

High Density Vertiplex: Scalable Autonomous Operations Prototype Assessment Simulation

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Urban Air Mobility (UAM) is a rapidly growing topic within the field of aviation because of the impact a refined ecosystem and uncrewed aerial vehicles could have on modern society, such as urban air mobility, cargo, and emergency transport. Before the UAM concept can be actualized, research is needed to understand how to integrate these new classes of vehicles and operations into the National Airspace System. One under-researched but critical piece of infrastructure required for UAM operations is Vertiport operations. Vertiports are the envisioned takeoff and landing locations for these uncrewed aerial vehicles. To accommodate the high use of the vertiport, new technologies and roles will be required for optimal use. At NASA, the High Density Vertiplex sub-project targets research into vertiports. The High Density Vertiplex team created an Urban Air Mobility ecosystem to test and evaluate different concepts and tools used to support higher density operations at vertiports. Part of the test and evaluation included the Prototype Assessment Operations simulation of high-density operations around a vertiport to study vertiport management and vertiport operations. The research team also evaluated how the prototype Urban Air Mobility ecosystem supported fleet managers, ground control station operators, and vertiport managers in execution of nominal and off-nominal high-density operations. Results from this simulation provided insight regarding UAM ecosystem research and development and vertiport automation systems.

I. Introduction

The Urban Air Mobility (UAM) concept is helping to usher in a new age of aviation that holds the potential to change how people commute, transport cargo, execute missions for the public good; thereby potentially affecting the daily lives of people across the globe. These envisioned flights will be frequent, of short-duration, and unpiloted using highly autonomous general aviation-sized vehicles (approximately 4 passengers). The associated UAM industry, regulatory authorities, and relevant stakeholders are in the early stages of development across a wide range of necessary topic elements such as, but not limited to, vehicle manufacturing and testing, aircraft certification, acoustics assessments, and public acceptance. In addition, research is being conducted to support moving towards actualizing near-term operations, promoting

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scalability, and developing greater levels of autonomy. The High Density Vertiplex (HDV) sub-project is a part of the National Aeronautics and Space Administration's (NASA) Airspace Operations and Safety Program and the Advanced Air Mobility project. The goal of HDV is to develop, integrate, and assess autonomous technologies and architectures that support envisioned terminal area operations for UAM. The approach taken within HDV is to perform rapid prototyping and assessment of the UAM ecosystem that includes representative onboard automated systems, ground-based systems, fleet management, airspace management, and Vertiport Automation System (VAS), which was the primary focus of development. During HDV's operations, small Uncrewed Aerial Systems (sUAS) were employed as surrogates for larger proposed UAM aircraft to both accelerate the prototyping development, ensure safety, and significantly mitigate cost of testing. Usage of sUAS also generates results applicable to sUAS operational expansion, such as beyond visual line of sight (BVLOS) operations. HDV's second schedule work package (SWP) called Scalable Autonomous Operations (SAO) featured an initial VAS, automated systems onboard the sUAS, and airspace management tools to help with high-volume vertiport operations and BVLOS operations. The scope of this paper is to describe the setup and execution of the human-hardware-in-the-loop (HHITL) SAO simulation that targeted high volumes of vertiport traffic at 60 operations per hour, called the Prototype Assessment Operation (PAO). Specifically, this paper provides an explanation of the tools used, the simulation setup, scenarios conducted, human factors data collection process, necessary infrastructure, and takeaways.

II. Background

The HDV SAO SWP concluded in 2023 and the goal of was to develop and evaluate concepts, prototypes, procedures, and technologies supporting operations at higher frequencies from a vertiport. Three related high-level tasks were derived to support the goal. The first task was to develop and test a prototype VAS, which is an automated system that helps the Vertiport Manager with vertiport scheduling, vertipad status, and surveillance of the vertipads. The second task was to assess the UAM ecosystem prototype established by HDV. The evaluation included validation of systems in the ecosystem used and the human factors of the roles within the ecosystem. The final task consisted of BVLOS operations that utilized the HDV ecosystem to conduct operations with the personnel responsible for monitoring airspace in a remote operations center. Execution of the tasks included HHITL simulations followed up by flight testing to more closely represent an UAM ecosystem. The HHITL simulation provided validation to systems planned for flight operations by running on the same hardware used by the flight systems, providing confidence in taking the system to flight.

Three PAO objectives were created, mainly supporting tasks one and two: Connect fleet management tools and airspace management services to vehicle ground control stations, develop and test a vertiport automation system (VAS), and demonstrate vehicle, airspace, and vertiport automation technologies supporting dense operations at a vertiport. From these objectives, the following low level-tasks were formed by the project for the scope of the SAO PAO simulation activity: within a representative simulation environment, create a UAM ecosystem prototype to support HHITL testing, use HHITL simulation techniques to perform an assessment of a prototype VAS with relevant Human Factor results, and as defined within the HDV Concept of Operations (CONOPS; [1]), demonstrate the integration of vehicle, airspace, and VAS technologies as required for UAM ecosystem prototype using HHITL techniques. Several minimum success criteria were established for the SAO PAO simulation activity based on the low-level tasks. The first was to exercise several custom software applications in HDV Scenarios representative of an UAM ecosystem – a prototype VAS, Vertiport Manager Display via the UAS Mission Analysis Tool (UMAT) tool and the HDV client, and the Integrated Airspace Display (IAD). These systems served as the basis of HDV's prototype UAM ecosystem. The next success criterion was to simulate and analyze the integration and connectivity of communication links between simulated vehicles, the MPATH (Measuring Performance for Autonomy Teaming with Humans) ground control station at workstations within the ROAM (Remote Operations for Autonomous Missions) UAS Operations Center, and the HDV client from Ames Research Center (ARC). The team aimed to integrate the VAS prototype with the HDV client and the NASA Provider of Services for UAM (PSU) airspace management system for UAM operation planning.

