The High Density Vertiplex Advanced Onboard Automation Overview

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While many studies have been performed examining Urban Air Mobility (UAM) operations from UAM Maturity Level (UML) UML-1 to UML-4, [1, 2] some uncertainty exists regarding the integration and role of onboard autonomous systems, airspace management systems, ground control and fleet management systems, and how they integrate with vertiport automation systems to ensure safe high-density future operations. One thrust of the Advanced Air Mobility (AAM) High Density Vertiplex (HDV) sub-project is to perform rapid prototyping and assessment of an Urban Air Mobility (UAM) Ecosystem within the terminal operational area to help inform future research investments and technology development. Another thrust within HDV is to perform integration, testing, and safety risk assessments required to acquire operational credit for several NASA small Unmanned Aerial Systems (sUAS) beyond visual line of sight (BVLOS) enabling technologies to expand test capabilities and to expedite technology transfer and ultimate effective usage. Both thrusts leverage sUAS to serve as surrogates for the highly-technologically-similar envisioned UAM aircraft as well as to provide significant contributions to sUAS Part-135 operators. This report provides an overview of the activities accomplished within the Advanced Onboard Automation (AOA) schedule work package of HDV.

Keywords— Human Factors, Simulation, small Unmanned Aircraft System (sUAS), Advanced Air Mobility (AAM), Urban Air Mobility (UAM), Vertiports, Beyond Visual Line of Sight (BVLOS)

I. Introduction

The High Density Vertiplex[1] (HDV) sub-project along with the other AAM sub-projects, National Campaign (NC) and Automated Flight and Contingency Management (AFCM), are working to advance several areas of focus identified in the AAM Mission portfolio. The HDV sub-project is responsible for the development and maturation of automation technologies and architectures to support AAM operations. To this end HDV focuses on the development and testing of concepts, requirements, software architectures, and technologies needed for the terminal environment around vertiports. Specifically focusing on how automation can increase safety, efficiency and scalability of flight operations in these environments. While HDV technologies, requirements, and architectures will be relevant to broad AAM operations, the HDV project focused on uses cases that are specific for urban operations, that which are closely aligned with UAM operations.

Key barriers for UAM operations in the vertiport domain include: a lack of standardization around required technologies and performance to support high tempo and throughput, UAM business cases around vertiports, mature concepts, procedures, and technologies supporting automated approach and landing, automated merging and spacing, and automated contingency decision making for eVTOL operations in vertiport environments. A barrier also exists in the development of evaluation and testing practices necessary for demonstrating that automated mitigations warrant "safety credit" from the regulator as a means of compliance to existing or future regulations. This is particularly true for the use of automation to support BVLOS operations for UAS. Furthermore, a key barrier exists between required data information exchanges between the aircraft, airspace service

[1]A *Vertiport* is defined as an identifiable ground or elevated area, including any buildings, or facilities thereon, used for the vertical takeoff and landing of an aircraft. A *High Density Vertiport* is qualitatively defined as a vertiport that supports an increasing number of aircraft movements at or near vertiport capacity. High density refers to the average aircraft movements at a vertiport needed to support UAM Maturity Level 4 operations. A *Vertiplex* is defined as multiple vertiports in a local region with interdependent arrival and departure operations.

provider, and the vertiport systems to support increasingly dense operations. Addressing these barriers are critical to ensuring that the industry is ready to support UML-4 operations

UML-4 consists of medium density and medium complexity operations with collaborative and responsible automated systems. At UML-4, medium density is characterized as hundreds of simultaneous operations over a single metropolitan area or region. Medium complexity includes low-visibility operations, aircraft operating near one another in high-density routes, and operations to/from high-throughput aerodromes. There are also automated systems that do not require human oversight or mitigation of potential failures for some functions. These collaborative and responsible automated systems enable humans to have roles that differ from those performed by humans in the traditional aviation system and it is anticipated that UAM aircraft at UML-4 will utilize a network of third-party providers of services to UAM (PSUs) to manage scheduling of routes and provide automated, tactical deconfliction, in addition to other services.

Operations at the UML-4 level will be inextricably linked with significant public usage and is considered key to financial solvency and viability of this transportation concept. An additional key UML-4 aspect is that the vehicle operator will likely not be on the vehicle allowing an additional seat to be payload. Taken together, actual ubiquitous UAM operations require a high-degree of system integration beyond today’s helicopter-like operations which is one of the thrusts of HDV.

UAM Ecosystem prototyping performed within HDV focuses on four primary areas that include: 1) Onboard autonomous systems, 2) Autonomous airspace management systems, 3) Ground control and fleet management systems, and 4) Vertiport automation systems with vertiport automation systems being the primary focus. While some elements of a UAM transportation system could be demonstrated using eVTOL aircraft operated in a similar manner to today’s helicopter operations, ubiquitous financially-effective UAM operations require more complete system integration as defined in UML-4.

Achieving operational credit combined with fully documented and disseminated safety risk assessment results are considered key to wide-spread NASA technology licensing and ultimate usage. Testing, safety risk assessments and documentation performed within HDV will be essential to achieve operational credit. Unlike industry efforts aimed at BVLOS sUAS operations, all material generated to support achievement of operational credit from the FAA will be fully published and disseminated. Subsequent industry NASA technology users will be able to easily refer to the published material and tailor for their applications.

