Progressive Development of Fleet Management Capabilities for a High Density Vertiplex Environment

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The High Density Vertiplex (HDV) Sub-Project, as part of NASA's Advanced Air Mobility (AAM) Project, has been developing a reference automation architecture with a far-term view of scalable, high-density operations in and around vertiport terminal areas. One of the components of that architecture under development has been focused on fleet management capabilities to support the management of multiple AAM operations from a supervisory role of a fleet manager. This capability relies on connectivity and information exchanges with other services for airspace and vertiport management as well as with flight crews responsible for operation execution. This paper will present this capability with a focus on its user interface developments as well as its integration into the simulation and flight testing performed as part of the HDV research roadmap.

I. Nomenclature

AAM	=	Advanced Air Mobility
HDV	=	High Density Vertiplex
UAM	=	Urban Air Mobility
HHITL	=	Human and Hardware In-The-Loop
ARC	=	Ames Research Center
LaRC	=	Langley Research Center
AOL	=	Airspace Operations Lab
FM	=	Fleet Manager
FOC	=	Fleet Operations Center
MACS	=	Multi Aircraft Control System
AVAL	=	Autonomous Vehicles Applications Lab
ROAM	=	Remote Operations for Autonomous Missions
sUAS	=	small Unmanned Aerial Systems
GCSO	=	Ground Control Station Operator
VM	=	Vertiport Manager
SIVL	=	Systems Integration and Validation Lab
NPSU	=	NASA Provider of Services for UAM

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VAS	=	Vertiport Automation System
TLOF	=	Takeoff and Landing area
MPATH	=	Measuring Performance for Autonomy Teaming with Humans
ICAROUS	=	Integrated Configurable Architecture for Reliable Operations of Unmanned Systems
DAA	=	Detect and Avoid
AOA	=	Advanced Onboard Automation
SAO	=	Scalable Autonomous Operations
TLX	=	Task Load Index
SART	=	Situation Awareness Rating Technique
PSSUQ	=	Post-study System Usability Questionnaire
VOA	=	Vertiport Operations Area
ETA	=	Estimated Time of Arrival
STA	=	Scheduled Time of Arrival
SDSP	=	Supplementary Data Service Provider
ATCSCC	=	Air Traffic Control System Command Center
AFP	=	Airspace Flow Program

II. Introduction

The Advanced Air Mobility (AAM) concept is paving the way for a new age in aviation that holds potential to change the way that people commute, cargo is transported, public good missions are carried out, and many other aspects affecting the daily lives of people across the globe. Although still in the early stages, the development and progression of AAM will take an evolutionary path from low density, low complexity operations to higher density, higher complexity operations in certain environments.

NASA has embarked upon a thrust of research in AAM on multiple fronts in collaboration with industry and other government agencies. One focus area has been on the management of scalable vertiport operations within the High-Density Vertiplex (HDV) subproject. HDV is responsible for addressing the technical challenge of developing a reference automation architecture to enable the scalability of Urban Air Mobility (UAM) operations in a multi-vertiport environment, particularly in the terminal areas. The development of the reference architecture includes the integration of multiple systems within a larger ecosystem that leverages envisioned capabilities for airspace management.

It is likely that there will be a progressive need for supervisory positions that manage multiple aircraft of a company's fleet with aggregate management of the entire fleet that does not rely on 1:1, operator to aircraft, mapping. This paper will present this capability with a focus on its integration into the simulation and flight testing performed by HDV, as well as its user interface developments.

III. HDV prototype demonstration and assessment

A. Prototype demonstration

In support of its objectives, the HDV sub-project integrated key elements of a UAM ecosystem to enable testing of the concept with the systems and information exchanges in place for in-depth operational exploration. HDV prototype demonstration included reference systems and technologies to test through distributed, large-scale, Human and Hardware in the Loop (HHITL) simulation first, followed by live flight tests that built upon the simulation work while integrating onboard vehicle systems. To provide a comprehensive and representative test environment, the HDV sub-project leveraged multiple NASA facilities [Fig. 1] that were inter-connected across the United States at NASA Ames Research Center (ARC) in California and NASA Langley Research Center (LaRC) in Virginia.

1. Ames Research Center

At NASA ARC, The Airspace Operations Laboratory (AOL) provided Fleet Management (FM) functionality and served as a Flight Operations Center (FOC). Control and management of simulated Multi-Aircraft Control Systems (MACS) [1] aircraft was also supported from AOL, which supplied the targeted traffic densities and scenario complexities necessary to test specific concept elements. The Autonomous Vehicles Applications Lab (AVAL) served to support trial planning system development and overall test quality monitoring as a shadow Vertiport Manager station.

