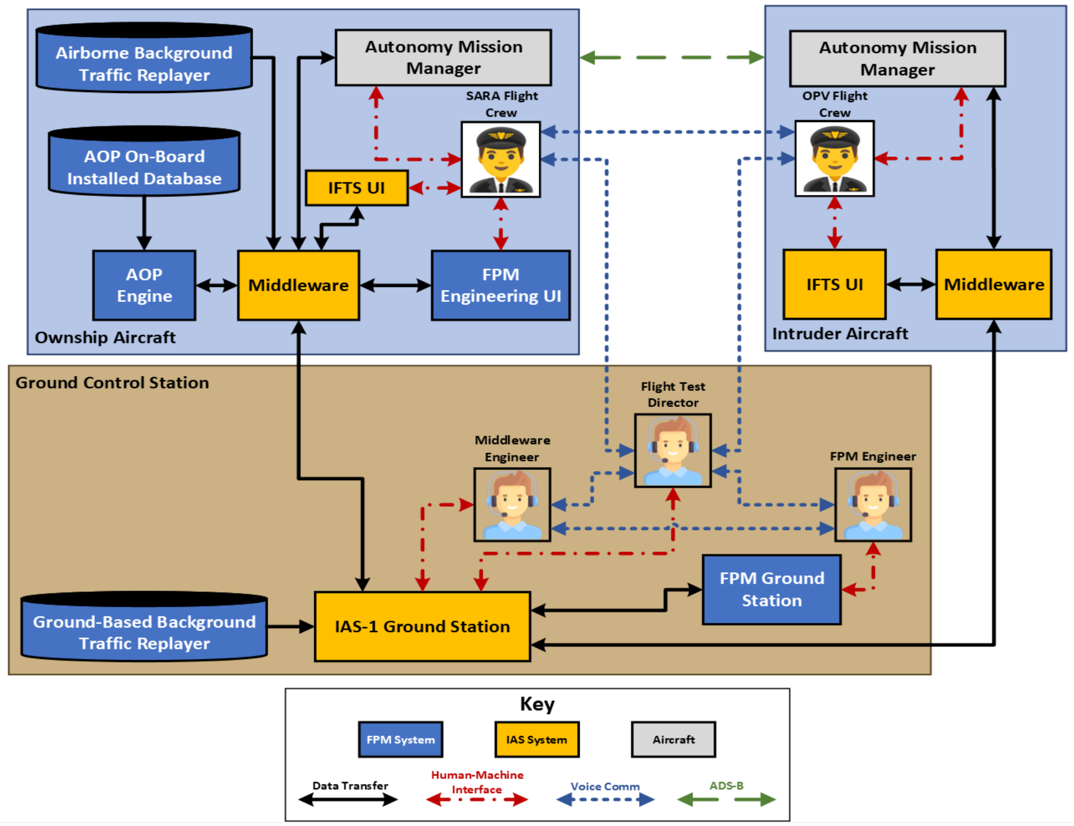

Fig. 3 Simplified IAS-1 Test System Overview

1. *AOP*

AOP generated the ownship 4D trajectory intent, detected conflicts (e.g., traffic, airspace, hazards along the active route), and computed trajectory change solutions in response to detected conflicts (e.g., lateral, vertical, speed, hybrid). Additionally, AOP generated AOP health monitoring data for situation awareness on current data reliability. AOP also logged a collection of data files for use in post-test research analysis activities.

2. *FPM Engineering UI*

The FPM Engineering UI provided a graphical display of the LVC operational situation and environment (e.g., present position, current route, winds, conflicts, applicable constraints), as well as a mechanism for the ownship research pilot to preview and select AOP-generated trajectory change solutions. The FPM Engineering UI also took the AOP health data from the AOP Engine and displayed it to the user. The display was only used by the ownship research pilot to interact with AOP, not the intruder pilot or ground crew. The FPM Engineering Display is pictured in Fig. 4 featuring the ownship active trajectory (magenta track), a hybrid resolution advisory (cyan track), and the intruder's trajectory intent (yellow track).

3. *FPM Ground Control Station*

Like the FPM Engineering UI, the FPM Ground Control Station (FPM GCS) provided a graphical display of the LVC operational situation from ownship's perspective (e.g., present position, current route, winds, conflicts, applicable constraints). It also provided a mechanism to view (no selection functionality) AOP-generated trajectory solutions via graphical interface, as well as displayed AOP health monitoring data. The display was only used by the FPM engineer on the ground, not the ownship or intruder pilot. The FPM GCS graphical display is shown in Fig. 5, which depicts the target ownship maneuver trajectory (magenta track), automated guidance to the maneuver start point (SP) (blue track), and the track actually flown by ownship (yellow track behind the ownship chevron). The bright yellow outline that the blue track passes through is a SUA from the DFW operating environment used for all FPM maneuvers. SUAs within the virtual environment were disregarded as obstacles through all flight operations prior to AOP engaging at the maneuver SP.