The HDV subproject transitioned into the execution phase in September, 2020, and is organized into schedule work packages lasting approximately 14 months each and referred to as: 1) Advanced Onboard Automation (AOA), 2) Scalable Autonomous Operations (SAO), and 3) Vertiport Operations (VO) over the 5-year lifetime. Each schedule work package (SWP) builds upon previous SWPs and are implemented as spiral wraps of a spiral development project. Each SWP adds increased capabilities and complexity and features dedicated high-fidelity human+hardware in the loop (HHITL) simulation and coordinated flight testing performed at NASA. The primary focus of the AOA SWP was to build the environment needed to adequately develop and test vertiport automation systems. The HDV subproject is organized into Technical Work Packages that include: Airspace Systems Integration (ASI), Vehicle-Vertiport Systems Integration (VVSI) and Flight Operations (FO). ASI is composed of personnel at Ames Research Center (ARC) while VVSI and FO are located at Langley Research Center (LaRC).

This report provides an overview of the activities accomplished within the AOA SWP. Results are provided to establish the level of prototyping accomplished in AOA and subsequent use cases and plans for the follow-on SAO simulation and flight test.

II. Method or approach

To achieve HDV subproject objectives several major areas of work were required to be completed by the HDV team. These general areas of work can be captured along the following efforts: 1) UAM Ecosystem prototyping, and 2) Test capability improvements. Both areas involved significant effort to get to levels adequate for testing as performed for the AOA Simulation and AOA Flight Test (AOA Sim and AOA Flt).

A. UAM Ecosystem prototyping

1) Autonomous airspace management

Within the area of UAM Ecosystem prototyping several technologies were leveraged from other NASA projects to establish a representative level of autonomous airspace management. One example was the usage of a PSU from NASA’s ATM-X project. Through collaboration with the ATM-X project, access to a representative PSU was acquired. Salient features of the PSU were the ability to perform pre-flight strategic deconfliction for the routes tested as well as volume-based conformance monitoring. The interface to the PSU was through the xTM Client developed at NASA ARC. The xTM Client also provided the capability to perform in-flight trial planning to manage non-emergency contingencies such as those that could arise from an unanticipated vertiport closure as well as display information from the PSU to the ground control station operator (GCSO) and Fleet Manager (FM) on the xTM display as shown in Figure 1. In Figure 1, three vehicles are portrayed by magenta dots. Their current conformance boundaries are indicated by the magenta polygons along the grey flight path lines. Conformant flight is when the vehicles translate to remain within the updating/moving magenta boxes as shown in Figure 1.

Figure 1 - xTM display image as used for AOA Flt.

2) Onboard Autonomous Systems

One aspect of onboard automation anticipated for UML-4 operation is the capability of the UAM vehicles to detect and autonomously avoid other aircraft. Given the expected high traffic density levels this type of functionality is considered required. Autonomous detect and avoid (DAA) functionality was also acquired from the ATM-X project as provided by the Integrated Architecture for Reliable Operations of Unmanned Systems (ICAROUS). ICAROUS [3, 4, 5, 6] was developed within NASA's UAS Traffic Management (UTM) project and enables integration of an array of autonomous systems with the vehicle's autopilot. For testing, ICAROUS was supplied vehicle traffic information from Flight Alarm (FLARM) devices integrated into the sUAS test aircraft. FLARM is essentially an ADS-B-like system operating in the open industrial, scientific, and medical (ISM) 900 MHz frequency band [7]. FLARM is certified for by the European Aviation Safety Agency (EASA) for use in aircraft. For AOA Sim and AOA Flt, well clear boundaries were 152m laterally and 30m vertically (500ft and 100ft).

Another element of the onboard autonomous systems prototyping was the usage of NASA's Safe2Ditch (S2D) contingency management technology [8, 9, 10, 11]. S2D, developed during the NASA's UAS Traffic Management (UTM) project, provides autonomous contingency management capabilities enabling the vehicle to re-route to alternate landing locations without direct human involvement during emergency situations. S2D contains a pre-compiled database of potentially usable landing locations. Emergency landing locations are classified by size and potential risk of usage. During an emergency, S2D selects the best landing location from the database and routes the vehicle to that location. During final approach, S2D optically scans the landing location looking for moving objects using a fixed 45-degree look down camera. If movement is detected in the landing zone, S2D automatically re-routes to the next landing site. Given the potential for minimally-trained pilots (or no pilots) autonomous contingency management is considered required for UML-4 operations.

3) Ground control and fleet management

Ground control was provided through the usage of the Measuring Performance for Autonomous Teaming with Humans (MPATH) ground control system. MPATH is based upon QGroundControl (QGC) which is an open-source ground control system (GCS) for sUAS. MPATH was provided through collaboration with NASA's Transformational Tools and Technologies project and included modifications to QGC to enable better integration and control of the onboard autonomous systems. An example of this includes the capability to show S2D ditch sites on the MPATH display. The ability to perform fleet management was provided through the xTM Client and enabled the FM to monitor vehicle progress and status and to create updated flight plans to manage vertiport closures and send those flight plans to the GCSO.

4) Vertiport automation systems

For the AOA Sim and Flight Test only very minimal vertiport automation capability was provided. This consisted of the ability of a Vertiport Manager (VM) to close the vertiport at a push of a button. Subsequent SWPs will greatly add to this capability.

B. Test capability developments

Several major developments were undertaken by the HDV project to greatly expand sUAS testing capabilities at NASA. These improvements included creation of sUAS simulation capabilities to support comprehensive testing, including Human Factors (HF) test capability, several improvements to NASA's City Environment Range for Testing Autonomous Integrated Navigation (CERTAIN) range, and transitioning to Extended Visual Line of Sight (EVLOS) operations.

1) Remote Operations for Autonomous Missions

The Remote Operations for Autonomous Missions (ROAM) sUAS lab is a quantum increase in NASA's ability to control sUAS, leverage them for advanced test capabilities, and provide shared situational awareness for the operations team.

Integration and display of local air traffic will be supported through the Anra Smart Skies control system (SS CTR) system that will fuse surveillance inputs from several radar systems, ADS-B, and Flight Alarm. Output from the Anra SS CTR system will be displayed on the Integrated Airspace Display (IAD) in ROAM for future testing with an example provided in Figure 2 that was generated using ground-based ADS-B data.