With all the systems integrated to form HDV’s prototype UAM ecosystem, the team conducted the HHITL simulations of the in HDV scenarios.

III. Simulation Setup

The HDV SAO PAO simulation ran for six days between March 1 and March 16, 2023, taking approximately 42 work hours. PAO simulation included three groups of participants, each consisting of three GCSOs, one Vertiport Manager (VM), and one Fleet Manager (FM). Each group participated in a single session that took place within the same week, with each group having their own week. Each session had five unique scenarios, all requiring different actions by the participants. The simulation activity operated out of four research locations with the ROAM UAS Operations Center and the uncrewed aircraft Systems Integration and Validation Lab (SIVL) located at NASA Langley Research Center (LaRC) and the Airspace Operations Lab (AOL) and the Autonomous Vehicle Applications Lab (AVAL) at NASA ARC. Verbal communication between the facilities occurred over an online conference call using microphones that captured the entire room. An overview of roles, lab setup and major components used can be seen in Fig. 1 and are described below.

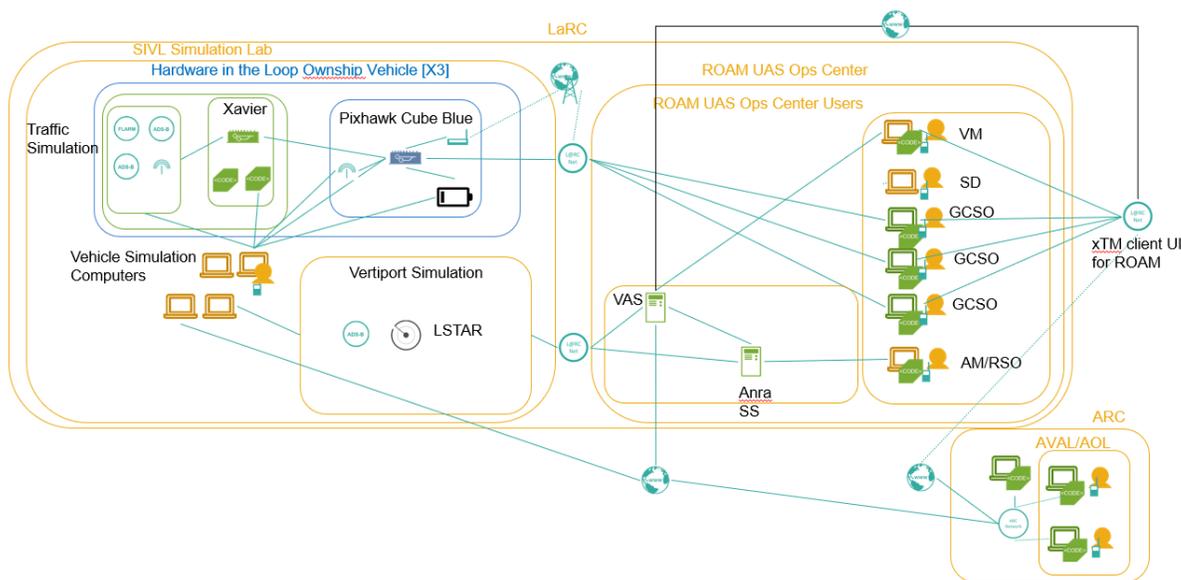


Fig. 1 Overview of Connections Between Systems at LaRC and ARC

A. Primary Simulation Actors

Ground Control Station Operator (GCSO). In the HDV’s prototype UAM ecosystem, the GCSO served as the remote operator of individual vehicles. Their main responsibilities were to request a flight plan from the FM, execute the flight plans received and monitor the vehicle status during flight. GCSOs were also required to execute plan updates issued by the FM, which involved speed changes, executing missed approaches, and diverting the vehicle to a new vertiport. More information on these actions is available in the *Scenarios* section below.

Vertiport Manager (VM). The VM was responsible for monitoring the status of vertipads, assessing inbound and outbound traffic to the vertiport, and closing vertipads when an issue was identified. VMs needed to evaluate when unplanned occupation of the vertipads occur such as emergency vertiport maintenance, ground hazards identified on the pads, or other hazards like a requirement for an emergency response vehicle to land at the vertiport. The VM did not have any direct interactions or communications with the FM or GCSOs.

Fleet Manager (FM). FMs managed the operation planning of all vehicles within their fleet, typically controlled by a GCSO. When a GCSO requested a flight plan at a certain takeoff time, the FM created that

flight profile and submitted it to the NASA UAS Service Supplier used by HDV for approval of the airspace volumes required. Once approved, the operation would become available to the GCSO. Typically, plan updates required by the FM were a result of a vertipad closure and required the FM to select the updated route, which is then pushed through to the GCSO.

B. Simulation Labs and Facilities

Remote Operations for Autonomous Missions (ROAM). ROAM served as the primary vehicle operations center for GCSOs and VMs. For PAO Simulation, ROAM supported up to three GCSOs and one VM for human factors data collection. The facility contained six workstations with three monitors each, a forward video wall at the front of the room for increased share situation awareness, and a control room behind the workstations for the human factors researchers and ROAM staff to help run the facility while in use. Three of the workstations supported software for the GCSOs, one used for the VM, while the other workstations were used by the Simulation Director (SD) and the ROAM operations engineer which is shown in Fig. 2. The SD role leads the execution of simulation studies within ROAM and coordinated the simulation plan to the participants. The ROAM Operations Engineer (ROE) was responsible for setting up all workstations for the participants, organizing the video wall contents, and addressing any facility issues that arise. At the end of each day, the ROE compiled all data logs from the workstations and uploaded them to the HDV data archives. Fig. 3 shows the view from the control room located at the back of the facility. For more information on ROAM, see [2].

