Flight Evaluation of a Flight Path Management System for High Density Advanced Air Mobility

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Urban Air Mobility at Scale

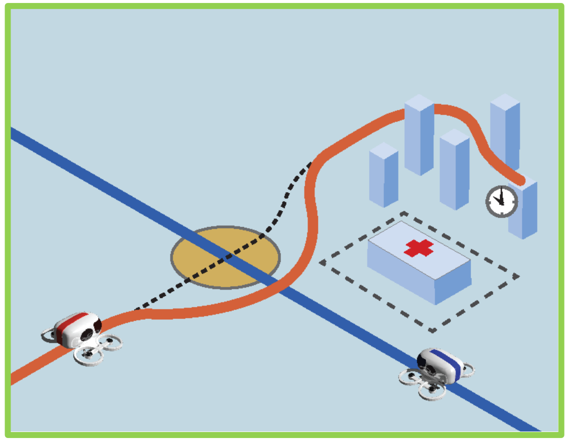
Urban Air Mobility (UAM): A vision for a future system that provides economical high-access air travel within urban environments

- NASA's UAM Maturity Level 4 (UML-4): **Services accessible and attractive to a significant percentage of the public**
  - Comparable to FAA's UAM Mature Operational Stage
  - Hundreds of aircraft aloft serving a metropolitan area
  - Dozens of vertiports, restricted airspace volumes, and corridors
- UML-4 poses significant challenges for air traffic management
  - Increasingly dense and complex operations
  - Tighter separation standards, requiring higher navigation precision
  - Dynamic scheduling of high-demand vertiports, requiring reliable on-time arrivals and departures

Credit: NASA

*In UML-4 definition: The operator employs **collaborative and responsible automation** to perform the separation function*

Flight Path Management Automation Concept (FPM)



In-flight autonomy in shared airspace

Continuous replanning to safely achieve mission objectives in the presence of traffic, flow restrictions, and weather

Goal:

A safe and operationally acceptable flight path is available to airspace users and aircraft systems throughout the flight

FPM Objectives: Create | Monitor | Evaluate | Revise | Coordinate the flight path to have:

Five Qualities:

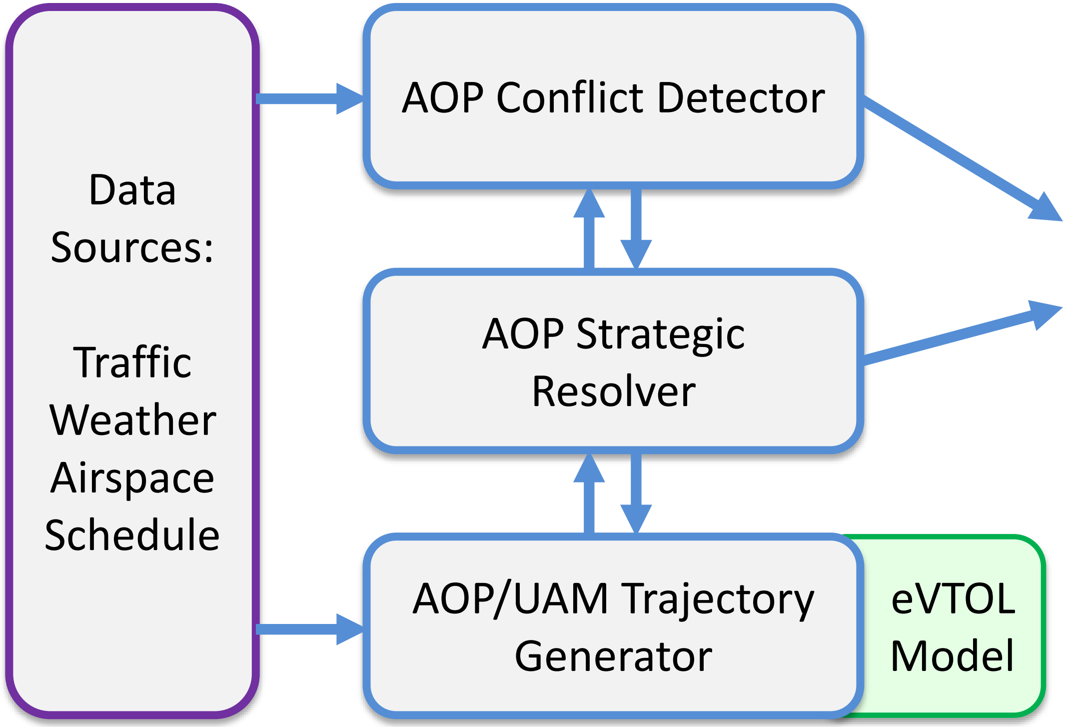
- **Feasible** – Conforms to aircraft performance and range; Complies with airspace structure, rules, and constraints
- **Deconflicted** – Avoids unsafe proximity to known traffic, terrain, obstacles, weather, and airspace hazards
- **Harmonized** – Follows cooperative rules and procedures to be compatible with other airspace users & systems
- **Flexible** – Provides adequate maneuvering room to enable future flight path changes, if needed
- **Optimal** – Achieves business objectives and preferences of the pilot and fleet operator