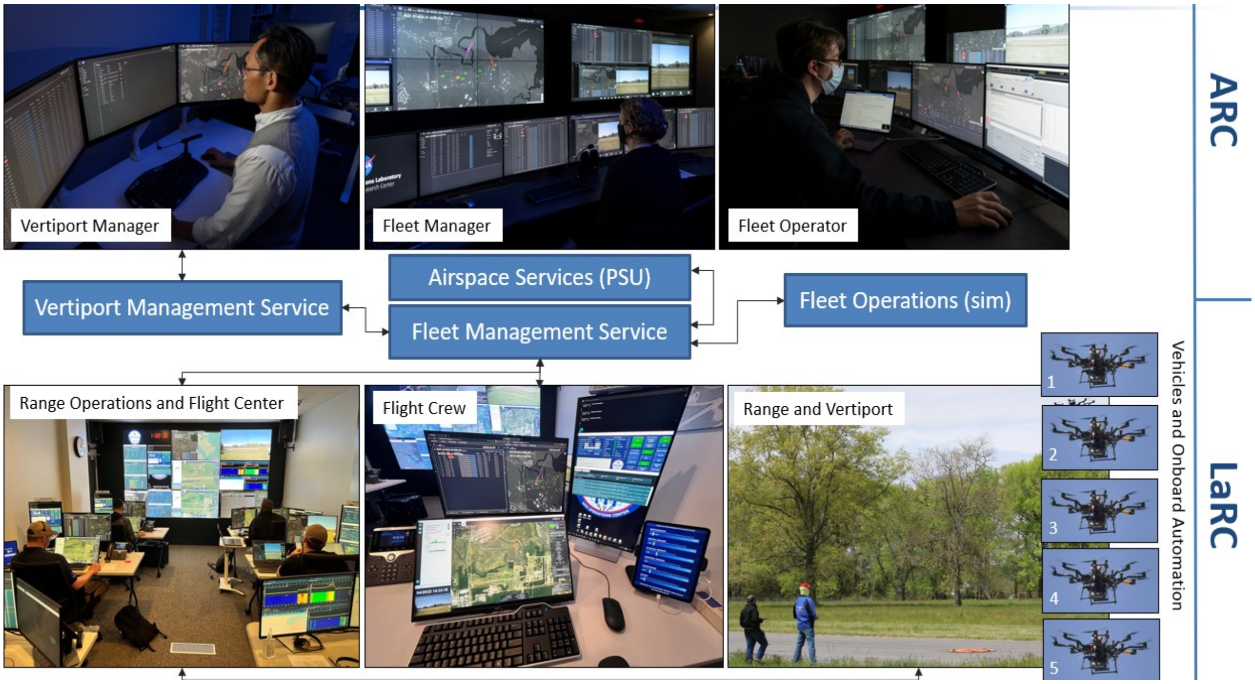


Fig. 1 Layout of testing infrastructure across ARC and LaRC.

2. Langley Research Center

The HDV testing environment included the Remote Operations for Autonomous Missions (ROAM) [2] sUAS control lab at NASA LaRC. ROAM contained six configurable workstations that were used for Ground Control Station Operators (GCSOs), Vertiport Managers (VMs), range safety officers, and flight test directors, and controlled both simulated and live aircraft. The systems integration and validation lab (SIVL) at NASA LaRC generated simulations of representative sUAS aircraft that were integrated with the actual aircraft hardware and software used for flight testing.

B. Summary of HDV system architecture

The following is a brief description of the current systems included in the HDV reference architecture, also shown in Fig. 2.

1. A Provider of Services for UAM (PSU)

The NASA PSU (NPSU) provided schedule deconfliction at takeoff and landing times. The available capacity at a target resource, such as the vertiport, was analyzed against the operational intents and schedule clearances were issued per each operational request. The NPSU is a cloud-based platform hosted by Amazon Web Services (AWS).

2. Vertiport management

Together, the Vertiport Automation System (VAS) [3] and the Vertiport Manager (human-in-the-loop) were responsible for managing resources at the vertiport level. The VAS assigned schedule slots for arrivals and departures and updated the status of operations as they arrived (e.g., “landing requested,” “cleared to land,” or “landing denied”). The Vertiport Manager monitored movements on the final approach and landing sites and could close the entire vertiport or individual Touchdown and Liftoff Areas (TLOFs).