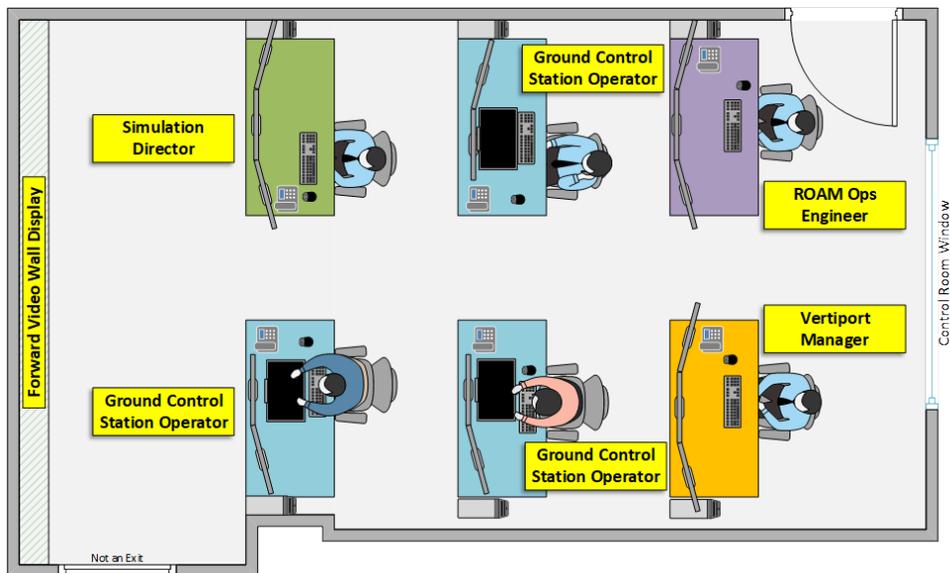


Fig. 2 ROAM Layout during PAO Simulation (Spring 2023)



Fig. 3 Users within ROAM during PAO Simulation

Systems Integration and Validation Lab (SIVL). The SIVL lab hosted the HHITL vehicle setup and the VAS configuration and management. This facility was staffed by the simulation operator who set up, monitored, and reset the HHITL simulation models during PAO simulation. Each GCSO was assigned a HHITL vehicle within the SIVL lab and the simulation operator established the telemetry streams from the HHITL vehicles to the ROAM workstations over the LaRC Enterprise Network for the GCSOs, allowing them to interact with their HHITL during the simulations. The simulation operator was also required to instantiate, monitor, and shut down the VAS developed by HDV for every test run. At the conclusion of PAO simulation, the simulation engineer consolidated the data logs from the HHITL simulations and the VAS, then uploaded them to the HDV archives. Fig. 4 presents the VAS and Vehicle Simulation Control in SIVL.



(a) Vertiport Automation System Control



(b) Vehicle Simulation Control

Fig. 4 SIVL VAS and HHITL Interfacing Stations

Airspace Operations Lab (AOL). The AOL lab provided a location for the FM to manage flight plans of the simulation vehicles, including operation scheduling, planning of operation deviations, and determining actions for the GCSOs. In addition to the FM, the AOL hosted the Multi Aircraft Control System (MACS) sim operator, who was responsible for beginning the stream of MACS traffic during the scenarios and resetting MACS after the conclusion of each scenario. AOL also included human factors researchers who helped setup the facility and monitored the FMs throughout the simulation. The AOL researchers coordinates the AOL setup with the SD and is responsible for collection and archiving of AOL data sources. A layout of the AOL lab can be seen in Fig. 5.