For this research: An FPM system is located onboard each aircraft

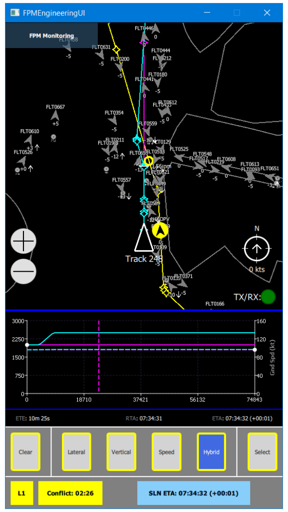
Autonomous Operations Planner (AOP)

Role: automation reference implementation

Platform for assessing FPM system requirements



AOP Implementation for UAM R&D



Pilot's FPM Engineering User Interface

AOP core functionality:

- Generates 4D flight path from present position to destination
- Monitors the flight path and the factors that may impact it
- Evaluates ongoing acceptability of the flight path and proposed changes
- Revises the flight path, as needed, to sustain mission objectives
- Coordinates the flight path with other airspace users and service providers

AOP's strategic resolver uses a pattern-based genetic algorithm (PBGA)

Flight Test Overview

Sikorsky Autonomy Research Aircraft (SARA) S-76B “Ownship”

Credit: Sikorsky

NASA partnered with Sikorsky, a Lockheed Martin Company

- Utilized Sikorsky optionally piloted research vehicles as surrogates for future eVTOL aircraft
- Operations conducted out of Sikorsky Memorial Airport (KBDR) over Long Island Sound
- 4D trajectory guidance utilized