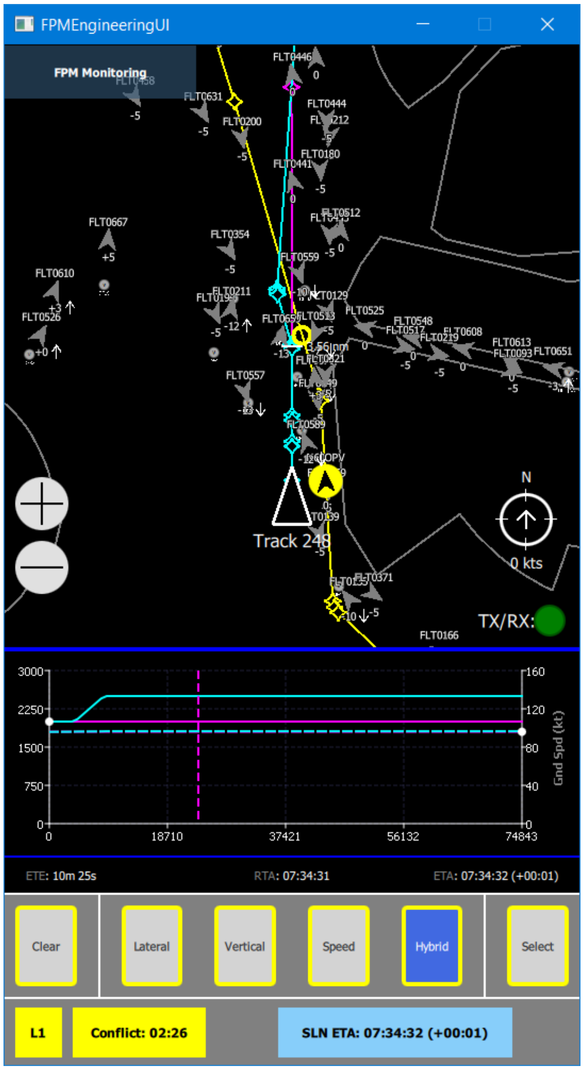

Fig. 4 An Acute Crossing Encounter on FPM Engineering UI

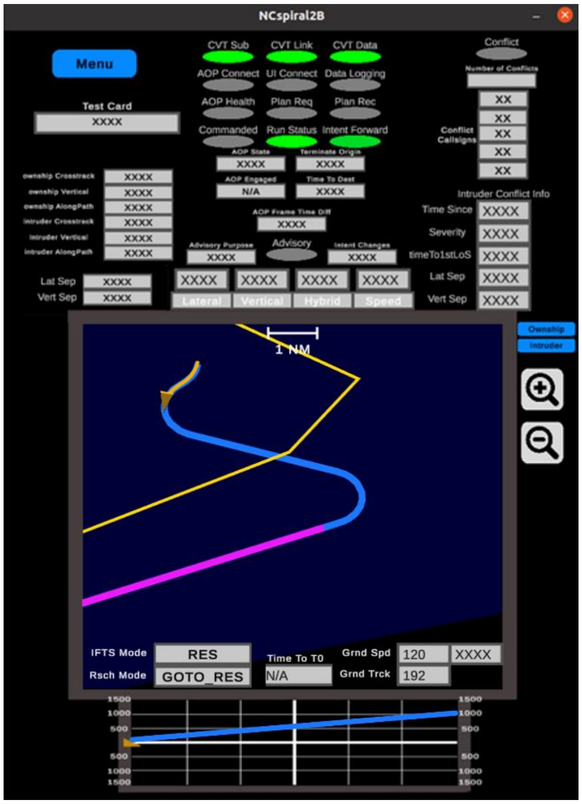

Fig. 5 FPM Ground Control Station

4. *AOP On-Board Database*

The AOP On-Board Database was a collection of AOP data specific to the FPM research test groups. The database included AOP configuration files, flight maneuvers and scenario information, wind data, and avoidance polygons. This database only outputted to AOP via disk.

5. *Background Traffic Replayer*

The Background Traffic Replayer provided the virtual traffic playback needed to achieve UML-4 traffic density to conduct FPM research. It provided playback background traffic state data at 1 Hz with intent data, which was distributed only when the background traffic intent was created or changed. The Background Traffic Replayer provided state playback in the air to the SARA aircraft and on the ground to the IAS-1 Ground Control Station (IAS-1 GCS).

6. *IAS-1 Ground Control Station*

The IAS-1 GCS was an interactive display that allowed the IAS test engineers to transmit test group specific scenario and AOP configuration data to the IAS Middleware (MW), which acted as a centralized data hub, for distribution (Fig. 6). IAS-1 GCS also played a role in setting up coordinated guidance to the start of each FPM maneuver. It was also able to receive AOP-generated and selected trajectory change requests for sending to the FPM GCS.

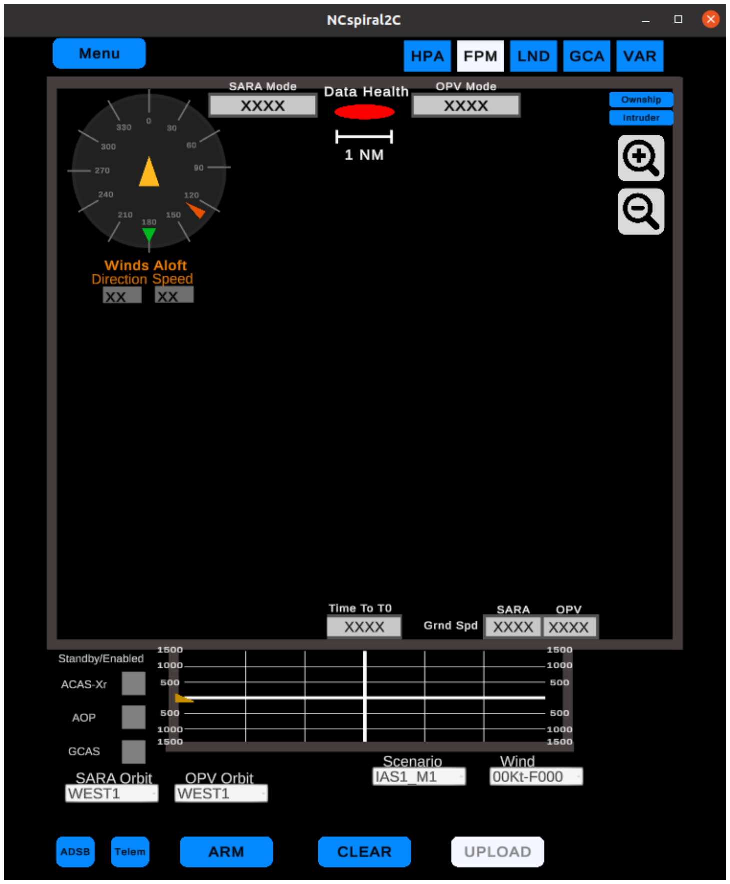

Fig. 6 IAS-1 Ground Control Station

7. *Autonomy Mission Manager*

Both Sikorsky research aircraft were fitted with the Autonomy Mission Manager system, which is what allowed the aircraft to automatically execute a 4D trajectory. The AMM was developed by Sikorsky to be their research autonomy system and is hosted on the onboard High Performance Computer, along with the other software onboard the aircraft. To fly AOP-generated 4D trajectories with the Sikorsky research aircraft, the MW interfaced with the AMM system, converting information into a format readable by the AAM. AMM interfaces with the aircraft systems by communicating with the Vehicle Management Computer (VMC), which hosts safety-critical flight software.

8. *Middleware*

AOP was integrated for flight test by the IAS team utilizing the MW. The MW provided an aircraft-agnostic method to integrate automation technologies, in which the aircraft specific interfaces were behind an abstraction layer. This abstraction layer allowed the automation technology to be integrated with the MW, and then become insulated to changes to the sources of the ownship and the intruder states as well as changes to the way that the autopilot was commanded. The automation technologies were integrated within a "Monitor" plugin that was hosted by the MW. A Monitor is the mechanism in the MW architecture to host systems that generate and send commands based on a Run Time Assurance framework as described in Reference [16]. The MW was able to host multiple Monitors while keeping the behavior predictable for individual Monitors. The MW was utilized on both SARA acting as ownship and OPV acting as the intruder. The IAS Flight Test System (IFTS) was also included in the MW as a Monitor. IFTS allowed the AOP test scenarios to be configured and executed from the IAS-1 GCS (Fig. 6) by a MW Engineer (MWE) in such a way that both the ownship and the intruder were at the desired location and a coordinated time. This allowed for precise test engagements to be coordinated that allowed the FPM team to repeatably execute test encounters.