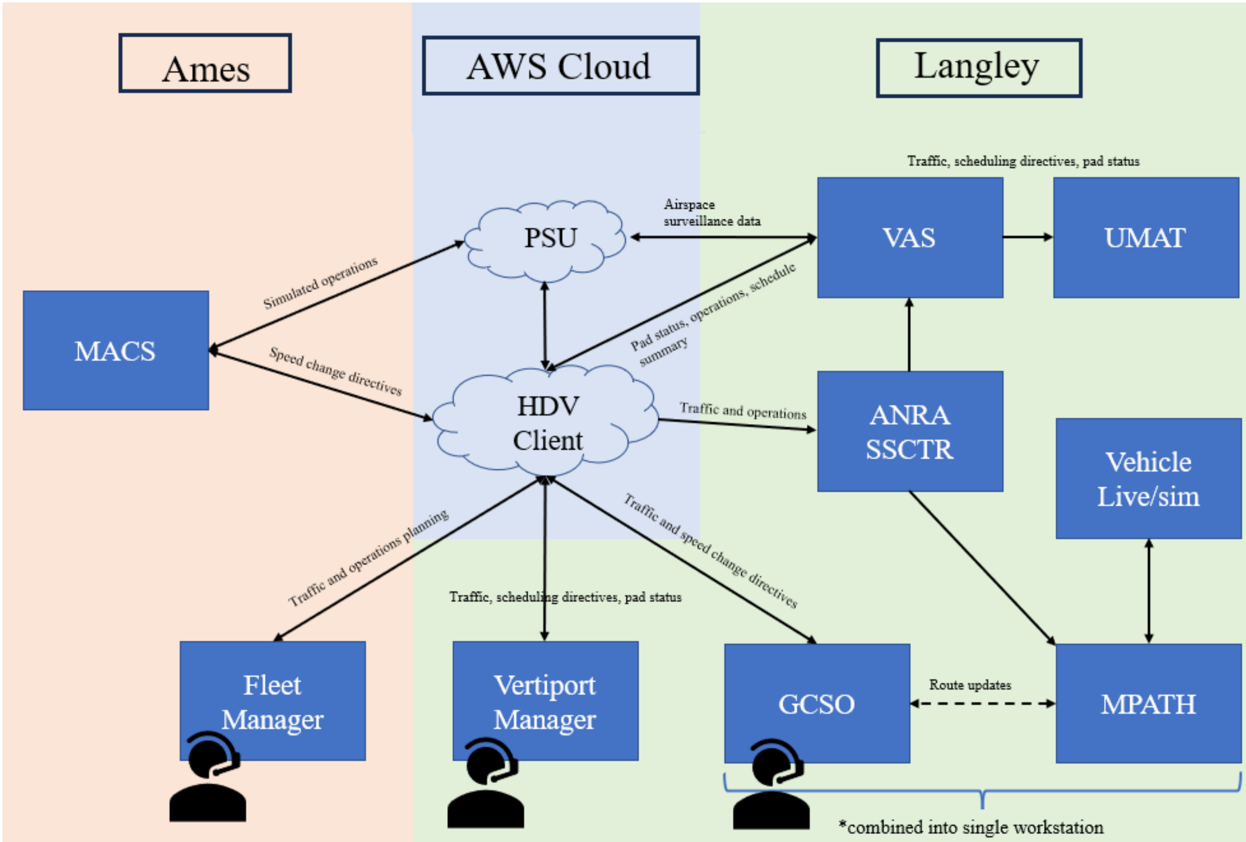


Fig. 2 Diagram of HDV system architecture.

3. Aircraft

Both simulated and live small UAS (sUAS) vehicles were used to create the traffic volume that was necessary for high-density vertiport operations. Of the simulated aircraft, "background" traffic was scripted and managed by automation (MACS), and "ownship" aircraft were provided by SIVIL and controlled by human operators. Of the live aircraft, surrogate sUASs represented UAM vehicles. Between one and five FreeFly Alta 8 vehicles were flown on the NASA CERTAIN flight test range. Ground Control Station Operators (GCSOs) with certified sUAS licenses flew simulated and live ownships using the Measuring Performance for Autonomy Teaming with Humans (MPATH) ground control station [4].

4. Onboard automation

Onboard autonomous systems were integrated in testing such as the Integrated Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS) [5] for detect and avoid (DAA) functionality and Safe2Ditch [6] autonomous contingency management systems.

5. Fleet Management services

The Fleet Manager (FM) was responsible for maintaining situation awareness and shared command of multiple simultaneous operations. Using the Fleet Manager interface [7, 8] the FM commanded between one and five operations, and throughout each testing scenario the FM monitored the missions and responded to emergent situations. By subscribing to NSPU and VAS data, the FM interface provided real-time alerts to the changing status of resources, such as schedule availability and vertiport status.

6. Operator user interfaces

The NASA developed software HDV Client was designed to be extensible to a variety of operational environments. It served as the primary user interface for the Fleet Manager, and Vertiport Manager, and secondary user interface for the GCSO. All human operators used HDV Client to perform all or part of their tasks. Each user interface was customized according to the operational role (e.g., GCSOs had access to some controls that FMs did not, and vice versa), but by sharing a common software backend the operators were able to send and receive notifications to each other using a uniform format, and status updates on operations were received synchronously.