FPM research testing

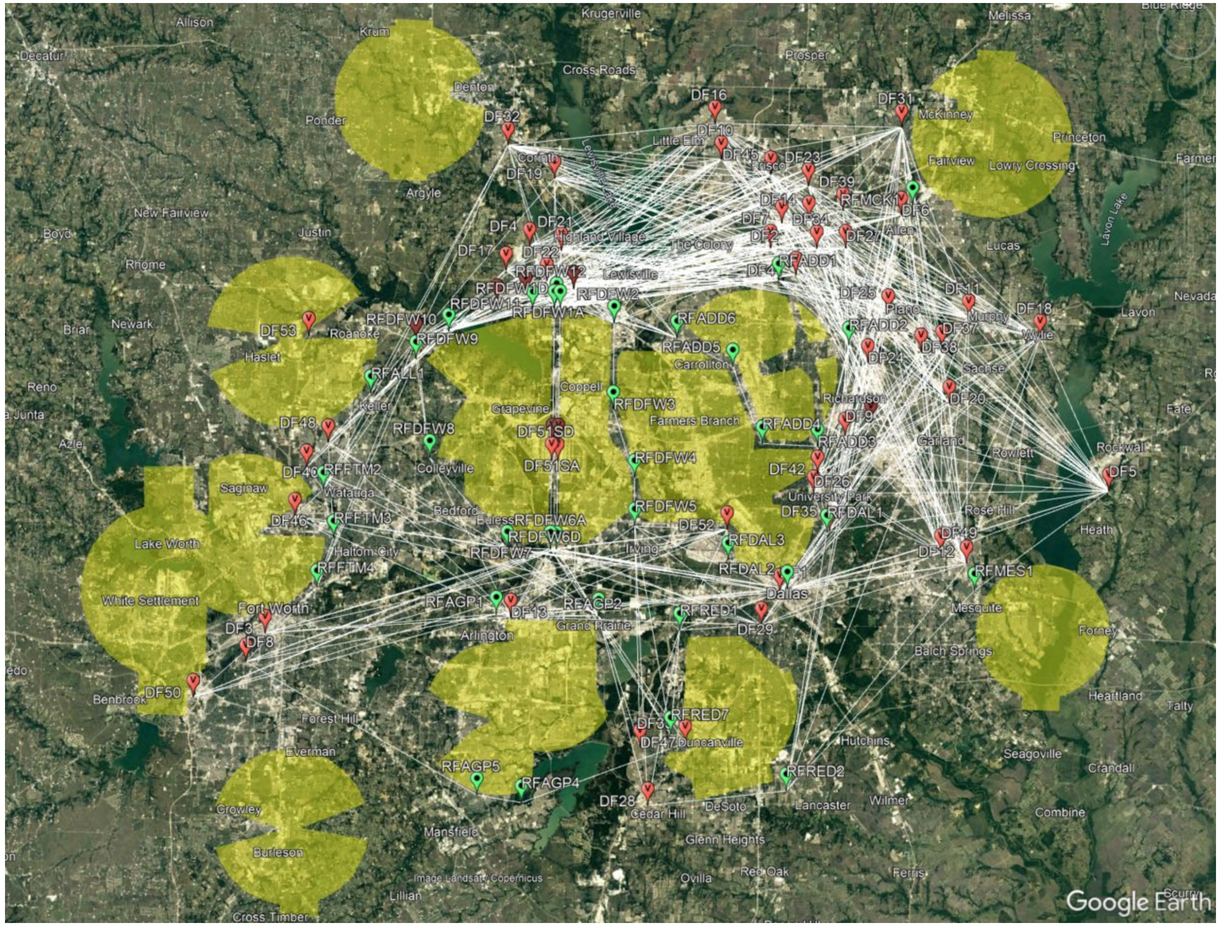
- Test aircraft (“Ownship”) equipped with AOP
- Cooperative traffic (“Intruder”) shared state and intent
- Maneuvers designed to create live encounters between Ownship and Intruder
- Mixed-reality airspace with up to 330 virtual traffic aircraft

Optionally Piloted Vehicle (OPV) S-70 Black Hawk “Intruder”

Credit: NASA

Virtual UAM Dallas Fort Worth (DFW) Airspace

- UML-4 simulated operating environment
  - Environment based on DFW surrounding airspace
  - Airspace restrictions represented as yellow polygons
  - 1500 ft lateral separation, 450 ft vertical
- All virtual playback traffic and area hazards fed to Ownship during flight test
  - Represents traffic aircraft broadcasting their state and intent info
  - Scripts used to represent a scheduler providing arrival time instructions



Virtual UAM Dallas Fort Worth (DFW) Airspace

FPM Flight Test Objectives

Research objectives

- Determine whether expected performance occurs in a relevant environment
- Provide data to support further research and technology development
- Uncover the “unknown unknowns” about system behavior
- Provide data to be used in validation and refinement of AAM models and simulations

Primary AOP functions under test

- Intent-based conflict detection (**CD**). Conflicts detected with traffic, restricted airspace, external constraints
- Strategic conflict resolution (**CR**) with traffic and restricted airspace, in conformance with external constraints and aircraft performance limits
- Conflict prevention (**CP**)
- Required time of arrival (**RTA**) compliance