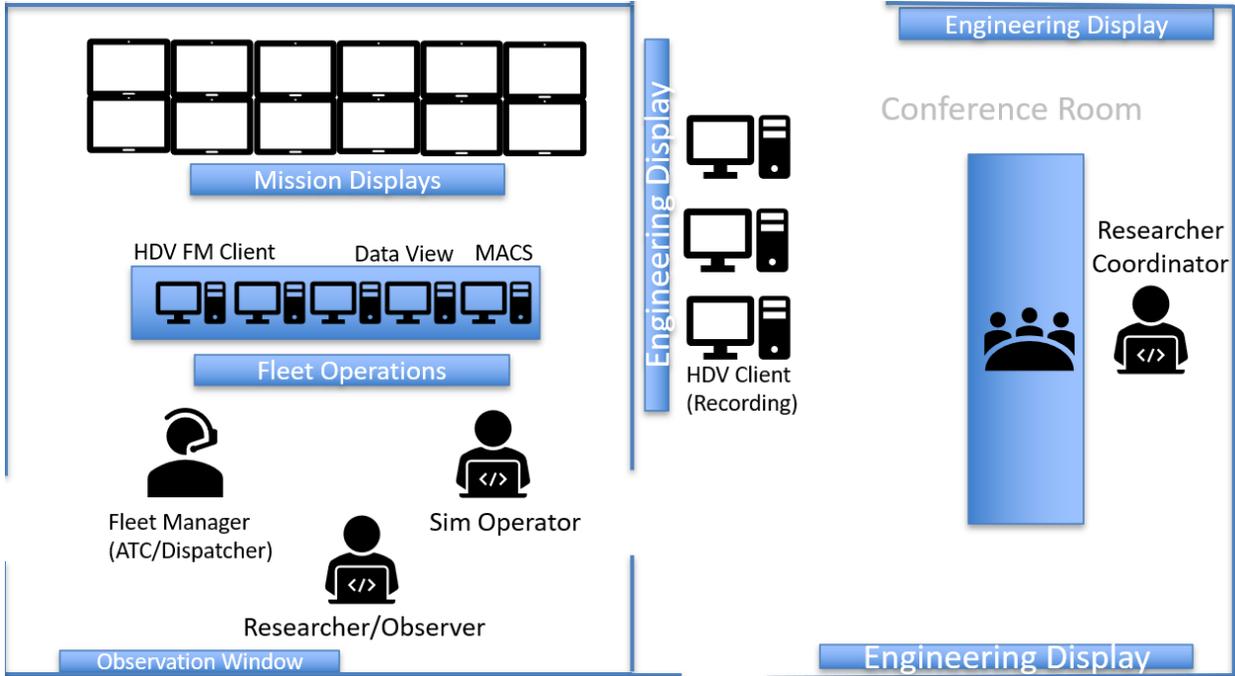


Fig. 5 AOL Overview

Autonomous Vehicle Applications Lab (AVAL). The AVAL hosted a workstation for testing and development of the VM and FM user interface in the HDV client. This workstation was occupied by a HDV team member who monitored systems used by the VM at LaRC and the FM at ARC. It provided insight into the ongoing test and troubleshooting tools for resolving software issues, particularly for use cases involving flight deviations at the FM position.

C. Simulation Components

Human Hardware in the Loop (HHITL) The HHITL used in the SIVL lab was a representative simulation of the flight vehicles used in live operations for HDV. This consisted of a Pixhawk Blue Cube autopilot hardware running the PX4 flight stack, an NVIDIA Xavier AGX, and a simulated model of a multi-copter. The Pixhawk autopilot running PX4 was used to match the hardware of the flight vehicle used for HDV, which was an Alta 8 Pro by FreeFly Systems. The NVIDIA Xavier AGX was the onboard computer for HDV vehicles and contained two NASA programs, Integrated Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS) and Safe2Ditch. ICAROUS provided autonomous Detect and Avoid functionality with the ability to provide warnings of incoming traffic, maneuver the vehicle away from other traffic in the area and around no-fly zones [3]. Positional data of the other vehicles within the simulation, both HHITL and MACS, were provided to ICAROUS and displayed on MPATH for the GCSO. Safe2Ditch provided an autonomous contingency management system enabling the vehicle to

perform safe remote landings [4]. In flight operations, it featured a machine vision system to scan the intended landing location, called a ditch site, to ensure it is free of people or moving objects. These technologies were not the focus of PAO Simulation but were included to get more operational credit with them to support future HDV PAO flight and BVLOS operations. The final component was the dynamics model of a multi-copter and simulated Global Positioning System (GPS) location provided to the autopilot during operation. The model was developed using wind tunnel data from NASA Langley and the weight, balance, etc. was adjusted appropriately to match an Alta 8 Pro more closely. A layout of the connections of the HHITL can be seen in Fig. 6.