C. Assessment

Beginning in 2021, each year HDV has executed a series of scheduled work packages that build in complexity and density of operations as the ecosystem under test is expanded. The first series called Advanced Onboard Automation (AOA) [9, 10], consisted of a simulation in October 2021 and a flight test from February to April 2022. The second series called Scalable Autonomous Operations (SAO) [11] ran a simulation in March 2023 and a flight test in May 2023. Each testing event, in addition to performing software and hardware in-the-loop system validation, provided an opportunity to focus on human factors considerations for the Fleet Manger operational role. The AOA series introduced the FM with two scenarios under low traffic density conditions (20 operations per hour). SAO expanded the FM role to five scenarios with higher traffic density (60 operations per hour). Human factors evaluations were centered on FM subjective workload, situation awareness, and the perceived usability and user experience of the interface. Results from earlier studies were applied to progressive adaptations of the interface with the goal of creating a usable and acceptable prototype tool for Fleet Managers.

D. Measures

1. Automated data collection by the HDV client

In addition to providing the front-end user interface for multiple operators, the HDV Client back-end was also a receiver of data from the NPSU, VAS, and MACS. Therefore, the HDV Client had knowledge of all system-wide data being shared throughout the simulations and flight tests. This included, but was not limited to, all aircraft state information, positions, user inputs, messages, and operation modifications. Data was automatically collected, time stamped, and post-processed using analysis tools through an HDV SQL database. This data was used to analyze airspace performance and user reaction times.

2. Ratings

2a. Cognitive factors

To measure the cognitive factors associated with performing FM tasks, as well as perceived interface usability and user experience, self-report surveys were administered to FM subjects post-run and post-study. The NASA Task Load index (TLX) [12] was used to evaluate FM self-reported performance and workload. Six questions of the TLX asked subjects to rate their own performance, mental, physical, and temporal demand, and level of frustration and effort. The Situation Awareness Rating Technique (SART) [13] was used to collect self-reported situation awareness ratings after each scenario run. FM situation awareness was measured along three dimensions, Attentional Demand, Attentional Supply, and Understanding. To understand the shared situation awareness, or how aware each operator was of the actions taken by other collaborating operators, a custom survey was administered to the FM, the VM, and the GCSO. It asked operators to rate the quality of notifications received from other operators, and whether they understood the notifications.

2b. Usability and user experience

To measure the usability of specific tools within the FM interface, custom questionnaires were developed and administered only after scenarios in which the tools were a focal point. Subjects were asked if the tools were acceptable, understandable, and trustworthy. They were also asked if the tools displayed enough, or too little information, and if they wished anything was different about the tools. To measure overall usability of the entire HDV Client FM interface, the Post-Study System Usability Questionnaire (PSSUQ) [14] was used. Three dimensions of usability were rated in the PSSUQ, System Usefulness, Information Quality, and Interface Quality.

3. Task Analysis and unstructured interview

Task analysis was performed to evaluate FM interactions with specific tools. Subjects were asked to perform targeted tasks (e.g., review trial planner route options, personally configure the workstation, evaluate the flow of information required for a schedule change), use a think-aloud technique to describe how they performed those tasks, and respond to open-ended questions about their reactions (e.g., “What are your thoughts on how the route options were presented?”, “Why did you choose this configuration?”, “What is that notification telling you? Who has taken action? What has changed?”). The dialogue between subjects and researchers was recorded using a voice recorder, and the responses were analyzed for themes.

4. Open-ended responses

Open-ended response boxes were provided for subjects to expand on their ratings. These written, optional responses were coded by categories of 1) which component of the interface or procedure the response was referring to, and 2) whether the response suggested to add, remove, or modify the component. Frequency metrics were computed to capture how often components were mentioned.

5. Observers

Throughout the studies, multiple human observers stayed in the room with the Fleet Manager subjects as they completed the study. Observers were deployed to record any unique actions they saw by the subjects, potential system errors, and any information that could be used to provide situational context. Data that was recorded by the computers was compared to the open-ended responses of the subjects and the notes taken by the observers. By triangulating multiple sources, we were able to achieve context-rich interpretations of the data.

IV. HDV Fleet Manager capabilities

In this section, the most current version of the FM interface is presented in detail alongside key findings from evaluations, user feedback, and progressive development. In the first part of this section, the three main components of the FM workstation: 1) the map, 2) the operations table, and 3) the schedule page, will be described. The second part of this section will focus on the individual capabilities of the FM interface broken down by scenario tasks.

A. Workstation

The HDV Fleet Manager user interface was developed to provide specific capabilities to support the Fleet Manager participant in fulfilling the defined role of managing arrival and departure operations. There are different views (seen in Fig. 3) available within the Fleet Manager workstation to provide situation awareness as well as a means of interacting directly with the fleet operations.