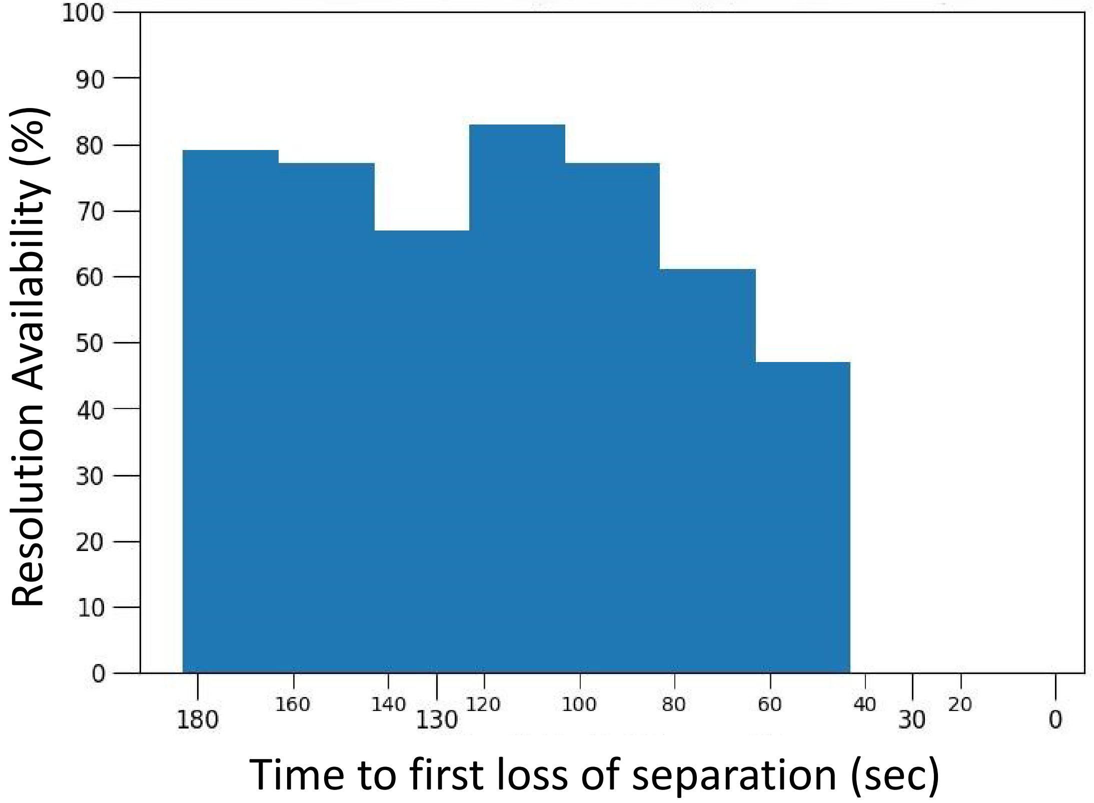
Conflict Detection Performance

CD Cycles	Predicted True	Predicted False		
Actual True	**True Positives** 1072	**False Negatives** 0	**Precision** 100%	**False Omission** 0%
Actual False	**False Positives** 10	**True Negatives** 3447	**False Discovery** 0.29%	**Negative Prediction** 99.71%
	Sensitivity 99.08% (True Pos. Rate)	**Misses** 0% (False Neg. Rate)	**Prediction Accuracy** 99.78%	
	Fall-Out 0.92% (False Pos. Rate)	**Specificity** 100% (True Neg. Rate)		