The ROAM lab is located within NASA Langley's Air Traffic Operations Lab (ATOL) and features 6 highly-reconfigurable control stations as shown in Figure 3 as used for during AOA Sim. Each control station can be used to be a Ground Control Station (GCS) for control of simulated or real vehicles, a flight test director (FTD) station, a Range Safety Officer (RSO) station, or HF test engineer, depending on the application or mission. A photograph of a GCS is provided in Figure 4. ROAM provides the capability to perform HF testing including eye tracking and HF questionnaires administered through a dedicated iPad located at each GCS. An example eye tracking heat map data is provided in Figure 5. These example data were acquired with a Tobii Pro nano eye tracker (off body sensor). Eye movements were recorded at 60Hz and analysis was completed using Tobii Pro Lab software. A forward video wall is used to show local air traffic, either through remote internet-based ADS-B systems or through actual radar and ADS-B receivers located at NASA LaRC.

The ROAM lab can be connected to simulated vehicles through internet connection to the System Integration and Validation Lab (SIVL) or through 4G connection to actual sUAS through a Botlink XRD [12] telemetry link. Selection of each type of vehicle is easy to accomplish.

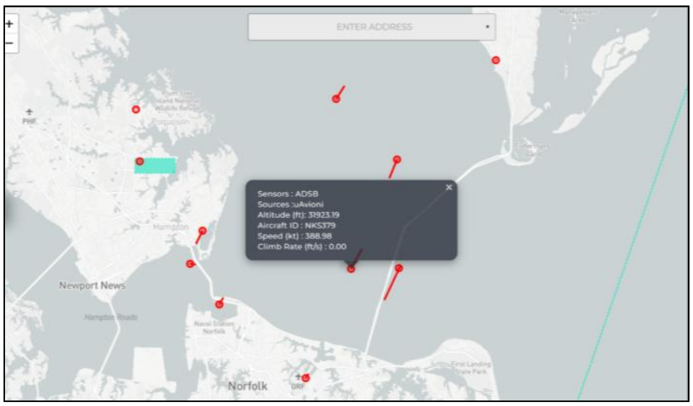

Figure 2 - Example IAD using ground-based ADS-B data.

For HDV testing, ROAM also served as the integration and distribution system for data moving through the HDV UAM Ecosystem prototype. Within this context, ROAM was integrated with the SIVL simulation environment, the Airspace Operations Lab (AOL) and Autonomous Vehicles Application Lab (AVAL) labs at ARC as well as real sUAS operated in NASA's CERTAIN range. ROAM's capability to seamlessly route data through several interfaces and labs across NASA was one of its' primary contributions to HDV testing.

Figure 3 - ROAM lab at NASA LaRC.

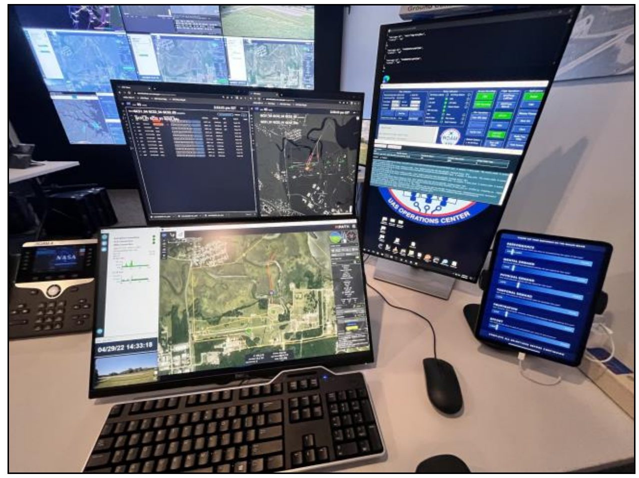

Figure 4 - Image of ground control station used for AOA Sim.

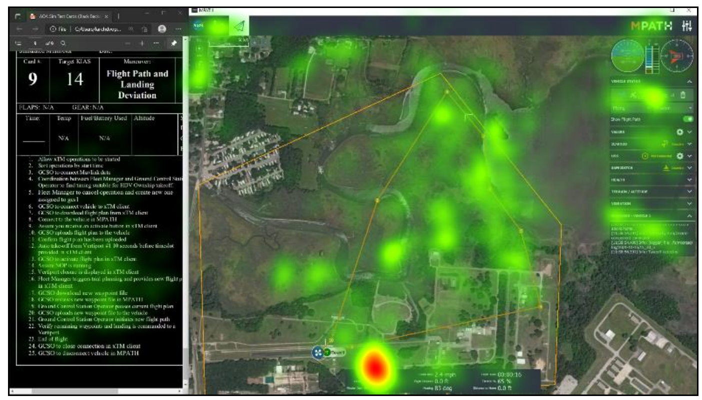

Figure 5 – Example of GCSO eye fixations for an AOA Sim run.

2) System Integration and Validation Lab simulation

The System Integration and Validation Lab (SIVL) is located at NASA Langley Research Center and can provide an integrated simulation environment. For HDV testing, the SIVL simulation environment was used to provide Human+Hardware-In-The-Loop (HHITL) testing and integrated a full 6 degree of freedom (6-DOF) model of a sUAS quadcopter with an actual Pixhawk autopilot.