The AOP Monitor that was hosted by the MW running on an Intel NUC (Next Unit of Computing) platform acted as a central hub for the AOP system (Fig. 7), which consisted of AOP hosted on a second Intel NUC, the FPM Engineering UI which was hosted on a Getac F110 tablet, and an FPM GCS (Fig. 5). The AOP Monitor was responsible for providing the AOP system with ownship state, intruder state, intruder intent, virtual background traffic state and virtual background traffic intent. The AOP Monitor set up each test encounter based on predefined scenarios which involved configuring virtual background traffic state and intent playback as well as configuring the AOP engine for that specific test maneuver. The intruder intent was received from the MW instance on OPV via a message repeater in the GCS. The AOP Monitor wrote key parameters to a MW-provided database called the Current Value Table that was written to a log and was also streamed to the ground to feed data to the FPM GCS. The MW handled the conversion of the time-based trajectories that AOP generated in the Efficient Universal Trajectory Language (EUTL) [17] format to the velocity-based commands that the SARA and OPV AMM expected. This was done through a velocity controller that minimized time error via velocity modulation. These velocity commands are then communicated by the AMM to the VMC, which is responsible for executing them.

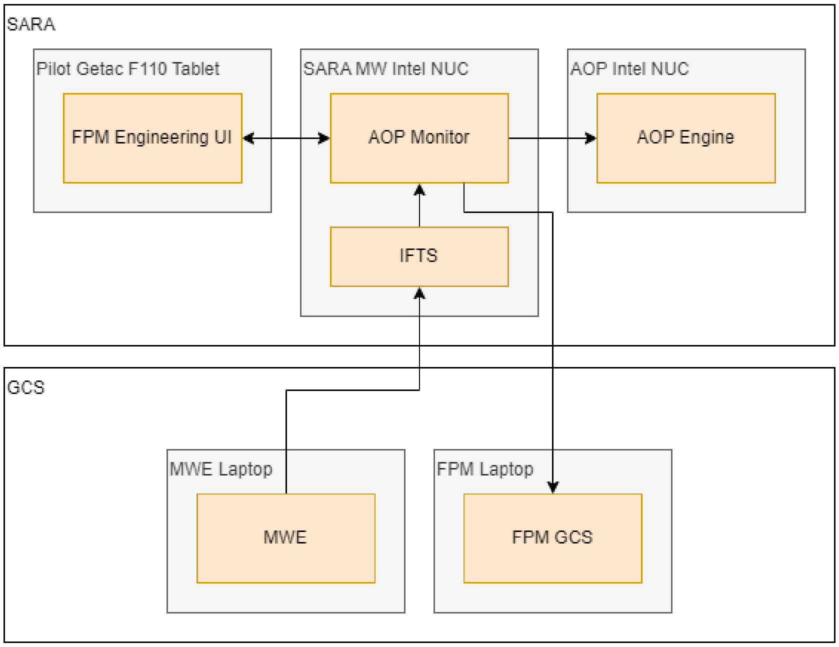

Fig. 7 Middleware Monitor Configuration

C. Final Design Considering Operational Constraints

Once the research requirements were formulated into a flight test design, the design was refined based on operational constraints and limitations associated with the selected test area. These constraints and limitations included test area boundaries, transposing the simulated UML-4 environment around DFW to the real-world test area of Long Island Sound near Bridgeport, Connecticut, accounting for daily wind forecasts, setting AOP configuration parameters, and conforming to mission rules. The following sections describe the impact of these factors on the flight test design.

1. *Test Area and Boundaries*

The test area was established over the Long Island Sound with flights originating from Sikorsky Memorial Airport (BDR or KBDR). NASA and Sikorsky partnered to define an area over the Long Island Sound to contain all flight-test operations, as shown by the magenta box in Fig. 8. The rectangular area was centered immediately south of BDR with a length of approximately 27.5 statute miles running southwest to northeast along the sound, and a width of approximately 13 statute miles. SARA and OPV aircraft remained within 20 NM of each other and within 25 NM of BDR to ensure a strong data link and to minimize interaction with nearby commercial operations. Within the 25 NM radius of BDR (red circle) were New York Class B airspace (dark blue), Long Island Macarthur Airport Class C airspace (purple), and the Bridgeport/Sikorsky Airport Class D airspace (light blue), along with many others as seen in Fig. 8.

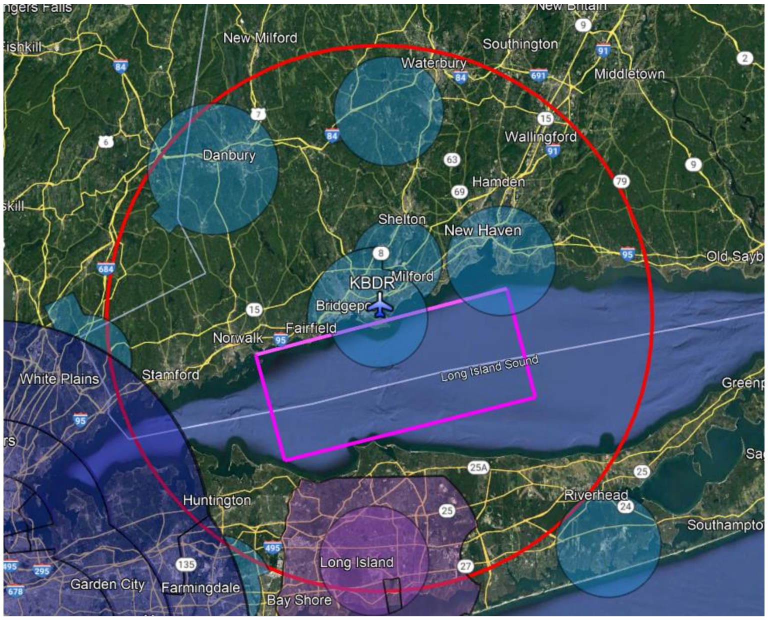

Fig. 8 Airspace Surrounding Sikorsky Memorial Airport (BDR)

Overlapping the test area with Class D BDR airspace was determined to be acceptable due to the familiarity of air traffic controllers at BDR with Sikorsky flight test operations. The flight crews of the SARA and OPV aircraft coordinated with BDR tower as necessary, though Class D airspace was avoided whenever possible to simplify the pilot's workload. Additionally, New Haven Class D airspace intersected the northeast section of the Sikorsky boundary box and was avoided completely to minimize ATC coordination.

2. *Transposition of the UML-4 Operating Environment*

To incorporate the simulated UML-4 DFW operating environment in the flight test, the environment was transposed and rotated to a geographical coordinate near BDR. A particularly aircraft-dense section of the environment was chosen to overlay within the Sikorsky boundary to ensure UML-4 traffic density was represented. This section along with vertiports (yellow pushpins), vertiport routes (white lines), and restricted airspace regions (yellow polygons) can be found in Fig. 9. The rotation angle varied between test points based on the ownship trajectory orientation and the purpose of the encounter. For some test groups, the restricted airspace needed to be repositioned to create certain constraints or encounter geometries. One such maneuver required one of the corridors from the UML-4 operating environment to be positioned within the magenta boundary, which led to a new transposition of the operating environment.