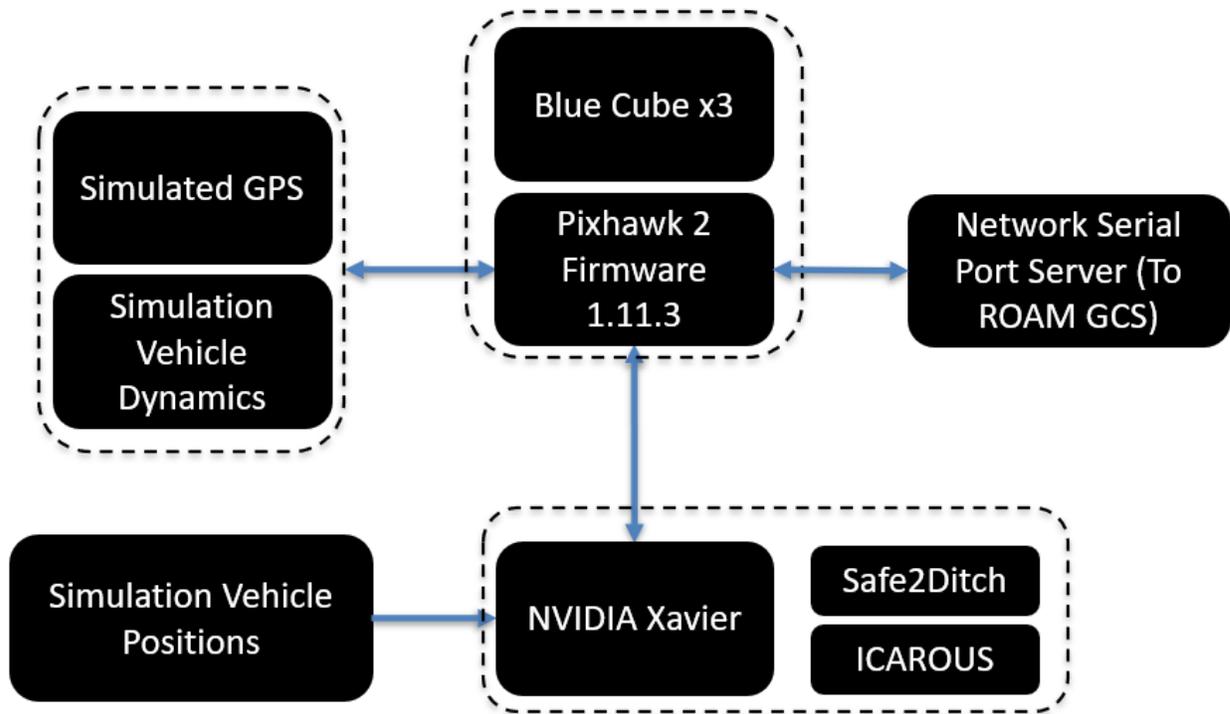


Fig. 6 HHITL System Diagram

Measuring Performance for Autonomy Teaming with Humans (MPATH). MPATH was the chosen ground control station (GCS) for the GCSOs. It is a NASA developed ground control station based on QGroundControl, a popular open-source GCS. QGroundControl provided the basic controls for the HHITL including mission development, displaying vehicle state information, starting missions, pausing the vehicle in flight, and commands for moving the vehicle to a specific location. NASA developed MPATH primarily for human factors research on GCSOs, which includes tracking mouse clicks and visual updates to the user interface. For PAO simulation, HDV further enhanced MPATH by adding more interactions with the onboard autonomy software, status information, and the addition of a speed change button. The GCSOs were able to view ditch sites for Safe2Ditch (ditch sites), engage an emergency landing from MPATH, view the traffic conflict information from ICAROUS, and enable or disable automatic traffic avoidance from ICAROUS. Traffic warnings provided by ICAROUS, called bands, indicated when a potential airspace violation may occur with the settings used during PAO simulation at 500ft lateral and 100ft vertical separation for other vehicles in the HDV ecosystem with a 20 second trajectory projection. The speed change button allowed the GCSO to enter a new speed and issue a speed change command to the vehicle while enroute to speed up or slow down, thereby avoiding a conflict with another vehicle or staying on scheduled arrival time.

Multi Aircraft Control System (MACS). MACS are simulated vehicles that supplemented the airspace with other UAM vehicles for the FM, GCSOs, and VM to interact with. Each MACS vehicle was started by a script that submitted an operation to the HDV client then provided positional reports once the assigned takeoff time came. From a participant’s view, these operations looked like standard vehicles. The MACS sim operator was responsible for starting and stopping a batch of MACS scripts based on direction from the SD.

High Density Vertiplex (HDV) client. The HDV client allowed coordination between the primary roles within HDV’s prototype UAM ecosystem and interaction with the various components. The four main pages of the HDV client for the participants were the schedule, operations, vertiport, and map pages. The schedule page was used by the FM to create and assign operations to GCSOs. The operations appear on the operations page, which allowed GCSOs to connect to their assigned operations. Once a GCSO claimed a particular operation by connecting to it within the HDV client, the GCSO can then download the matching flight plan that could be uploaded to the vehicle through MPATH. After the GCSO initiates vehicle take-off, the operation is “Activated” within HDV client and positional reports from MPATH were routed to the HDV client, allowing the vehicle to be shown on the HDV client map page. The map also showed the airspace volumes associated with operations, individual vertiports down to the vertipads, and the vertiport operational area, which are the grayed lined circles seen in Fig. 7. The inner circle indicates the final approach point and the outer circle represents the initial approach point for vehicles approach the vertiport. Closures could be initiated by the VM using the vertiport tab, which provided a list of vertiports available to the schedule page. Each vertiport row could be expanded to show individual vertipad, shown in Fig. 8. Once the close button is clicked, the VM puts in a start and stop time for the closure and the pad status is updated. Affected operations are flagged on the operations page, prompting action from the FM who engaged the trial planner within the operations tab. The trial planner, seen in Fig. 9, allowed the FM to change an operations flight plan and inform the GCSO through the operation’s status tab. Once notified, the GCSO then performs the appropriate action by changing speed, initiating a missed approach, or downloading the new flight plan for a diversion.