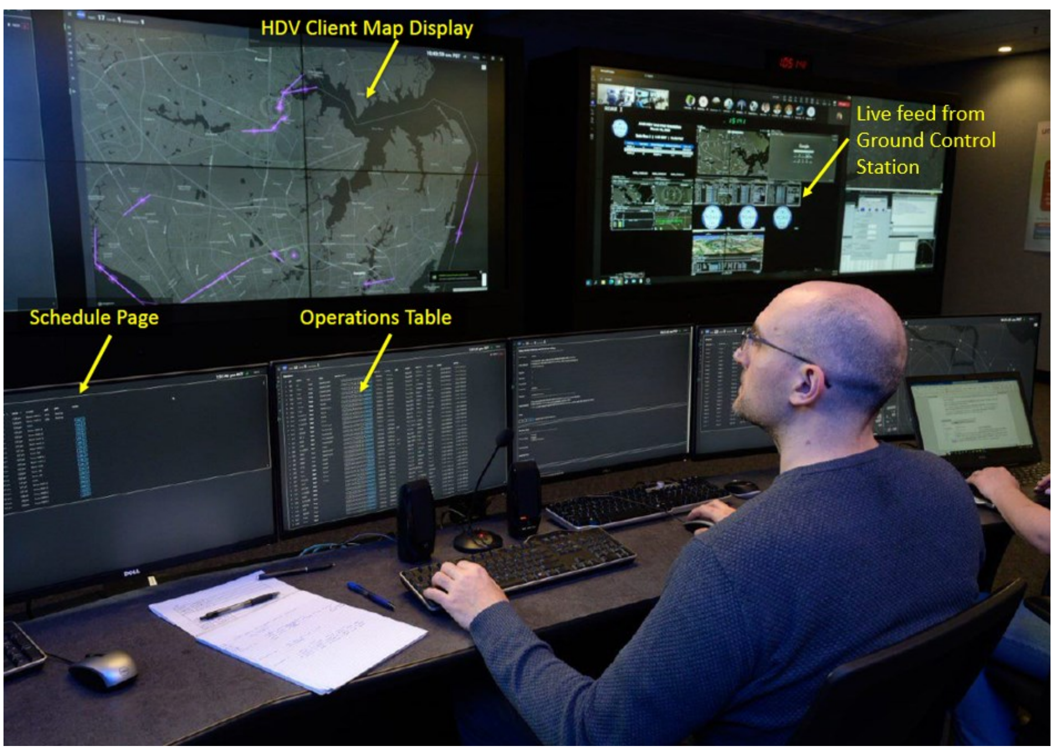


Fig. 3 Photo of the Fleet Manager workstation in operation during simulation.

1. Map

Fig. 4 shows different views of the map display where the airspace and associated structures are represented as well as the aircraft positions and operational intents. The magenta lines on the map represent the trajectories that vehicles intend to fly with the schedule segment highlighted as a volume. Arrival and departure routes as well as potential divert routes are also displayed along with the Vertiport Volume and Vertiport Operations Area (VOA) concentric circle airspace structures (top left panel in grey). Vertiports and TLOFs are represented by green polygons (bottom panel) and turn red when closed.