Through wind-tunnel testing at NASA LaRC's 12-FT Wind Tunel, the Helix Pro vehicle model was created [13] to help support trajectory estimates for off-nominal conditions. The Helix Pro sim was repurposed for HDV HHITL applications. The size/weight of the vehicle was adjusted to replicate the HDV research test vehicles. The simulation model runs on a PC and sends vehicle position, attitude, and body axis rates and accelerations to a Pixhawk autopilot. The Pixhawk autopilot is the same make/model as used for flight testing and uses the PX-4 autopilot system. The result is that the Pixhawk is in a "flight like" condition and can be used to support UAM prototype assessment and HF testing as well as perform comprehensive checkout of the onboard autonomous systems. Output from the Pixhawk autopilot was routed to

ROAM resulting in high-fidelity HHITL test capability. For AOA Sim, SIVL playback simulations were used to help trigger ICAROUS DAA actions for testing.

3) Airspace Operations Lab

To support operation of the Multi Aircraft Control System (MACS) simulated aircraft, interface with the xTM Client and PSU, and to host the fleet manager workstation for human factors data collection, the AOL at NASA Ames Research Center was used. The AOL can flexibly facilitate a large array of airspace traffic management research applications and is shown in Figure 6. The MACS simulation engineer was located in the AOL along with the research coordinator. The AOL was very effective for integrating with the PSU given the location of that system at NASA ARC. MACS aircraft simulations could be initiated from the AOL and subsequently routed to the PSU and observed on the xTM Client display, both at AOL and ROAM. The research coordinator observed the test runs and provided overall qualitative assessment regarding the effectiveness and accuracy of each run.

Figure 6 - Airspace Operations Lab at Ames Research Center.

4) Autonomous Vehicle Applications Lab

The AVAL at NASA ARC provided Vertiport Management functionality for AOA Sim and AOA Flt tests. Fleet management located in the AOL required the FM to generate an updated route during simulated vertiport closures. The VM simulated vertiport closures that prompted the FM (hosted in the AOL) to update routes for the affected aircraft. This route was integrated with the PSU and was strategically deconflicted before sending the route to the GCSO for uploading to the vehicle. For AOA Sim and AOA Flt, VM functionality was limited to a simple press of a button to initiate the simulated vertiport closures. A photo of the AVAL lab as used for AOA Sim is provided in Figure 7.

Figure 7 - AVAL lab at NASA ARC.

5) Multi Aircraft Contol System

The MACS simulated aircraft were used to increase effective traffic density for both the AOA Sim and AOA Flt tests. MACS aircraft could fly their intended route and send real-time data to the xTM Client and PSU. During testing, a series of MACS aircraft could be initiated to reach the desired traffic density level. MACS aircraft were integrated with the xTM Client and PSU for airspace management testing. For AOA Sim and AOA Flt, 20 operations per hour were tested. Future testing includes up to and beyond 60 operations per hour. For AOA Sim, MACS aircraft were not fully integrated into the SIVL Sim environment necessitating usage of SIVL sim playback aircraft to trigger ICAROUS DAA reactions. Plans call for more complete integration of MACS aircraft within the SIVL sim environment to enable ownship simulations to be able to autonomously react to and remain well clear from MACS aircraft.

6) Alta-8 test aircraft

HDV flight testing was performed with Alta-8 octocopters acquired from the FreeFly company as shown in Figure 8 as flown for HDV Flight. Primarily designed for the movie industry, the Alta-8s provided a substantial improvement to sUAS operations at NASA. Their design is a quantum improvement over previous generation sUAS used at NASA and has several significant features making them ideal for HDV applications. One feature of the Alta-8 is the approach to vibration isolation of motors from the payload mounting areas. Alta-8s feature a ring of vibration isolators to greatly limit motor vibrations being transferred to the top and bottom payload areas which is very valuable to improve video quality from onboard cameras. Another feature is the enhanced integration of internal components of the vehicle using custom produced printed circuit boards to minimize wire and connections and the usage of high-quality components resulting in reliable research operations.

The Alta-8s were equipped with Pixhawk Blue cube autopilots and had a stock empty weight of 22.2 lbs with up 17.8 lbs of payload based on manufacturer’s specifications. For HDV AOA Flt, the Alta-8s were flown at 28.9 lbs with a 13-minute endurance and 30% battery margin using dual 6S

10 amp hour batteries. Systems integrated for AOA Flt included: Nvidia Xavier computer, FLARM Power Mouse, uAvionix Microlink, 4G Botlink, and uAvionix Ping ADS-B. Note the Ping ADS-B receives both 978MHz and 1090MHz and meets MOPS DO-282B and DO-260B Class A0.

An internal view of the Alta-8 is provided in Figure 9 showing the extensive use of custom fabricated interface circuit boards and approach to cabling and wire routing. Modifications performed to the Alta-8 are illustrated in Figures 10 and 11. As a result of a near tip-over during autonomous landings, the landing gear of the Alta-8 was shortened and the vehicle main power batteries were relocated to the lower payload to lower the vehicle's center of gravity as shown in Figure 8.

Figure 8 – Alta 8 flight test vehicle.

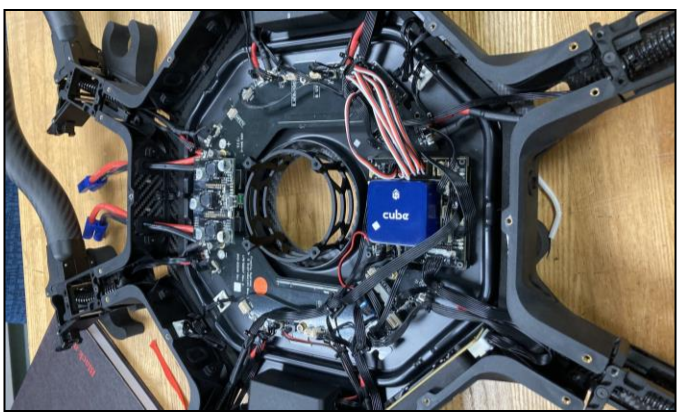

Figure 9 - Internal view of Alta-8 octocopter.