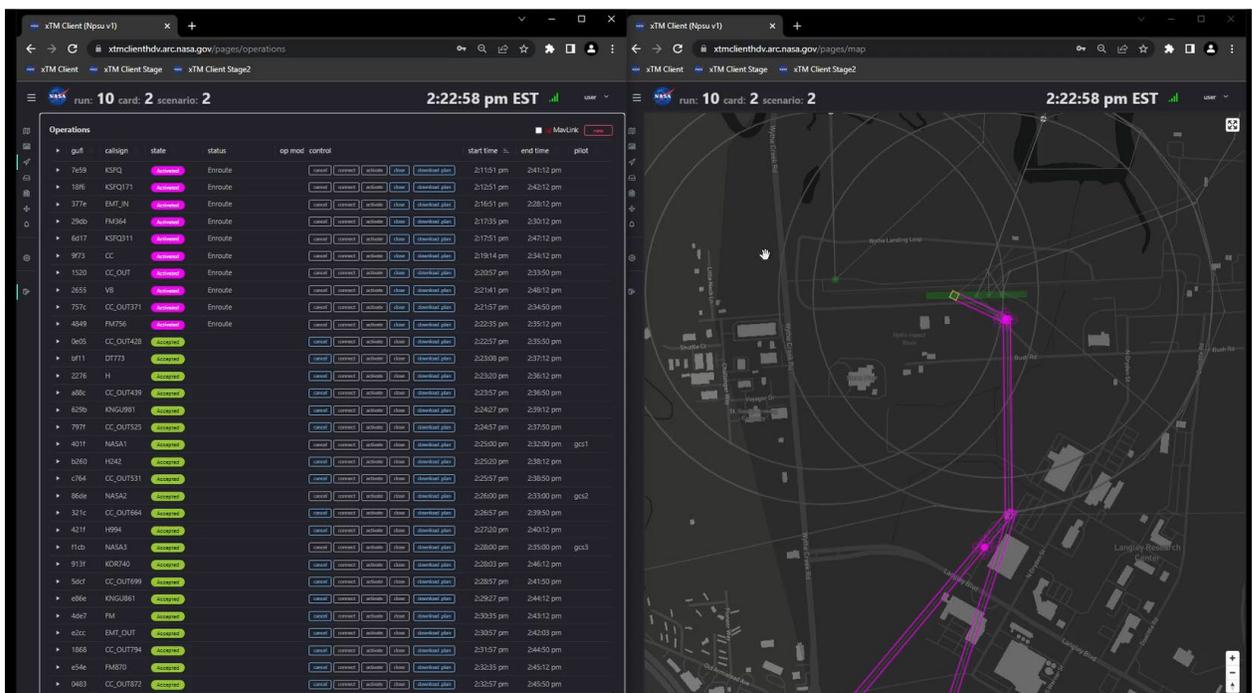


Fig. 7 HDV client User Interface - Operations and Map Tab

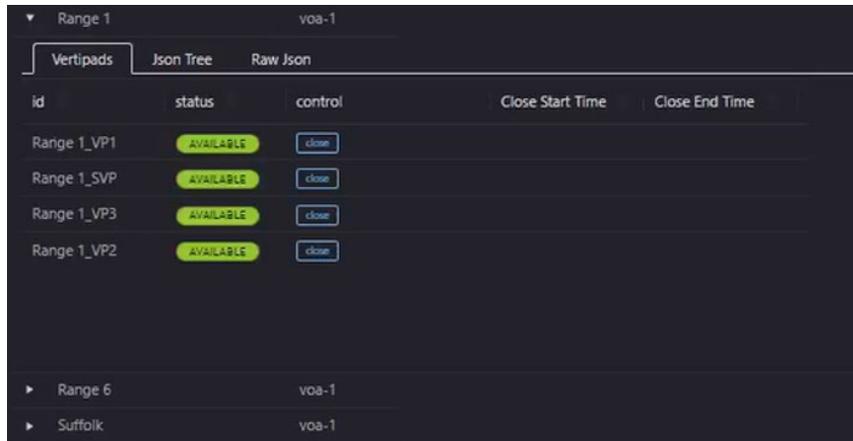


Fig. 8 HDV client User Interface - Vertiport Tab

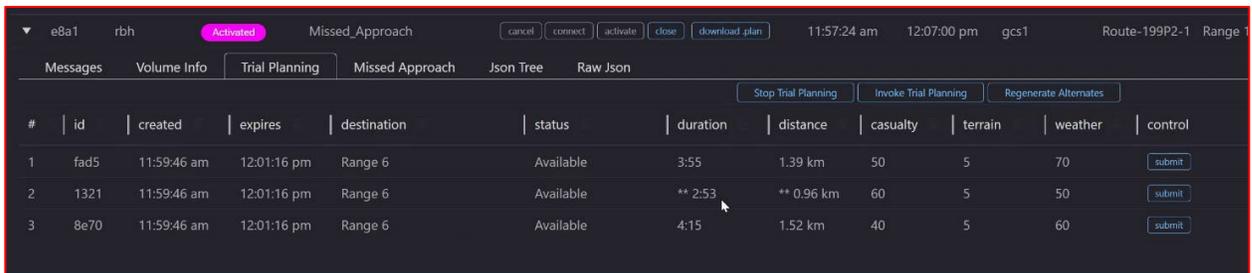


Fig. 9 HDV client User Interface - Trial Planner

Vertiport Automation System (VAS). The VAS ran on a local LaRC server in the SIVL lab and connected the HDV client to other systems. Configuration of the VAS was the responsibility of the SIVL sim operator. The VAS helped with the monitoring of vertipads, communicates with the PSU to help manage approval of vehicle takeoff and landings clearances, and collect surveillance traffic information. The VAS deconflicted takeoff and landing based on the operation start time, end time, beginning vertipad and ending vertipad compared to the current schedule. Monitoring the vertipads required the VAS to update the status of the vertipads based on data from a visual monitoring that looked for hazards, manage the opening and closure commands from the VM and approved incoming landing approval requests when a vehicle is on approach. Landing approvals occurred at the final approach fix point, which is the inner circle of the vertiport operational area. A vehicle would have been approved for landing if the pad is clear of obstacles, open, and not occupied with another vehicle. PAO simulation did not have a simulated visual monitoring system, so all hazards for the scenarios were communicated to the VM from the SD. When a VM submitted a closure request through the HDV client, the status of the vertipad when from available to closed, resulting in a landing denial for all vehicles on approach for landing at that specific pad. The landing denial needed to be handled by the FM by either putting the vehicle on a missed approach or diverting it to a new vertiport.

Integrated Airspace Display (IAD). The IAD provided situational awareness of the airspace to the roles of the simulation by providing fused surveillance. During the simulation, all MACS traffic and HHITL vehicles were input into the system from the HDV client positional reports and displayed on the forward video wall of ROAM. This data was made available to the VAS to help populate other airspace tools (discussed next). During simulation, the fused surveillance capability was not exercised since all traffic inputs came from the same source. Fused surveillance becomes critical during live flight operations when the IAD is being provided multiple radar feeds and Automatic Dependent Surveillance–Broadcast (ADS-B) feeds.