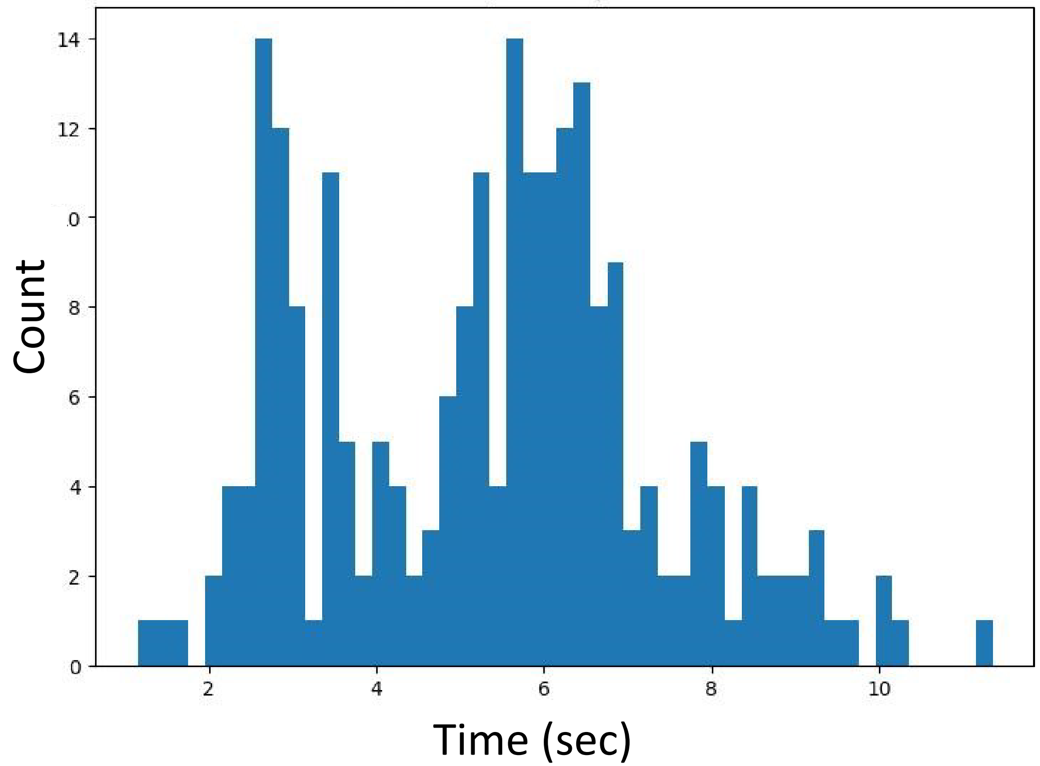
- CD cycle repeats every three seconds
- Total CD cycles across all runs: 4529
- AOP uses additional buffers to drive missed alerts (false negatives) low, resulting in ~1% false alerts