Rotating the DFW environment not only repositioned the restricted airspace regions but also changed the cardinal direction of the virtual traffic. Due to how the simulated background traffic is currently generated, changing the cardinal direction of the traffic at its origin point also altered at what altitude the traffic flew. All simulated background traffic flew at either 1500 ft, 2000 ft, or 2500 ft based on if the aircraft was traveling 0°-120°, 120°-240°, and 240°-360°, respectively. This was accounted for when designing each maneuver to ensure the ownship would be influenced by an adequate amount of co-altitude simulated background traffic.

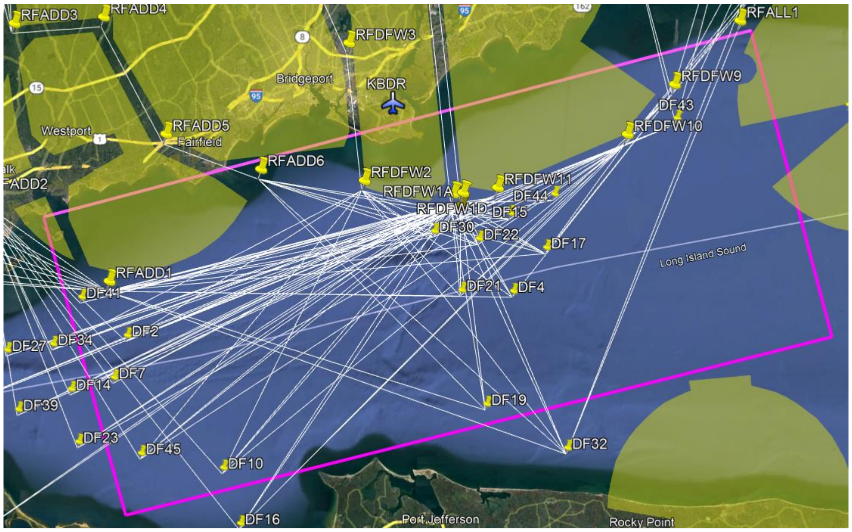

Fig. 9 Dallas/Fort Worth (DFW) UML-4 Database Overlaid on the Surrounding BDR Airspace

3. *Encounter Scenario Generation*

In order to construct 4D trajectories that ensured the intended encounter between the two flight test aircraft, the scenario generation tool that was used to generate the FPM-2 random scenarios was extended to also produce 4D trajectories for the ownship and intruder for the specific encounter geometry (crossing, head-on, overtaking, and overtaken) and other factors (RTA changes and additional, hand-placed constraining traffic) required for each cell in the test matrix. The scenario tool is built around the same Behavior-Based Trajectory Generator (BBTG) that is used in AOP [9, 18]. The BBTG is used to compute kinematically complete, flyable trajectories for each UAM vehicle type and origin-destination pair needed in the scenario. For background traffic, these trajectories were used to schedule non-conflicting operations at each vertiport. For the ownship and intruder, these trajectories were used to time align the flights to each other at the conflict point and then extract the necessary initial conditions (position and velocity) to stage the vehicles a specified time before the point of interest. For background aircraft and the intruder, the time-aligned 4D trajectories were recorded using the EUTL for use by the Airborne Background Traffic Replayer and the Middleware running on the intruder [17]. For ownship, a mission specification was captured and passed to AOP at the beginning of the scenario to enable AOP to recreate the desired ownship trajectory using AOP's copy of the BBTG. To ensure that the Ownship did not encounter a conflict with a virtual background traffic before the intended encounter with the Intruder aircraft, the scenario tool checked all background traffic trajectories for conflict with the ownship trajectory beyond the initial condition and removed the few conflicting background flights.

Because the generated scenarios are based on ground-referenced 4D trajectories that dictate what ground speed each vehicle must fly, the scenario generation process must include a wind prediction so that the vehicle trajectories reflect the desired vehicle airspeeds. The scenario data needed to be generated weeks before the flight test, so scenario data for each test matrix cell was generated using a set of wind condition permutations to create a database of flyable scenario data indexed by wind condition. Because the 4D guidance systems onboard the two test vehicles would be adjusting airspeed to conform to the ground speeds prescribed by the 4D trajectories, it was only necessary to use a wind condition matrix fine enough to be within about 10 kt of the actual winds present during the sortie. The completed database resulted in the ability to select a maneuver configuration based on the wind conditions during that sortie to successfully achieve the desired conflict. The full list of wind speed and direction combinations generated for each maneuver totaled 37, including a 0 kt case (Table 1).

Table 1 Wind speed and direction combinations for each maneuver.

Wind Speed (kt)	Wind Direction (degree)
0	N/A
10	000, 060, 120, 180, 240, 300
20	000, 060, 120, 180, 240, 300
30	000, 030, 060, 090, 120, 150, 180, 210, 240, 270, 300, 330
40	000, 030, 060, 090, 120, 150, 180, 210, 240, 270, 300, 330

The scenario tool included checks to flag wind conditions that would result in ownship or intruder exceeding the vehicle ground speed limits or that placed the vehicle initial conditions in the middle of a turn or other non-steady-state condition. This was used to provide the flight director with a matrix of which wind conditions were acceptable for each maneuver.

As an additional safety precaution, each maneuver was intentionally designed to never have a closest point of approach (CPA) closer than 0.2 NM between the two aircraft. The lateral LOS distances used by AOP to detect conflicts for this test was approximately 0.25 NM, so this precaution did not cause any additional difficulty in setting up conflicts.

4. AOP Parameter Alterations and Simplifications

To prepare AOP for the UAM use case at UML-4 traffic density levels, as opposed to commercial transport operations, several modifications needed to be made to the technology. To accommodate the increased density levels, many algorithmic efficiency improvements were implemented. The separation standards assumed by AOP were lowered to 1500 ft laterally and 450 ft vertically. Along with the two reference eVTOL performance models that were created for UAM, an additional eVTOL model was created that specifically incorporated the speed limitations of the Sikorsky research aircraft. To work with the eVTOL models, modifications were made to AOP's trajectory generator so that the fitness function could use battery energy storage as a trajectory optimization measure. Furthermore, the number of resolution degrees of freedom was increased to four with the addition of speed-change-only resolution type. Another update modified the ownship and traffic trajectory prediction functions to be based on ground-referenced 4D information shared between aircraft, which used the EUTL format. This came with the assumption that the aircraft would conform to shared 4D trajectory intent for the entire duration of the flight.

For the purposes of IAS-1, AOP's detect and avoid (DAA) capability was turned off. In previous applications of AOP, a tactical layer of AOP was employed to handle deconfliction once a conflict had progressed past the strategic intervention window into close proximity of the LOS event. For this flight test, AOP's DAA capability was not needed because only AOP's strategic capability was under test. Furthermore, AFCM's Hazard Perception and Avoidance research team conducted a series of tactical scenarios to test their DAA technology during the flight test alongside FPM.