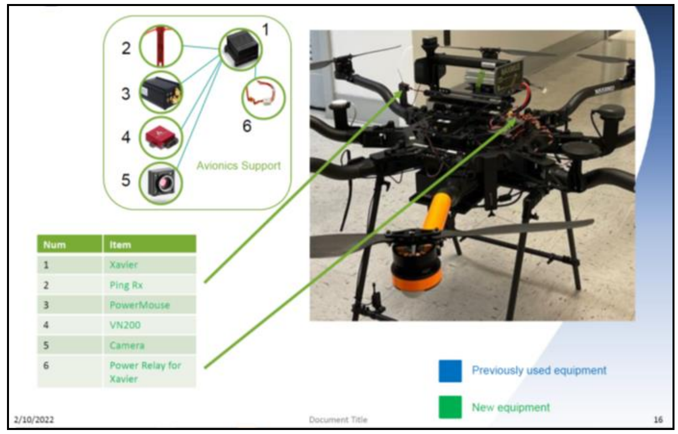

Figure 10 - Alta 8 system hardware overview upper vehicle.

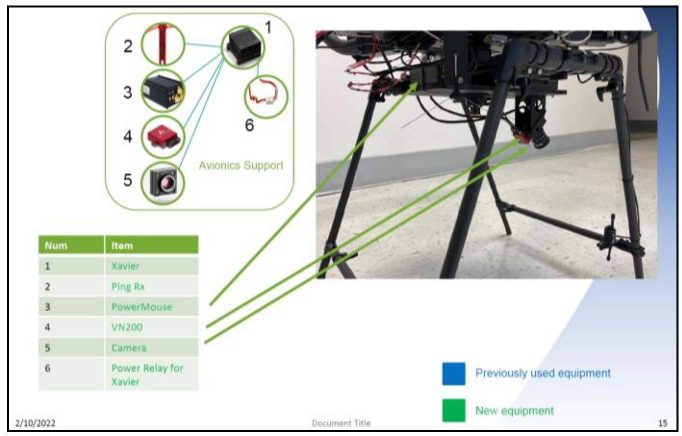

Figure 11 - Alta 8 system hardware overview lower vehicle.

7) CERTAIN range and flight test operations

HDV flight operations were performed using the CERTAIN test range and NASA LaRC. Figure 12 shows the NASA LaRC area with the CERTAIN range highlighted in blue. While sUAS operations are permitted below 400 ft throughout CERTAIN, operations in the northern area are less restrictive due to decreased risk from sUAS overflight of people and buildings. All of the HDV flight operations were performed in the northern area of CERTAIN in the vicinity of the LaRC Ref 2 location.

Figure 13 shows the nominal flight path employed for HDV Sim and HDV Flt testing. All ownship flights originated in the lower left area at the bottom of Figure 13 at Vertiport 1. The geofence boundary is indicated in Figure 13 by the tan line. Both the PX-4 and ICAROUS geofences were configured for the same boundary. The area at the extreme north end of the flight path is referred to as Snoopy's Head due to the similarity of the path of the creek to an outline of the famous cartoon character. All ownship flights took off from Vertiport 1 and flew counter-clockwise flight paths starting to the East heading towards Langley Air Force Base, then turning North and flying along the coast. At approximately 1.1 km from Vertiport-1, the flight path turned back towards the south to Vertiport-1. The final approach was intercepted at Waypoint 11 that included a 10-degree glide slope. Nominal vehicle cruising speeds were 7 m/s (~14 kts). Designing the flight path in this manner provided an approximately 3.5-minute inbound approach that enabled adequate testing in support of UAM Ecosystem prototype assessments.

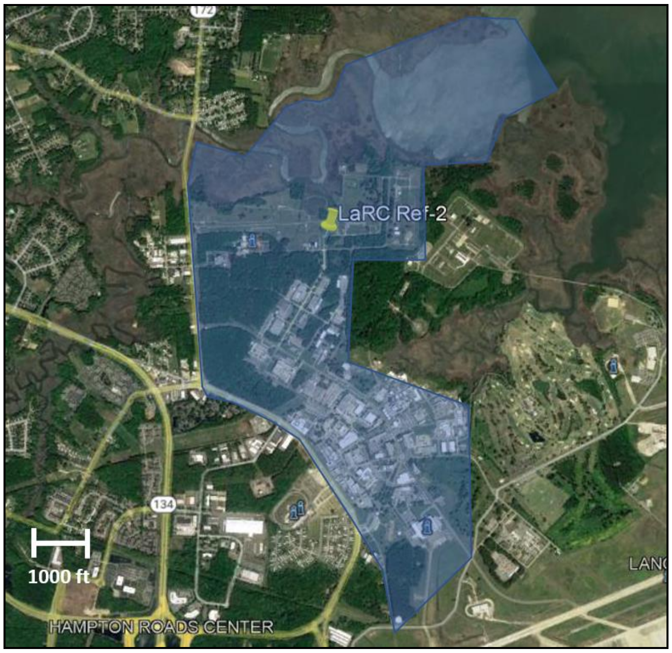

Figure 12 - CERTAIN test range and NASA LaRC.