Conflict Resolution Performance

Avg. Fraction of Strategic Resolutions Available



Conflict Resolution Compute Times

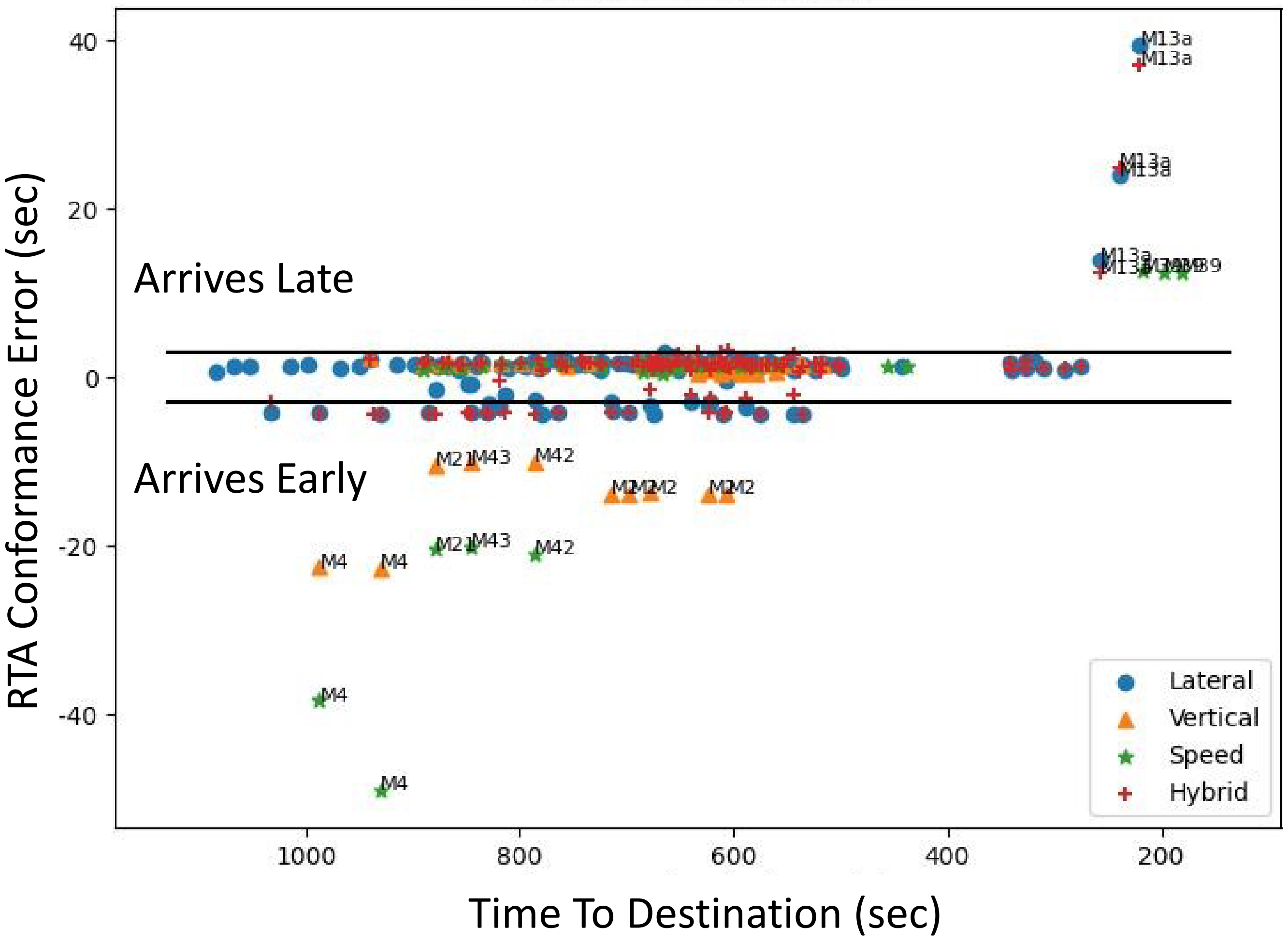


- Up to four resolutions generated in each CR cycle (lateral, vertical, speed-only, combined lateral and vertical – “hybrid”)
- Decline in availability occurs as time to first loss decreases, starting around 80 sec.

- Average processing time: 5.4 sec
- No traffic filtering was employed; resolution algorithm considered all traffic to prevent creation of new conflicts

Arrival Time Conformance

- All 478 resolutions were required to comply with a required time of arrival (RTA) at the vertiport destination
- 95% of advisories were within or just outside tolerance boundaries (shown by horizontal lines)
- Late arrivals occurred as aircraft approached destination
  - Avoiding traffic/restricted airspace typically extends flight path; speed-ups are limited by aircraft performance
  - Algorithm is designed to minimize error if conformance is not achievable



Results Summary

- CD, CR, CP, and RTA-change compliance was almost perfect in the tested 4D-guidance environment. RTAs were met with an average precision of one second.
- Small assumed separation standards posed no issue
  *Missed detections and post-resolution recurring conflicts did not occur**
- Pilots were adequately "in the loop," although they would prefer more time
  More research is needed to determine feasibility of human-in-loop decision making at UML-4
- AOP operating on a current-generation 4-core processor easily processed 330 traffic aircraft
  CR computation times averaged 5.4 seconds. (Pilot's decision cycle was 20 sec.)
- Post-flight simulations closely matched flight test runs
  Indicates existing NASA medium-fidelity UAM traffic simulations can produce trusted results

*Excluding two cases that arose from known software defects

Conclusions

Results provide positive indications that a vehicle-centric FPM implementation is feasible for high-density UAM operations

- All functional performance success criteria for maneuvers in an open airspace environment were met or exceeded
  - Automation reliably supported core FPM functions of strategic conflict detection, resolution, and prevention, as well as arrival time compliance
  - Further R&D is needed to support high-density operations in flow corridors
- Potential barrier: developing collaborative and responsible automation
  - Additional research needed to establish feasible human operator responsibilities
- When combined with an arrival scheduler, FPM automation may address critical long-term air traffic management challenges

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Backup

More Information

Flight Test Design and Conduct

- Stewart Nelson / stewart.l.nelson@nasa.gov

  Nelson, S. L., Ballin, M. G., Barrows, B. A., Underwood, M. C., Wing, D. J., Williams, E. R., and Sturdy, J. L., "Designing a Flight Test of a Flight Path Management System for Advanced Air Mobility Research," AIAA SciTech, January 2024.