Based on initial batch testing, a series of AOP time parameters were updated for the denser airspace resulting in the following baseline time parameters: a 3-minute Conflict Detection (CD) Horizon, a 6-minute Conflict Resolution (CR) Buffer, a 40-second Resolution Freeze Horizon, and an 18-second AOP Resolution Refresh Cycle. The CD horizon determines how far out AOP looks to detect a traffic conflict. The CR Horizon is a combination of the CD Horizon and the CR Buffer, which determines how long after the LOS point a resolution is guaranteed to prevent another conflict. The Resolution Freeze Horizon refers to a portion of the original trajectory starting where the ownship currently is that must remain unaltered by the computed AOP resolution. The AOP Resolution Refresh Cycle is how long AOP waits before it begins computing new resolutions. As part of the FPM research conducted, one test group focused on altering these time parameters to investigate their effect on AOP performance.

One concern associated with using 4D trajectories was the trajectory conformance capabilities of the research aircraft. To account for uncertainty in the trajectory being flown, AOP utilized Trajectory Prediction Uncertainty Bounds (TPUBs) [13]. TPUBs can be visualized as 4D boxes surrounding the aircraft defined by cross-track, altitude, and time along path. These boxes provide buffer zones that allow trajectory uncertainty to be accounted for. The TPUBs used for IAS-1 were set based on early 4D trajectory conformance testing, which resulted on relatively tight tolerances. The TPUB buffers flown during the test were ±150 ft cross track, ±25 ft altitude, and ±3 seconds along path.

To ensure there was always an aircraft designated with the responsibility to resolve a conflict with other aircraft, AOP used priority rules to make that determination. However, for the purposes of IAS-1, only one aircraft (the ownship) was fitted with an AOP system. Due to the way the priority rules were set up, some maneuvers in simulation would result in the ownship aircraft having priority, which meant AOP would wait for the intruder aircraft to resolve the conflict. Since the intruder aircraft was not equipped with AOP, the only option was to wait until priority switched over to the intruder aircraft, permitting the ownship aircraft to utilize AOP to resolve the conflict. It was desired to avoid these situations because it reduced the amount of time AOP had to resolve a conflict once priority was switched, and it ultimately altered the intended execution of each maneuver. For these reasons, AOP was configured to recognize all other traffic aircraft as "unequipped", or operating without AOP, to ensure the ownship would always yield the right-of-way (thus, allowing the ownship aircraft to utilize AOP for the maximum extent practical) during the flight test maneuver.

5. *Conforming to Mission Rules*

For safety, flight mission rules were developed by the IAS-1 operations team at NASA Armstrong Flight Research Center. Specific to FPM, all FPM encounter geometries were designed so the closest point of approach of the SARA flight plan and the OPV flight plan was never less than 0.1 NM laterally. There was no equivalent vertical offset. Additionally, encounters between the SARA and OPV aircraft were designed so separation would never actually be lost; maneuvers were procedurally terminated well prior to separation loss (at least 30 seconds prior to LoS). If the two aircraft were separated by less than 500 ft vertically, visual acquisition of the other aircraft by one of the pilots was required within 0.75 NM. The two aircraft were only allowed to be within separation standards if an AOP generated resolution had been executed and the two aircraft were in the process of diverging from each other. Unless otherwise specified, maneuvers were designed to be flown at a 2000 ft altitude. However, all maneuvers were subject to a 500 ft above ground level altitude floor. Furthermore, if any anomalous behavior from the research maneuver or test system was experienced, that run was subject to termination. Finally, if any non-participating aircraft were observed within 2000 ft vertically and 3 NM laterally of either flight test aircraft or the non-participating aircraft and could not be determined to be a non-factor (i.e., flying a non-convergent flight path with either test aircraft), the test run was terminated. All present personnel had the ability to terminate a run that they deemed unsafe at any time using the NASA "Knock-It-Off" best practice [19].

IV. Creating Intentional Traffic Conflicts

One of the most difficult challenges to be solved for IAS-1 was reliably creating conflicts between the ownship and the intruder so AOP could resolve them. As explained below, specifying a predetermined 4D trajectory for each aircraft to follow was found to require extra steps to create a conflict that meets test objectives. The need for preprocessing to create the conflict also resulted in a requirement for the two aircraft to coordinate their starting locations and speeds, as well as a procedure for arriving at their SPs simultaneously.

A. Establishing Starting Points

As discussed in Section III.C.3, FPM created a preprocessing tool to generate a given 4D trajectory for a multitude of wind speed and direction combinations that might be present on test day. This scenario generation tool helped ensure that, despite the airspeed and ground speed limits of the Sikorsky research aircraft, each maneuver could almost always be flown if the test day winds were included within the matrix of compensated winds (Table 1). In a few specific wind conditions and maneuver combinations, it was not possible to fly the maneuver without exceeding the Sikorsky ground speed limits. These specific instances were noted before the test and precautions were incorporated into the execution plan for the test. The tool used the intended location of separation loss as an input, and it computed the trajectories of each aircraft that would create the loss. It therefore determined the starting locations, which were a function of wind speed and direction at the time of the test. These starting locations were referred to as the T_0 points.

A T_0 point was generated for both aircraft for a given maneuver and consisted of a latitude, longitude, altitude, groundspeed, and ground track angle where the aircraft was required to be at the start of the maneuver to ensure the intended scenario was achieved. Depending on the effect of the wind compensation, the T_0 point would shift approximately 1 to 2 nautical miles in either direction along the initial track angle at the start of the maneuver trajectory. The combination of location and speed at T_0 allowed the two aircraft to arrive at the intended location in time to coordinate the desired CPA based on the specific maneuver's objective.

Trajectories computed by different trajectory generators will likely not be identical, even if they are provided the same trajectory constraints. Different trajectory generation algorithms use differing approaches and assumptions in their computations. In preparation for the flight test, it was discovered that specifying a trajectory that was not computed by the AOP's trajectory generator, BBTG, often resulted in an unintentional removal of the conflict as the trajectory was recomputed by AOP. In computing the trajectories of the aircraft, the scenario generation tool therefore executed the BBTG to ensure no trivial resolutions removed the conflict. Additional details may be found in Reference [9].

B. Navigating to the Starting Points On-Time

In addition to the challenge of creating the correct T_0 points in conjunction with the desired 4D trajectory to successfully create the intended conflict, functionality was needed to ensure the two aircraft arrived at T_0 simultaneously to start the test run. IFTS was responsible for configuring the test runs for AOP and ensuring that SARA and OPV were at the desired location, and velocity vector at a known time for T_0. T_0 was a foundational parameter for each AOP test scenario, that could only be computed and coordinated with both SARA and OPV moments before the scenario began. To accomplish this coordination, an operational flow (Fig. 10*)* was created that allowed both aircraft to loiter at a known and predefined orbit location while the coordination was completed prior to release from the orbits.