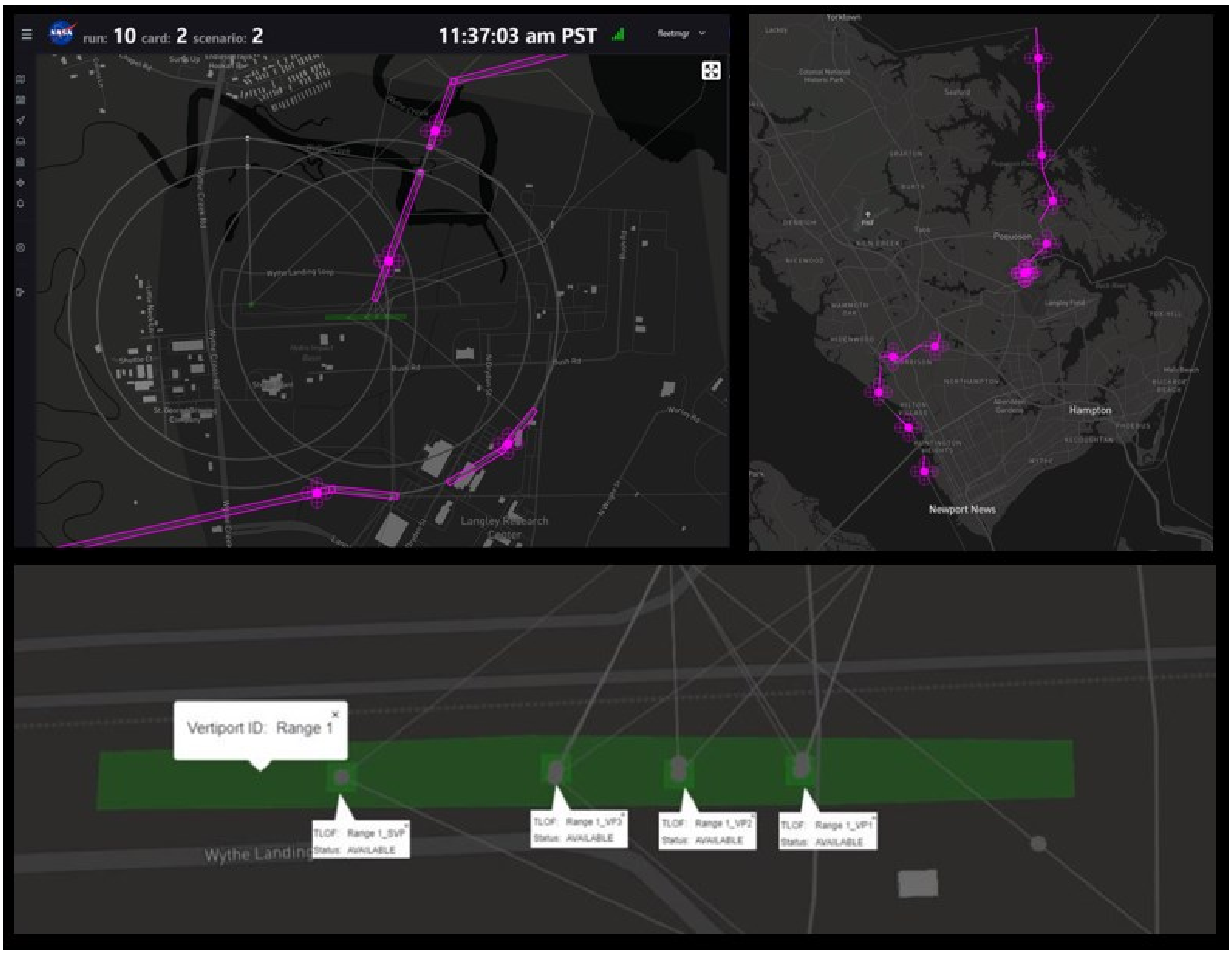


Fig. 4 Different views of the map display.

Clicking on an aircraft icon will cause a pop-out data tag to appear with vehicle information such as callsign, state, altitude, speed, latitude, and longitude. Likewise, clicking on route segments, vertiports, and TLOFs will produce data tags for each structure. FM workstations were always set up with a map display, zoomed into the VOA of a Vertiport. However, users could choose to display multiple maps, and configure the zoom level or areas of interest according to their preferences.

Users reported the map was their most used feature for situation awareness and liked to center the map screen on their workstation. Some said more highlighting and filtering options would have been useful to quickly distinguish between their operations and other background traffic. Also, more detailed information about the vertiport status, such as schedule, capacity, and available infrastructure was desired.

2. Operations table

The Operations table displayed all operations in the system with one operation per row. Multiple columns contained details for each individual operation. These columns, shown in Fig. 5 from left to right are gufi (i.e., a unique alphanumeric code for an operation, mostly used for logging and debugging), callsign, state (e.g., Accepted - green, Activated - magenta, Non-conforming - orange, or Closed - black), status (there were ten status options ranging from Enroute, to Approach Request, to Cleared to Land, among others), operation modification or "mod," (e.g., nominal or replan required), control buttons (cancelling the operation predeparture is the only control button available to the FM), scheduled time of arrival (STA), estimated time of arrival (ETA), start and end time of the operation, assigned pilot identification, route identification, departure and destination names, time the operation was created, and time the operation was last updated. Users customized the table according to their preferences by sorting columns alphabetically or chronologically, and filtering columns they did not want to see. They were typically sorted by state, bringing all active operations to the top rows, or by callsign to see all their operations grouped together. The most commonly filtered columns were 1) created, (not particularly relevant) 2) gufi (identifying operations by callsign was preferred), and 3) end time (redundant with ETA/STA).