AOP

- David Karr / david.a.karr@nasa.gov

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- Bryan Barrows / bryan.barrows@nasa.gov

  Barrows, B. A, Ballin, M. G., Barney, T. L., Nelson, S. L., Underwood, M. C., and Wing, D. J., "Sim to Flight: Evaluating Flight Path Management in High Density Urban Environments," AIAA SciTech, January 2024.

FPM / Dynamic Path Planning

- David Wing / david.wing@nasa.gov

FPM Testing Overview

Test Group	Completed Maneuvers	Type	Research Objective
1: Conflict Detection (CD)	9	Nominal	Verification & Advancement
2: Conflict Resolution (CR) and Conflict Prevention (CP)	7	Nominal	Verification & Advancement
3: Required Time of Arrival (RTA) Change	3	Nominal	Verification & Advancement
4: RTA Change Compliance with Conflict	3	Nominal / **Stressor**	Advancement, Discovery, & Sim Validation
5: Time Parameters Variation	5	Nominal	Advancement & Sim Validation
6: Intruder Intent Change	2	**Stressor**	Discovery & Sim Validation
7: CR and CP in Corridors	3	**Stressor**	Discovery & Sim Validation
8: High Traffic Density	2	**Stressor**	Discovery & Sim Validation

Testing Summary

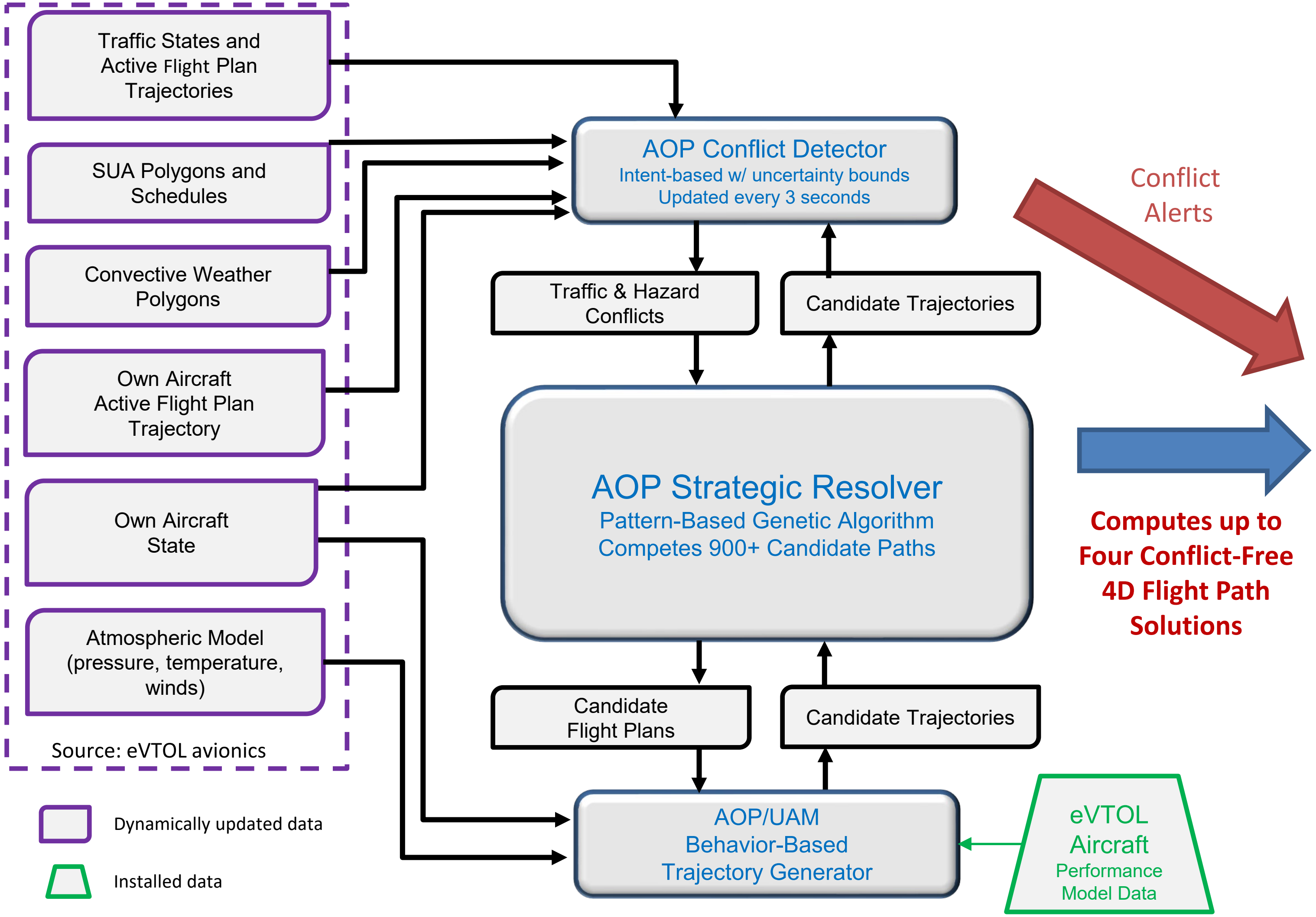
34 test maneuvers completed

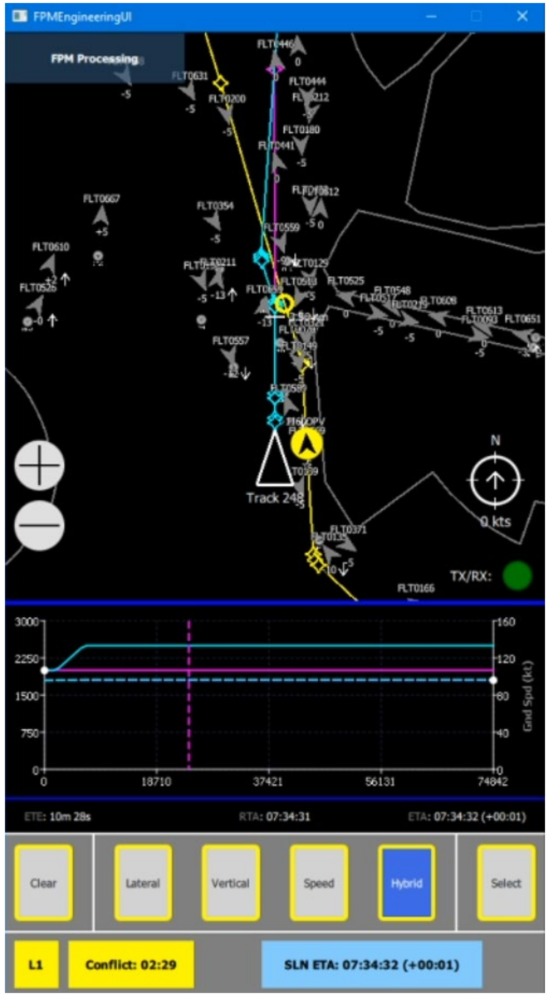
- 31 total conflict encounters created
- 7 total RTA changes issued
- 41 total conflicts and RTA change events detected
- 478 PBGA* resolutions computed (all types)
- 24 total PBGA resolutions executed by the flight crew (all types)

*PBGA: Pattern-Based Genetic Algorithm; the heart of AOP's strategic resolver

Autonomous Operations Planner

Functions used for UAM flight test





Pilot's Engineering Interface

Test Area and Boundaries

Airspace surrounding KBDR

- Sikorsky defined telemetry range and testing boundary (red circle and magenta box)
- Class B, C, and D airspace (dark blue, purple, and light blue)

Overlay of virtual environment on test area

- Transposed and Rotated
- Includes airspace restrictions and Background Traffic
- Highly dense-traffic section chosen for testing