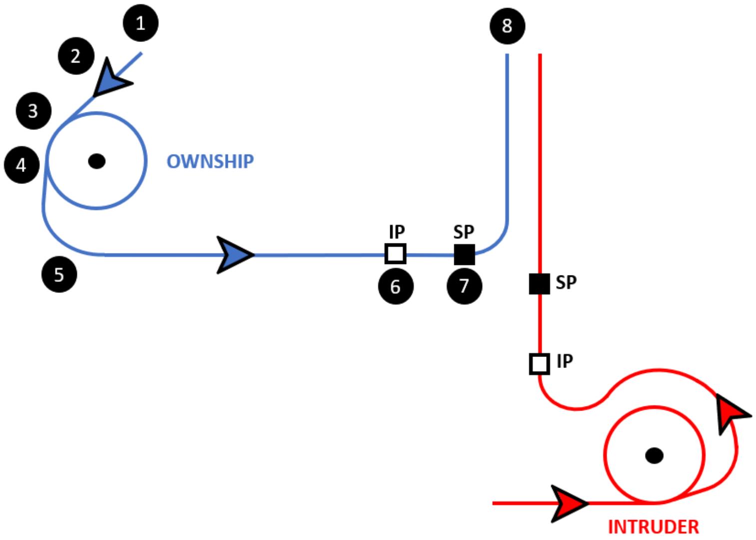

Fig. 10 Operational Flow of IFTS Navigation to Run Start Points

The operation flow used to enable the execution of FPM maneuvers was completed with the following steps:

1. Idle: System idle and waiting for test scenario setup. During this stage, the aircraft will fly straight and level allowing for an accurate wind estimate.
2. Orbit Staged: The test orbit location for both the ownship and the intruder is selected and staged. The specific test maneuver is selected, and the wind estimate is used to select between the quantized set of wind speeds and directions.
3. Orbit Approach: The test aircraft is approaching to enter the desired orbit location tangentially at the desired orbit direction.
4. Orbit Idle: Both aircraft loiter in the desired orbit locations until both are ready to begin the test run.
5. Research Approach Coordination: IFTS on both aircraft computes the time it would take to arrive at the Initial Point (IP) when flying straight and level, which is determined to be 10 seconds away from the SP. The SP corresponds to the same location at T_0. The aircraft with the longest time to arrive at the IP is used to set the T_0 time, and that aircraft is staged and ready to proceed with its computed route pending coordination with the other aircraft. The aircraft with the lesser time iterates through 1 second intervals in the orbit, and then recomputes the time to arrive at the IP until it is near the first aircraft's longer period to T_0.
6. Research Approach: Both aircraft finish coordinating a T_0 time, and the approach trajectories are commanded.
7. Research Mode: T_0 is achieved, so the MW hands control over to the AOP Monitor to fly the FPM maneuver.
8. End Mode: FPM run is completed and the test run ends.

V. Test Design

A set of eight test groups were developed to conduct FPM research during IAS-1, each of which was made up of several test maneuvers. The maneuvers were designed to account for the limitations of the test area and research aircraft, and incorporated the insights made from the outcomes of preliminary flight testing. Each test group was crafted to gather flight test data to support four research elements that will help increase the understanding of AOP functionality and its effectiveness in a relevant environment. These research elements were Function Verification, Concept and Technology Advancement, Discovery, and Simulation Validation. The *Function Verification* element determines whether expected performance of AOP was achieved in the flight test environment. The *Concept and Technology Advancement* element provides additional data to support future development and research of AOP. The *Discovery* element uses the flight test environment to reveal emergent and unexpected behaviors. The *Simulation*

Validation element uses the flight test data to validate current AAM simulation models, increase confidence in simulation results, and promote simulation refinement. For preliminary details on the research activities and test results, refer to References [9] and [11].

A. Test Groups

To successfully meet specific research purposes, each test group consisted of a set of maneuvers with varying encounter geometries, altitude changes, AOP parameters, and execution instructions. Most maneuvers were designed to create encounters between the two aircraft that caused a conflict for AOP to resolve.

The four research elements were supported by two types of test scenarios: nominal operations and stressor operations. Each of the eight test groups were designed for a primary focus on one or the other, although a shared focus was possible. Nominal test scenarios contributed to the *Function Verification* research element. Maneuvers were designed to stay within the range of operational conditions and constraints for which the technology under test was designed. The nominal scenarios are used to evaluate algorithm performance and system performance in meeting deconfliction and time-compliance objectives. Stressor scenarios were used to explore concept behaviors and limits of the enabling technology. With a goal to gain insight from failure, stressor maneuvers were designed with the expectation that some would fail. Technology failures would contribute to Development (*Concept and Technology Advancement* and *Simulation Validation* research elements) and concept failures or unexpected behaviors would contribute to the *Discovery* research element as well as *Simulation Validation*.

The test groups were prioritized as shown in numerical order below to ensure that high-priority tests were completed within the flight hour constraints. With 52 unique test points available to fly, there were not enough available flight hours to fully execute all 8 test groups. The test day run priority was adjusted during the first half of the flight test campaign to ensure a sufficient sampling of each test group was collected before revisiting any unfinished test groups.

- Test Group 1 – Conflict Detection: Designed to explore AOP's conflict detection functionality by flying encounters that intentionally create a conflict with an intruder aircraft. The purpose of Test Group 1 was to verify the conflict detection function performs as expected. It also had a goal to generate large quantities of CR data given limited flight test hours. This was achieved by allowing AOP to continuously generate resolution advisories as the two aircraft converged. Pilots were instructed not to execute any advisories. Because they were not executed, resolution advisories generated by Test Group 1 could not be verified to resolve conflicts, and therefore were not used for that part of CR function verification. The test aircraft were allowed to converge until mission safety rules required an end to the maneuver. By executing the maneuver for the maximum amount of time before LOS, a stressor objective was also achieved: data were collected to determine how close to the point of first separation loss AOP could generate conflict resolution solutions. Test Group 1 was also used to provide a final verification that both test aircraft flew in conformance with their 4D trajectory guidance. Finally, as the first test group flown, Group 1 provided a final verification of test procedures. Test Group 1 was made up of nine unique maneuvers.
- Test Group 2 – Conflict Resolution and Prevention: Sought to verify conflict resolution and conflict prevention functions performance as expected. Test Group 2 used the same nine maneuvers from Test Group 1, but pilots were instructed to select a resolution trajectory from the set of resolution advisories provided by AOP. Test runs were typically continued until the test aircraft were beyond their closest point of approach and trajectories were clearly diverging. Because a trajectory was executed, the data recorded was limited to a single trajectory, but that resolution was important in verifying that it resolved the conflict without creating new conflicts. Pilot insights and preferences were collected regarding their decision making in selecting a resolution from the set offered by AOP. As confidence was gained in test aircraft trajectory conformance, flight test time was conserved by reducing the requirement for all test runs to continue the test maneuver until the aircraft had diverged.
- Test Group 3 – RTA Change Compliance: Tested AOP's ability to detect and resolve a required time of arrival change while staying deconflicted. The purpose of Test Group 3 was to verify that AOP can detect non-conformance of active trajectory with an RTA that has been changed, as well as compute a new trajectory that complies with the changed RTA while meeting airspace constraints and without generating traffic conflicts. As in Group 1, Test Group 3 runs did not execute AOP resolutions so each run would generate large amounts of resolution data. Also, similar to Test Group 1, this group provided data for a stressor objective to determine how close to the RTA point AOP is capable of generating resolution trajectories. During the test, Group 3 occasionally approached boundaries of the test range because of the longer time duration of the runs. Test Group 3 was made up of five unique maneuvers.