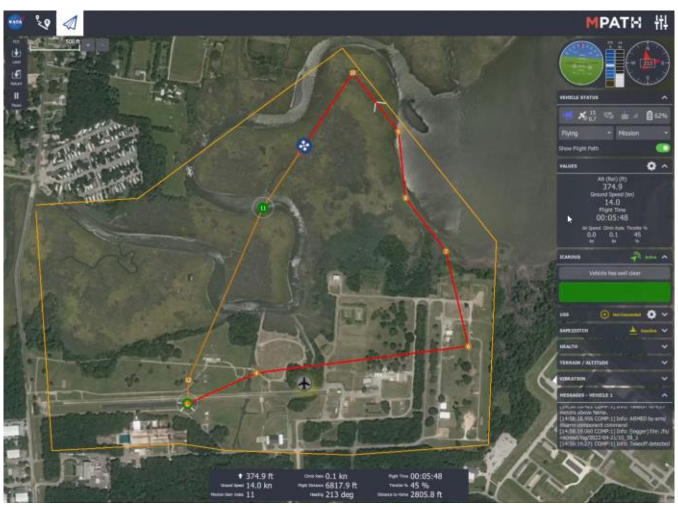

Figure 13 – Nominal flight path for both AOA Sim and AOA Flt

For AOA Sim and AOA Flt, multiple vehicles were flown along the nominal flight path and spaced approximately 3 minutes apart. At a nominal cruising speed of 7m/s (16mph) the vehicles were separated by approximately 420 meters (1378ft). Several alterations of the nominal approach path were used for AOA Sim and AOA Flt to construct the test matrix that is presented in Table in A 1.

8) Test scanarios and matrix

Test scenarios employed included flights with the ownship progressing along the nominal flight path along with emergency and non-emergency reroutes along with geofence testing. For AOA Sim and AOA Flt vehicles were either "simulated" aircraft that would simply execute their pre-defined flight path or are considered "ownship". Ownship vehicles were "live" in the sense that they were being controlled by a GCSO who could command actions such as Takeoff, Hold, Return to Launch (RTL), Mission Mode, and Land among other commands as well as monitor vehicle progress and health. GCSOs could upload and modify missions (waypoint files) to change the flight path of the vehicle. Ownships were also configured with HDV onboard autonomous systems and could execute emergency/contingency landings and perform autonomous detect and avoid maneuvers.

Table A 1 presents the scenarios included for both AOA Sim and AOA Flt testing. Scenario 1 was performed with all vehicles flying the nominal flight plan without any deviations. Scenarios 2a and 2b were tested to evaluate how the ownship would respond to two different levels of incursion and were flown simultaneously with scenarios 3a and 3b. Scenario 2a is one where ownship would be required to perform an autonomous detect and avoid maneuver to remain well clear of the intruder aircraft, yet the level of incursion was designed such that ownship could still remain in, or near, conformance. Scenario 3a was designed to be flown with 2a and represented a scenario where a vehicle would be in an emergency situation and would land at a nearby vertistop. Scenario 2b was performed to evaluate the autonomous DAA system to resolve a more significant incursion. For Scenario 2b, the intruding vehicle was simulating an emergency situation where landing at the vertiport was the only option to resolve the emergency, such as for an onboard vehicle fire. Scenario 3b was performed to evaluate S2D's ability to reroute the vehicle back to the vertiport with no option to land at an alternate (off vertiport) location. Scenario 3b could be associated with a vehicle that had just departed the vertiport but entered into an emergency situation a few minutes after takeoff and was designed to provide maximum impact to the UAM Ecosystem.

For the current UAM Ecosystem construct, flight plans are filed to support strategic deconfliction before takeoff and then monitored for conformance. Non-conformance alerts are sent to the GCSOs and FMs. Re-routes are assumed to be the role of the FM. For off-nominal situations involving intruding aircraft, it is also considered to be FMs role to identify the potential conflict and work with the GCSO to resolve it by developing, uploading, and executing a new strategically-deconflicted flight plan. While this could potentially be a viable path for larger conflict time horizons (ie on the order of several minutes), high-density operations, especially with multiple vehicles being managed by a single FM, would likely challenge that approach since at any instant any vehicle could transition into an emergency situation. The role of autonomous DAA systems are more tactical and resolve conflicts that can be less than 1 minute (ie 30 seconds) to loss of well clear. The blending between strategic and tactical deconfliction (tactegic) is an area of uncertainty given the current UAM Ecosystem assumptions. Research and testing performed within HDV is intended to help reduce uncertainties and inform future research in this area.

Scenario 4 was included to evaluate non-emergency vehicle re-routes, such as those associated with an unanticipated vertiport closure. In this situation, the vehicle is not in distress since it is assumed to have adequate endurance to travel to a designated alternate landing. Given the anticipated limited flight times and highly-constrained margins, even non-emergency re-routes would benefit from being handled expeditiously. For Scenario 4, the vertiport would be closed with the vehicle approaching the northern most waypoint near the top of Snoopy's head. The FM would generate a new flight plan to Vertiport 6 (west end of the range) and send that to the GCSO. The GCSO would review that updated flight plan and then place the vehicle into Hold mode and upload the new flight plan. Once the flight plan was uploaded, Mission mode would be selected and the vehicle would route to Vertirport-6.

Scenarios 5a, 5b, and 5c were included to evaluate ownship GCSO control and reactions to geofence encounters. For Scenario 5a, the geofence for ICAROUS was set to the same location as the PX-4 geofence. ICAROUS continually looks along the vehicles track and commands off board mode when a loss of well clear is predicted. In this way the vehicle never actually gets to the geofence and routes around it and continues the mission once clear.