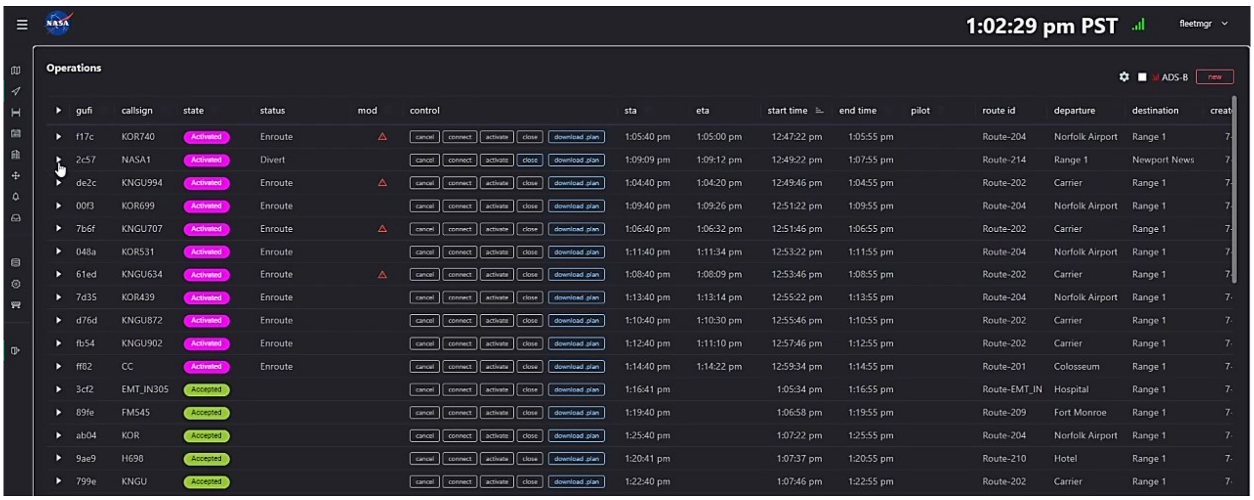


Fig. 5 The operations page.

Each row of the Operations table provided users the ability to expand and interact with that operation. By clicking the row, a user could access all the system messages for an individual operation. The messages tab showed the gufi, timestamp, origin of the message, the message itself and any associated notes or description. Fig. 6 shows the messaging process in ascending order of an operation submission, starting with the slot reservation for both departure and arrival, and ending with activation, or takeoff. A tab containing volume information was also accessible, which showed the chronological route segments contained in the operation. The start and end times of each segment were listed, and the segment bolded if the vehicle was active and within the segment coordinates.