- Test Group 4 – RTA Change Compliance with Traffic Conflict: Evaluated AOP's ability to detect and resolve an RTA change that creates a conflict with traffic. Maneuvers were designed with the intruder on the same arrival path as the ownship, in conflicts when an RTA change was received. Test Group 4 involved selection and execution of an AOP resolution advisory for function verification purposes and to collect pilot opinions, as was done for Group 2. One test maneuver was designed specifically to test AOP's intended function to relax the RTA constraint if achieving both conflict resolution and RTA compliance is not possible. Test Group 4 was made up of three unique maneuvers.
- Test Group 5 – Time Parameters Variation: Investigated the impact of changing internal AOP time horizon parameters on detecting, resolving, and preventing traffic conflicts in a UML-4 operating environment. The purpose of Test Group 5 was to gather in-flight data that would provide insight for later optimization of the AOP parameters. It also had the goal to provide a reasonably comprehensive data set for post-test validation of FPM simulations. Test Group 5 was designed to have twelve unique maneuvers, which when combined with Group 2's runs that contained default parameter settings, would produce a sixteen-maneuver data set. Unfortunately, not enough flight test time was available to complete all planned maneuvers. Five maneuvers were completed for Group 5.
- Test Group 6 – Intruder Intent Change Stressor: Examined conflict detection and resolution performance when sudden traffic intent changes by the intruder result in conflict detection well within AOP's detection horizon. The purpose of Test Group 6 was to provide data for an initial investigation of interoperability between strategic path planning systems such as FPM and tactical systems such as Airborne Collision Avoidance Systems (ACAS). Maneuvers were designed to represent a situation where a traffic aircraft changes its intent when in close proximity to the ownship, thereby creating a conflict. Although the FPM concept has a conflict prevention function to preclude such a situation, future operations may reveal it to occur occasionally. Because of a test design philosophy to substitute virtual test elements for live elements only when necessary, Test Group 6 required the intruder to downlink its change of intent to the ground station, which immediately uplinked the new intent to the ownship. As with Test Group 5, not enough flight test time was available to complete all planned maneuvers for Group 6. Two maneuvers were completed.
- Test Group 7 – Conflict Resolution and Prevention in Corridors Stressor: Exercised the ability of AOP's algorithms to allow aircraft to operate safely and maintain traffic flow within airspace corridors. AOP's current algorithms were designed for operations in open airspace. The open airspace may contain regions of restricted airspace that are small relative to the overall airspace. Flow corridors, with boundaries defined by large regions of restricted airspace, will likely be required for many UML-4 operating environments. Test Group 7 was designed to provide data for an initial exploration of UML-4 operations within corridors. The DFW UML-4 operating environment's corridors were utilized for Group 7. The corridors are necessary for UAM aircraft to access DFW terminals without encroaching on the surrounding runway operations, or to provide shortcuts through large regions of restricted airspace. Test Group 7 relied heavily on the virtual elements of the LVC test, as the regions of restricted airspace were much larger than regions of unrestricted airspace. Group 6 was made up of three maneuvers. All aircraft were required to comply with an RTA. For one maneuver, the ownship and the intruder were required to merge prior to entering the DFW terminal corridor. Their RTA point was located at the terminal.
- Test Group 8 – High Traffic Density Stressor: Explored FPM automation behaviors and functionality at traffic density levels expected for the higher end of UML-4. The purpose of Group 8 was to stress the AOP algorithm in several ways. High traffic levels directly impact the speed of the CR computation and the ability of the CR algorithm to compute resolution solutions. AOP's conflict prevention function, which prohibits solutions that create new conflicts, may also adversely impact the ability to determine CR solutions. Test Group 8 maneuvers modified a Group 1 maneuver by adding additional virtual traffic. Group 8's design goal was to double and triple virtual traffic density, but a limitation in the virtual traffic generator prevented density to increase more than 32 percent over the Group 1 baseline case. As currently implemented, the traffic generation capability requires every virtual aircraft to have an origin and destination. The simulated UML-4 environment's vertiports reached maximum capacity at the traffic limit used for Group 8. Two test maneuvers were executed.

B. Encounter Geometries

To effectively meet the research purposes of each test card, a collection of distinct maneuvers was designed. A maneuver refers to a specific trajectory flown by the ownship and the intruder to create an intended encounter or event.

For traffic conflict maneuvers involving both research aircraft, one of five encounter geometries were used. Figure 4 shows an acute crossing encounter displayed on the AOP engineering user interface used during IAS-1.

- <u>Crossing:</u> An opposing direction encounter where the trajectory of the ownship and the intruder crosses at approximately 120° while maintaining a safety margin of 0.2 NM.
- <u>Acute Crossing:</u> A same direction encounter where the trajectory of the ownship and the intruder crosses at approximately 30° while maintaining a safety margin of 0.2 NM.
- <u>Head-On:</u> An opposing direction encounter where the trajectory of the ownship and the intruder align toward one another with a safety margin of 0.2 NM.
- <u>Intruder Overtake:</u> A same direction encounter involving a significant speed difference where the intruder starts behind the ownship on a parallel trajectory, which includes a safety margin of 0.2 NM.
- <u>Ownship Overtake:</u> A same direction encounter involving a significant speed difference where the ownship starts behind the intruder on a parallel trajectory, which includes a safety margin of 0.2 NM.

VI. FPM Test Execution

Prior to flying each day of the two-week flight campaign, a safety briefing was held which covered expected environmental conditions and planned test operations. During a nominal flight test sortie, SARA and OPV flew 4D trajectories defining flight paths that would have resulted in the two aircraft losing separation. To begin the setup for a maneuver, the MWE would designate an orbit location for both aircraft to head to and upload it to each aircraft. During this part of the setup, an onboard wind reading would be taken to be used in selecting which maneuver wind combination file most closely represented the current wind conditions at test altitude. Once in range, the pilots were commanded by the test conductor to initiate an action on their tablet that guided their aircraft into their designated orbit location. After the aircraft were established in their orbits, the pilots would be commanded by the test conductor to release from their orbits and fly toward their respective time-synchronized starting locations via automated guidance by the Middleware. After both aircraft crossed their respective T_0 point, the FPM maneuver began.

From there, AOP would continually monitor its 4D trajectory for conflicts with traffic, time of arrival constraints, or area hazards. Once AOP detected a conflict, it would notify the pilot of the conflict via FPM Engineering UI and compute several resolution trajectories (up to 4 types: lateral, vertical, speed, and hybrid lateral-vertical-speed resolutions). The research pilot could select, review, and execute any of the provided resolutions depending on the current test group's procedures. If a resolution was executed, AOP then sent the executed 4D trajectory resolution to the AMM system, which commanded SARA to follow the updated 4D trajectory from the AOP software. A safety pilot ensured the safety of all executed trajectories.