Id	Name	Description	Ops/Hr	Vehicles
1	Nominal flight	Flight(s) are executed per flight plan	20	1/2/3
2a	Tactical ownship conflict conformant	Flight path deviation needed to address traffic incursion: sUAS. This scenario could be due to scenario 3a low-conflict	20	1/2
2b	Tactical ownship conflict non-conformant	Flight path deviation needed to address traffic incursion: sUAS. This scenario could be due to scenario 3b high conflict	20	1/2
3a	Emergency re-route S2Dmanual	Flight path deviation needed to address vehicle health issues manually triggered. Single alternate landing location vertistop (lowconflict).	20	1/2
3b	Emergency re-route S2Dmanual	Flight path deviation needed to address vehicle health issues manually triggered. Single alternate landing location vertiport (high-conflict).	20	1/2
4	Re-route for non-emergency reasons	Needed to simulate/assess vertiport closures. Fleet managertriggered to a Vertiport.	20	1
5a	Geofence test (BVLOS)	Test vehicle encounter with geofence	20	1
5b	Vehicle Control	Test GCSOs knowledge of creating a flight plan and geofence in MPATH	--	1
5c	Emergency Descent	Test GCSOs knowledge of observing a straight vertical descent mid-flight	--	1

Scenarios tested: only in sim, only in flight, both sim & flight

Table A 1 - Test matrix for AOA Sim and Flt.

III. Advanced Onboard Automation Simulation Overview

The AOA Sim test was completed in October, 2021. While actual sensor and communication link performance, winds, turbulence, etc, were not simulated for AOA Sim, a significant amount of required test elements were represented to a high-level of fidelity. Test elements simulated to a high-degree of fidelity were: 1) Integration of the vehicle autopilot with the Xavier companion computer including autonomous onboard systems (ie ICAROUS and S2D), 2) GCSO interface and control of the vehicle through MPATH, 3) Integration with the xTM Client and autonomous airspace management system, 4) Vehicle performance including representative operational speeds, 5) Comprehensive testing of the onboard autonomous systems (ICAROUS DAA and geofence containment and S2D autonomous contingency management functions), and 6) Realistic team communication (ie GCSO, FM). For the AOA Sim test, a total of 6 separate GCSOs participated. Results from the AOA Sim can be found in [14, 15].

IV. Advanced Onboard Automation Flight Test

The AOA Flt test was conducted from February 1st through April 30th, 2022. The build-up to AOA Flt included a flight test effort referred to AOA Flight Path Assessment (AOA FPA) conducted during the summer of 2021 that greatly expanded sUAS operations at NASA LaRC. Prior to AOA FPA, vehicle range was limited to approximately ~500m from takeoff/landing location. Within AOA FPA, range was expanded up ~1.1km including evaluation of diverting to alternate locations. AOA FPA helped to form the basis for maneuvers for both AOA Sim and AOA Flt.

A certificate of authorization (COA) from the FAA was acquired to enable Extended Visual Line of Sight (EVLOS) flight at CERTAIN. This COA enabled people manipulating the controls (PMCs) to not be required to have direct line of sight to the vehicle they were controlling. This was required in order to effectively use the ROAM UAS operations center as intended for HDV flight testing. The build-up for AOA Flt included several flight sessions conducted within visual line of sight (WVLOS) to perform vehicle testing and checkout, however the transition to EVLOS operations was accomplished as part of AOA Flt.

To best manage schedule and resources, the AOA Flt test started with Scenarios 1 and 4 since the Alta-8 vehicles did not require the Xavier computer and associated onboard autonomous systems to perform non-emergency re-routes. After an initial required amount of single-vehicle Scenario 4 were completed (3) the AOA Flt test team integrated the Xavier computer and conducted single-vehicle operations to acquire required data and mitigate risk to multi-vehicle operations.

The largest part of the AOA Flt test was for dedicated dual-vehicle operations as required for Scenarios 2a, 2b, 3a, and 3b. For Scenario 2b/3b larger deviations from ICAROUS was required to maintain well clear from the intruding vehicle. Recall that the intruder vehicle was generated from Scenario 3b that included an S2D emergency reroute back to the vertiport. This created a significant collision hazard as both vehicles were approaching nearly the same landing location (landing locations were separated by ~33 m).

In Figure 14, the flight paths for ownship and the S2D intruder aircraft are presented. The green arrow represents the ownship final approach course and red line represents the intruder vehicle in the simulated emergency state returning to the vertiport. Both vehicles are descending with the intruder vehicle executing several altitude and speed changes as it executes a S2D-commanded approach. During this approach the intruder aircraft maintains altitude at the start of the S2D approach (approximately 300 ft) towards the vertiport, then acquires a 45-deg glideslope to the intended landing location. The intruder vehicle then initiates a descent to 30m (100ft) followed by slow taxi to overhead landing location to a vertical descent. The 45-deg glideslope enables the aiming of a fixed-mounted camera onto the landing location to scan for moving targets to ensure the location is safe to land. The magenta flight paths correspond with the vehicle being in Mission mode. When ICAROUS commands the autopilot into Offboard mode, the flight path line color transitions to tan. This is shown in Figure 14 approximately when the ownship vehicle crosses the creek at approximately 76 m (250 ft). To maintain well clear, ICAROUS commanded flight path deviations to the south-west to avoid the intruder approaching from the east. Figure 15 provides an expanded view of the flight path generated by ICAROUS to remain well clear. ICAROUS checks the surroundings at set times to ascertain if it was clear to return to its original flight path. For AOA Sim and Flt, ICAROUS would check every 15 seconds to see if a return to the original course was possible. The flight path deviations and repeated turns away from the vertiport were a result of ICAROUS functionality to maintain well clear. While the flight path seemed erratic to visual observers on the ground, the anticipated vehicle response was demonstrated although some enhancements to the ICAROUS command system dynamics are warranted. At approximately 16m (50ft) the FLARM system was shut-down on the S2D intruder aircraft that resulted in ownship being able to resume its planned flight path.

The AOA Flt test culminated with simultaneous EVLOS operations of 3 vehicles to both acquire additional Scenario 1 and Scenario 4 data as well as to confirm the capability to operate 3 vehicles simultaneously to support subsequent high-density flight testing. An example of the 3 vehicle operations for Scenarios 1 and 4 is illustrated in Figure 16. For this scenario, the last vehicle in the flight sequence was the one to divert to Vertiport 6. Table A 2 provides the test matrix for AOA Flt indicating the number of test cases performed for each scenario. Results from AOA Flt will be published in [16].