UAS Mission Analysis Tool (UMAT). UMAT is a three-dimensional spatial tool that allowed the VM to monitor the airspace around the vertiport for traffic on approach and departure from the vertiport. UMAT overlaid the vertipads of the vertiport, the standard arrival and departure paths, called STARs and SIDs in HDV, as well as the surveillance traffic coming from the VAS. The combination of these overlays assisted the VM to ensure that vehicles arriving and departing the vertiport were landing at the appropriate vertipads, following the STARs and SIDs, and maintaining proper clearance of other vehicles in the vertiport area of operation.

IV. Human Factors

One of the benefits of performing HHITL simulations was the ability to collect data on the “human in the loop”. The human’s positive contribution to safety has been explored in commercial aviation [5], however, very little is known about the human’s role within UAM operations. HDV has conducted some research on the human’s role performing UAM operations within an initial setup of ROAM [2, 6 - 11]. During the HDV SAO SWP, GCSOs, FMs, and VMs served as participants and completed several questionnaires about the five scenarios, including the NASA-TLX [6], SART [7], and a Perceived Risk of Scenarios questionnaire, each given at the end of each scenario. Additionally, participants filled out a series of pre-post experiment questionnaires about their trust in the onboard automated systems, their workstations, and display elements using a modified version of [8]. After the end of the experiment, participants filled out a system usability questionnaire (PSSUQ) on the HDV client. In addition, researchers engaged in informal qualitative interviews with the participants. Some of the data collected are discussed in detail in [9, 10]. Although studying the human factors associated with these operations is important, it falls outside of the scope of this paper.

V. Scenarios

During each session of the simulation, the participating GCSOs, VMs, and FMs were presented with five unique scenarios, each of which represented different potential situations of vertiport operations. The scenarios were characterized by the required actions of the GCSOs from the FM. The actions a GCSO had to take consisted of speed changes of the vehicle in flight, diversion to a different vertiport, or a missed approach procedure, all of which may be caused by the VM closing the vertipads. The pacing of the routes of simulated vehicles were planned to have one vehicle land at a vertiport every minute, with a one-minute buffer between every two landings. The buffer was to allow for adjustments to the schedule without interfering with other flight operations. Descriptions of each scenario are provided below:

- 1) *Nominal*. The nominal scenario represented a situation where the flight is executed as expected. This required GCSOs to only to take actions used in typical nominal operations, which included uploading flight plans, initiating takeoff, monitoring systems during flight, and landing their aircraft.
- 2) *Missed Approach*. The missed approach scenario was intended to represent a situation where a vehicle must circle back around after the initial approach and land at a different slot than originally intended. A missed approach is required for various reasons, such as a vertipad closure, a vertipad being occupied longer than expected by a previous arrival, or the need for expedited landing of an aircraft with an onboard emergency. For the HDV SAO PAO simulation, the chosen narrative was a medical emergency onboard the second vehicle that took off.
- 3) *Speed Change*. For the speed change scenario, the vertipads at the vertiport were closed for a short amount of time. In the HDV SAO PAO simulation, wildlife was detected on the vertipads by the VM, requiring closure of the pads occupied by the wildlife. If the closure affected the arrival times of incoming vehicles, the FM engaged the trial planner to determine the speed the vehicle needs to go to shift the arrival time until after the vertiport reopens. The FM then instructed the GCSOs to slow down their vehicle based on the output of the trial planner.

- 4) *Divert*. When the divert scenario was executed, the vertiport is closed for longer than the speed change scenario, prompting the FM to take different actions when replanning the operation. Once the vertiport was closed, the FM engaged the trial planner aspect of the HDV client which allowed them to generate a new trajectory to a nearby vertiport and avoid the closure. The new trajectory was provided to the GCSO through the HDV web client. The GCSO then uploaded the new flight plan to the vehicle which updated the trajectory to the nearby vertiport.
- 5) *Combination of Missed Approach, Divert, and Speed Change*. The final scenario was a situation where a combination of a missed approach, speed changes, and diversions were required by the GCSOs. This was due to a long shut down of the vertiport caused by an incoming emergency services vehicle that was landing at the vertiport for a medical pickup, requiring all operations at the vertiport to stop during that time. This scenario required the most complicated maneuvers for the participants. This intended to simulate the worst-case scenario for vertiport operations as it required the most complicated actions out of all scenarios executed in the SAO PAO simulation.

VI. Takeaways

The team observed many different takeaways during setup and execution of PAO simulation. The takeaways included discovering the intricacies of how to handle landing denials, how to organize a distributed team to setup a complex and distributed system, how positional inputs from different sources interact within the system, how well takeoff and landings deconflict, and how the onboard autonomy reacts to the traffic density of different operations.

Several insights were gained about performing landing denials during vertiport operations. First, GCSOs had no required actions during a landing denial unless prompted by the FM. During the simulated operations, after a vehicle was denied landing by the VAS, the FM was required to resolve the conflict by either diverting the vehicle or sending it on a missed approach to try and get approval the next time it entered the final approach. The GCSO served as a monitor of these maneuvers and confirmed the execution of the maneuver to the FM. Second, when landing was denied, the HDV client did not prompt any action from the FM other than changing the status of the operation to “Landing Denied”. This may cause the denial to be missed by the FM since required operation modifications are notified under the “op mod” column of the HDV client Operation’s tab. If the operation is not replanned, vehicles may land without clearance from the VAS and, by extension, the VM. Third, temporal execution of commands by the FM was an important factor for errors during the simulated operations. The FM was able to issue all commands needed during the scenarios, but these commands had small temporal windows in which they had to be executed. The FM did not always issue them in time to avoid landing denials that occur from closures. This resulted in vehicles being denied landing without any corrective actions taken to resolve the denial. If vehicles are allowed to land when they have been denied landing clearance, it may result in near misses or collisions near the vertipads which could result in property damage and loss of life in UAM ecosystems. Overall, the FM experienced high workload during flight replanning events [10][15].