The FPM Research Engineer was responsible for making the call to end each run, which was determined on a case-by-case basis depending on when all valuable data had been obtained. If the specific maneuver called for no execution of resolution advisories, the FPM Research Engineer would make the call to the test conductor to end the run at approximately 30 seconds until LOS. Furthermore, if a resolution advisory was executed, the FPM Research Engineer would make the call to end the run once the resolution was complete and the two aircraft had diverged by at least 0.5 NM. If a circumstance arose that a FPM Research Engineer decision could provide valuable data, and it was safe to do so, the FPM Research Engineer was allowed to make the end-run call when they saw fit. All decision making done by the FPM Research Engineer was aided using the FPM Ground Station display.

IAS-1 was conducted from October 16 - 26, 2023. During those two weeks, 8 sorties were flown resulting in the completion of 34 FPM test points. In-flight performance of AOP met desired expectations as compared to pre-test simulations. Conflict detection and resolution were successfully achieved for all maneuvers that involved an expected traffic conflict with the OPV. All test systems and their functionalities performed sufficiently, resulting in the successful collection of FPM data. Additionally, there were no test days lost to adverse weather.

VII. Discussion

While IAS-1 was a success, it also uncovered several challenges, a few areas for improvement, and some expected future work. Regardless, the development of this flight-testing capability will prove useful for future flight tests of autonomous systems.

One difficult challenge that was revealed through the development of the flight test was the unplanned complexity of setting up intentional traffic conflicts. This capability is needed for testing purposes but would never be needed in normal operations. However, this non-simple task had to be accomplished to successfully test AOP in a live flight environment. As discussed in Section IV.A & B, the capability of intentionally setting up traffic conflicts was developed through an accurate establishment of the coordinated SPs, and by autonomously guided navigation to those

SPs. The need to compensate for test day winds when flying a 4D trajectory was a large contributing factor to the need for the scenario generation tool developed by NASA. Without this tool to generate coordinated and time-aligned 4D trajectories for both aircraft to fly, creating the intended conflict would have been unreliable and resulted in costly flight time loss.

To ensure both aircraft arrived at their respective SPs with the correct initial conditions, NASA developed a method utilized during the setup of each FPM maneuver. Overall, the approach coordination facilitated by IFTS provided excellent results and allowed AOP to conduct the desired test scenarios. There were some difficulties encountered when selecting the desired orbit locations for some test encounters due to an issue with the approach coordination algorithm in which the desired orbit location was too close to the IP and an appropriate route could not be generated. This difficulty was overcome by setting a minimum distance between the orbit location and the IP, and if this minimum distance was exceeded, the orbit location was rejected and required a new orbit location to be supplied. The orbit locations were selected such that they were a minimum distance from the T_0 point and were added to a list of possible orbit locations. The set minimum distance was a factor of turn radius at a standard rate at an initial ground speed. However, there were orbit locations selected for a few test scenarios that were too close due to the ground speed varying for the test encounter based on the quantized set of wind speeds and directions, which required new orbit locations to be selected. While this allowed every test scenario to be completed, it did result in orbit locations in some instances that were far away from the IP, which caused some time to be wasted in transit. Future improvements to this system would involve making the approach trajectory generation more tolerant to scenarios where the IP is too close to the orbit location such that less test scenarios would require more distant alternative orbit locations to be commanded.

Another consideration that should be included in future autonomous system flight testing activities involves the direction at which a maneuver is flown. Even with the work done in generating maneuvers that compensate for a wide range of test day winds, extremely heavy winds in certain directions could have caused issues (e.g., a heavy tailwind could cause the aircraft to exceed ground speed limits). This issue could be mitigated by designing multiple versions of each maneuver that each fly in a different direction. However, this would result in a longer and more strenuous design process. One preferred alternative for future tests would be to use vehicles that do not have ground speed limitations. In addition to the ground speed limitations of the aircraft, maneuver direction is also an important consideration within the context of telemetry system restrictions. The same extreme tailwind that can cause an aircraft to exceed ground speed limits could also result in the aircraft covering more ground than desired, causing the aircraft to fly outside of telemetry range.

Throughout the flight test, there were approximately 250 simultaneous virtual background traffic operations during each run, and approximately 330 simultaneous operations for the high traffic density runs. This quantity of operations exceeded the typical operational load of the UML-4 simulated operating environment used in past FPM studies, however, it was discovered through the execution of Test Group 8 that the stressor scenarios designed for this flight test were not as difficult for AOP as expected. Test Group 8 was designed to increase the density of the virtual traffic experienced by the ownship past the levels of UML-4 used in previous batch studies. Upon initial modification to the DFW UML-4 environment, it became clear that there were limitations to the supporting simulations preventing the development of a traffic density that was truly stressing to the automation system. To increase the density, the outputs of all the surrounding vertiports within the simulated operating environment were increased to expectantly achieve local traffic densities of 1.5, 2, 2.5, and 3 times greater than the current density used for UML-4 operations within the simulation. However, the vertiports were quickly oversaturated, resulting in a max traffic density increase of approximately 1.32 times the typical UML-4 simulation amount. As a result, there was no observable increased difficulty to AOP when solving Test Group 8 maneuver conflicts during flight. For future work using a LVC environment, limitations such as this one need to be accounted for in capabilities of the supporting simulations.

VIII. Conclusion

The design, implementation, and execution of a flight test for UML-4 strategic deconfliction research was found to be a challenging task that ultimately yielded effective results. As described in this paper, several unique technical challenges were discovered and resolved. Solutions were developed in a series of flight test campaigns, supported by hardware-in-the-loop laboratory testing, over a period of approximately two years. The final flight test in the series generated research data. The developed solutions should be applicable to future tests of multiple interacting vehicles.

The developed capability is recommended as an enduring asset for testing autonomous systems in a live flight environment. The capability may prove critical in addressing the research challenges involved in future high density air traffic operations. Additional benefits to execution efficiency could be realized by designing a system that can effectively handle a wide range of wind conditions. A larger test range would also simplify some aspects of testing.

Although the tests were successfully conducted in an environment containing nonparticipating aircraft, future efficiencies may be achieved with the use of a sterile test environment.

There are several remaining challenges to solve. The ability to create unscripted conflicts for future tests would be an extremely valuable research capability for testing automated deconfliction systems. Unscripted conflicts present both technical and flight test safety assurance challenges, but they should enable significant efficiency gains in data collection and facilitate discovery of corner case behaviors. Expanding the testing capability to include multiple aircraft equipped with the automation technology will be a valuable next step. It will enable the in-flight study of the behaviors of distributed-authority path planning concepts. A further recommended capability enhancement is the addition of prototype communication links needed to support future UML-4 levels of data transmission.

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