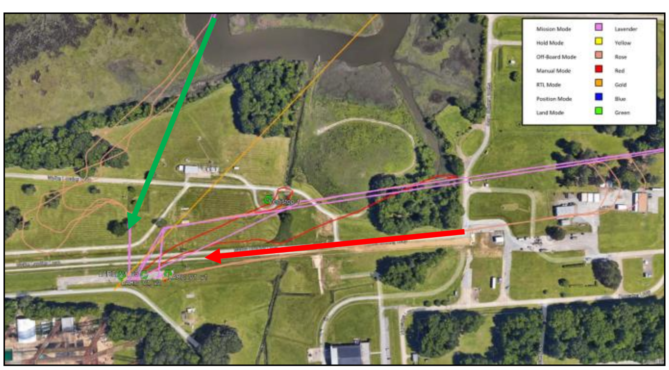

Figure 14 - Summary of 2 vehicle Scenario 2b/3b.

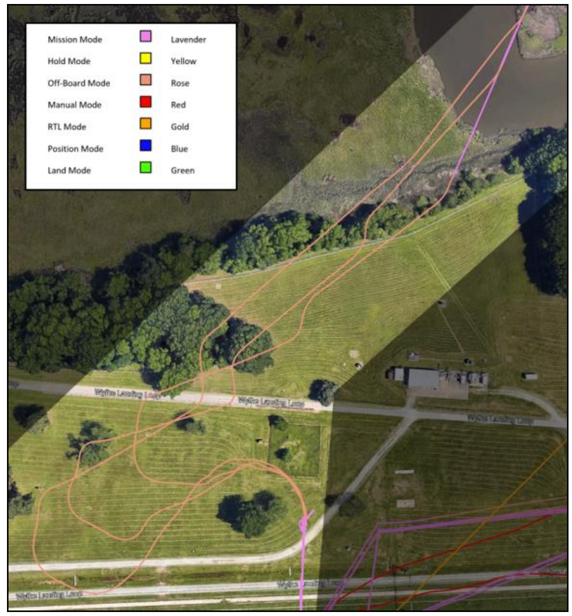

Figure 15 - Expanded view of the ICAROUS driven ownship deviations to maintain well clear.

Figure 16 - Example 3 vehicle Scenario 1 and 4 flights.

# Comp	Id	Scenario Name	Scenario Description
17	1	Nominal Flight	Flight executed per flight plan.
10	2a	Tactical Ownship Conflict Conformant	Flight path deviation needed to address traffic incursion.
6	2b	Tactical Ownship Conflict Non-Conformant	Flight path deviation needed to address traffic incursion.
10	3a	Emergency Re-Route S2D Manual	Flight path deviation to Vertistop needed to address vehicle health issue, manually triggered.
3	3b	Emergency Re-route S2D Manual	Flight path deviation to Vertiport needed to address vehicle health issues, manually triggered.
6	4	Re-Route for Non-Emergency Reasons	Flight path deviation needed to address vertiport closure, manually triggered.
2	5a	Geofence Encounter	Flight path deviation needed to address geofence encounter.

Table A 2 - AOA Flt scenarios with numbers of successful runs completed.

V. Overview of Scalable autonomous operations

With the completion of the AOA SWP, the HDV project is transitioning into the SAO SWP that will run through mid-2023. One major difference for the SAO SWP will be the inclusion of a prototype vertiport automation system (VAS). The VAS will provide required automation and information to help VMs safely manage traffic in a high-density environment. The VAS will enable the VM to adjust vehicle schedules and swap arrival sequences among other controls. Situational awareness of vehicle flights within the vertiport operations area will be provided to the VM to help manage traffic. In addition to the maneuvers performed in AOA SWP, missed approaches will be included within the mix. The missed approaches will be designed to build-up complexity and initially not affect other aircraft as well as affecting the trajectory of one and then more than one other aircraft.

Another major difference for SAO compared to AOA is the inclusion of BVLOS flight at NASA CERTAIN. One enabling technology being incorporated at NASA LaRC is the inclusion of a series of ground-based radar systems. Results from initial HDV radar testing can be found in [17]. These radar systems will be used to provide airspace awareness to the UAS operations team in ROAM as well as providing air traffic data for routing directly to the vehicle. Ground-based radar data to the vehicle will be fused with on-board ADS-B and FLARM data received directly by the vehicle. The resulting system will enable the vehicle to maintain well clear with cooperative as well as non-cooperative aircraft for a fully-operational vehicle and enable autonomous DAA for cooperative vehicles for occasions when link with the vehicle was lost

VI. Summary

The High Density Vertiplex (HDV) sub-project is part of the NASA Advanced Air Mobility (AAM) project. One thrust of the HDV subproject is to perform rapid prototyping and assessment of an Urban Air Mobility (UAM) Ecosystem within the terminal operational area to help inform future research investments and technology development. Another thrust within HDV is to perform integration, testing, and safety risk assessments required to acquire operational credit for several NASA small Unmanned Aerial Systems (sUAS) beyond visual line of sight (BVLOS) enabling technologies to expand test capabilities and to expedite technology transfer and ultimate effective usage. At this time, the HDV project has recently completed the Advanced Onboard Automation Schedule Work Package (AOA SWP) and is transitioning into the Scalable Autonomous Operations SWP that will feature Vertiport Automation System (VAS) development as well as Beyond Visual Line of Sight operations in high-density (Class-D) airspace.

An overview of the developments required to complete the AOA SWP are presented herein along with a summary of results. References for a series of 2022 DASC conference reports from the AOA SWP are included herein.

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