Next, these operations required the organization of a complex and distributed ecosystem over multiple geographical locations. To accomplish this required careful coordination and testing of resources. Over five months of preparation was required to coordinate execution of PAO simulation with the large and complex team. Within that time, the research team performed multiple planning meetings, component level development, integration testing, and simulation dry runs to ensure mission success. One challenge was the logistics of executing the simulated operations across two different NASA centers that had a three-hour time difference. Integration tests and simulations needed to be planned so that all personnel arrived at their stations on time and that the operators knew their roles during each session. To accomplish this goal, a temporal breakdown of the estimated schedule of the day was mapped to the assignments for the facilities at each timeslot. Using this schedule allowed for the simulations and integration sessions to work seamlessly across the two centers throughout the entirety of the operations. In addition to the scheduling, numerous tests of the full HDV ecosystem were required prior to simulation start to ensure all integrated functionality worked properly. Software components that worked well within the local testing environment

at each NASA Center sometimes faced integration issues when brought into to full ecosystem. To help alleviate these integration issues, the software components of the ecosystem were replicated in local environments provided to each center for more robust isolation testing. This allowed for the software components to be more reliable for when the full system integration testing began.

Another finding demonstrated the need to implement a standard approach speed or have different approach and taxi points for vehicles approaching at different speeds. To create the simulated traffic required to model vertiport operations, the research team used simulated MACS and simulated HHITL vehicles. However, with the traffic coming from two sources, the speeds of the vehicles did not sync up. This discrepancy in speed was critical during a vehicle's approach to the Vertiport with the MACS traffic coming into land faster than the HHITL traffic, causing the MACS traffic to occasionally overtake the HHITL traffic. In live operations, managing differential speeds would likely increase workload upon the traffic management system, including FMs and VMs. To avoid this critical event, a vertiport can implement a standard approach speed that all incoming vehicles would need to follow or have different approach lanes for different approach speeds.

Next, using a 20-second trajectory projection of potential in-air conflicts was too long. ICAROUS, the onboard detect and avoid system, provided GCSOs with a warning indicator in the direction of a potential conflict that was projected 20 seconds beyond their trajectory. However, given the nature of the operations in a small area and with the speed of the MACS traffic as they approached, these bands were inconsistent and confusing for the GCSOs. The GCSOs consistently asked why they would see bands and that when they would see bands, it was for traffic they did not initially know the location of. This trajectory projection may be suitable for wider area flights or faster speeds, but for operations close to a vertiport, it provided more confusion than guidance. A variable projection time may be desired based on the airspace and vehicle used in the operation.

Finally, the VAS may need to be upgraded to create a buffer around take-off and landing time to account for vehicle taxi time. During the simulation, the vehicle takeoff and landing times would occasionally be close enough for vehicles to overlap their positions over the vertipads. This means that as a vehicle is coming in for a landing, another may be scheduled to take off slightly before at the same pad. There was a need for the VAS to be stricter when it comes to takeoff and landing windows by adding longer buffers around it. Another takeoff and landing conflict within the system was if two operations are scheduled to arrive or depart the vertiport at the same time but from different pads, the vehicles would have been using the approach or departure path at similar times, creating a potential loss of separation. The VAS did not flag this as a conflict, but the PSU should have been able to resolve this by spotting the conflict with the airspace volumes and denying the conflicting operation.

VII. Connected Follow-on Work

The HDV SAO PAO simulation activity was a precursor to the planned HDV SAO PAO flight operation beginning in May 2023. This flight activity replaced the hardware in the loop simulated vehicles with sUAS equipped with NASA technology transmitting to HDV's prototype UAM ecosystem. There were up to five GCSOs and matching aircraft in a scenario at one time instead of three from simulation. Additional roles were required within ROAM for live flights, like the Range Safety Officer, Radar Operator, and Airspace Surveillance Monitor. To prepare for this, updates were made to the HDV setup, like the addition of another room within ROAM, the installation of a new communication system, and software updates made to the systems used in simulation to prepare them for the flight operations.

Following PAO flight operations, the SAO spiral continued with the BVLOS training, simulation, and flight data collection activities. This included the use and upgrade of the HHITL and live flight vehicles from PAO to conduct no visual observer BVLOS operations. During these operations, the surveillance systems set up by HDV in PAO were essential for roles in ROAM to maintain awareness of the airspace, most importantly the Airspace Surveillance Monitor and the Range Safety Officer. To train GCSO personnel for live flight, HDV developed a training plan for to train a GCSO for BVLOS operations. This training includes classroom education and simulation of nominal and off nominal procedures. Once trained, the GCSOs were then run through a randomized set of these scenarios and human factors data was collected

on them to evaluate the effectiveness of the training. HDV also targeted a BVLOS flight test, which required multiple sensors of traffic for deconfliction of airspace between other UAS and manned vehicles, such as radars, ADS-B sensors, and Flight Alarm (FLARM) sensors. Each data stream was input into the Integrated Airspace Display, traffic was fused together, and displayed for the user on one map, including identification of the aircraft from things like ADS-B and FLARM streams. This display is intended to be used by the Airspace Surveillance Monitor and the Range Safety Officer for aircraft deconfliction to avoid collisions. This system supported the BVLOS flight testing in September of 2023.

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