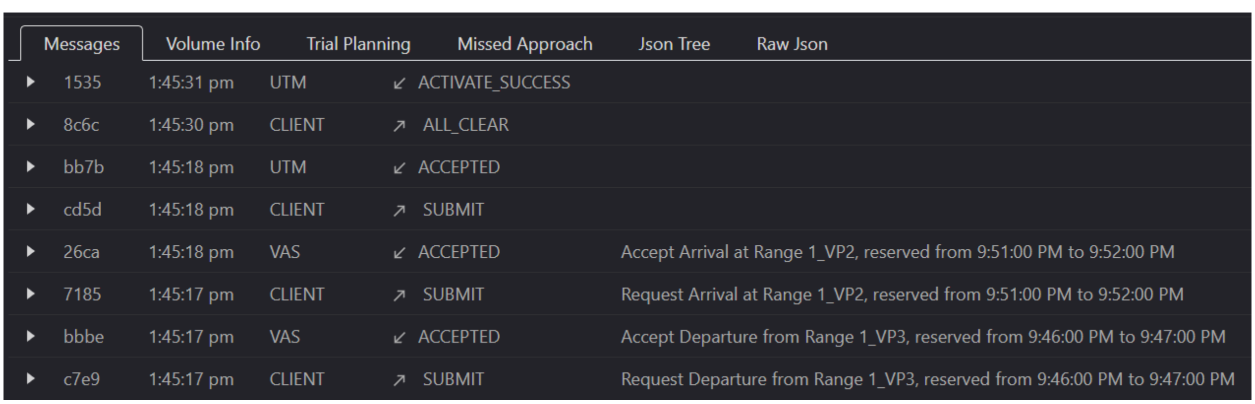


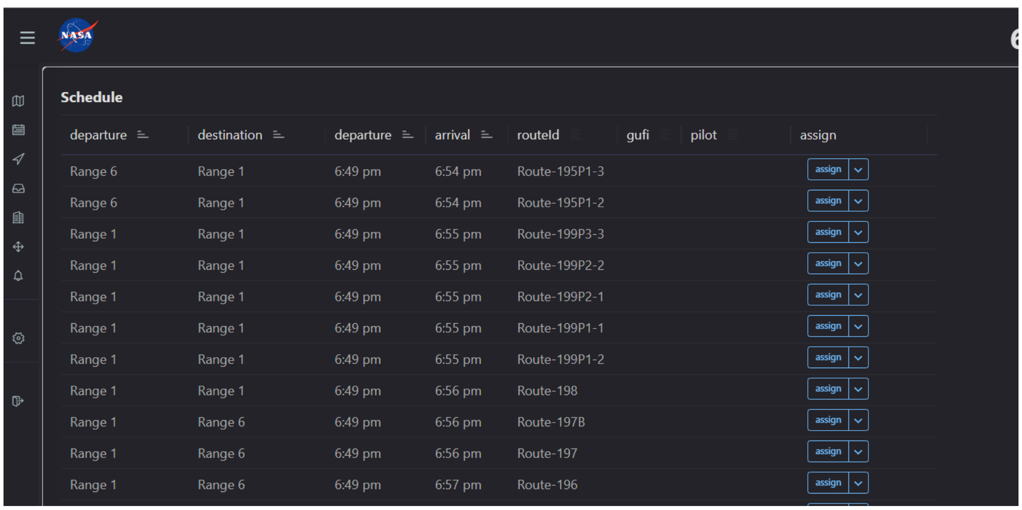
Fig. 6 Drop down menu within the row of an operation.

The Trial Planning and Missed Approach tabs contained tools that the FM used to update an operation after it already took off. These tools will be described in more detail in the following section. The Json Tree and Raw Json tabs were viewable by the user but were primarily used by the software developers for logging and debugging.

Overall, users reported positive feelings towards the operations table and thought it was very easy to use. A repeated theme among users was that integrating tools between the operations table and the map page was preferred. Some examples included having the ability to click an operation on either the table or the map and have that operation highlight on both the table and the map. Also, having the ability to access operation controls from the map such as trial planning missed approach, and speed change.

3. Schedule page

A key responsibility of the Fleet Manager role was the management of fleet operations according to the schedules defined by the departure/destination vertiports. Fig. 7 presents the schedule window through which the Fleet Manager viewed the available schedule slots. The schedule was established via connection to the VAS through the Fleet Management backend for real-time updates on vertiport status and schedule.



Schedule

departure	destination	departure	arrival	routeId	gufi	pilot	assign
Range 6	Range 1	6:49 pm	6:54 pm	Route-195P1-3			assign
Range 6	Range 1	6:49 pm	6:54 pm	Route-195P1-2			assign
Range 1	Range 1	6:49 pm	6:55 pm	Route-199P3-3			assign
Range 1	Range 1	6:49 pm	6:55 pm	Route-199P2-2			assign
Range 1	Range 1	6:49 pm	6:55 pm	Route-199P2-1			assign
Range 1	Range 1	6:49 pm	6:55 pm	Route-199P1-1			assign
Range 1	Range 1	6:49 pm	6:55 pm	Route-199P1-2			assign
Range 1	Range 1	6:49 pm	6:56 pm	Route-198			assign
Range 1	Range 6	6:49 pm	6:56 pm	Route-197B			assign
Range 1	Range 6	6:49 pm	6:56 pm	Route-197			assign
Range 1	Range 6	6:49 pm	6:57 pm	Route-196			assign

Fig. 7 Schedule Window available to Fleet Manager for flight assignments.

Using a similar format to the operations page, the schedule page displayed one available schedule slot per row, with associated information in the columns. From left to right, the columns include departure and destination identifications, departure and arrival times, and route identification. The gufi and pilot column populated with information after an operation and flight crew were assigned to a slot. The assign button was used to assign a flight crew to an operation and will be discussed more in the next section.

Users felt the process of scheduling an operation was understandable, but it was not easy to visually search the table to find a specific route and departure. Rows could be banded, or filtering options could be implemented to quickly locate the desired time slot.

B. Scenario based tools

HDV developed detailed scenarios to provide context for the FM to perform specific tasks. Within each scenario, multiple operators synchronously communicated with each other and with partially automated systems to conduct real-time fleet operations. Based on the story line of each scenario, the FM procedures were defined, and therefore the capabilities of the HDV Client interface were tailored to the tasks. With the understanding that the operator tasks were still being developed incrementally, many FM capabilities were a mix of both manual and automated steps. Although the far-term HDV concept envisions most tasks will be mostly or fully automated, it was first necessary to evaluate the information requirements for individual tasks on a granular level. This included initial testing of the flow of information, the amount of information being exchanged, and exploring task allocation between multiple operators collaborating on a mission. The primary HDV Client FM capabilities included:

1) (All scenarios) Exchanging voice and digital communications with other operators
2) (All scenarios) Scheduling operations
3) Performing a nominal mission
4) Performing a missed approach procedure
5) Performing a speed change procedure
6) Performing a divert procedure

1. Exchanging voice and digital communications with other operators

The information exchanges and shared situation awareness between multiple human operators in the HDV environment were incorporated into each testing scenario. In addition to the Fleet Manager, other human operator roles were:

1) *Ground Control Station Operator* - The GCSOs commanded the target aircraft and executed flight plans. They monitored their workstations for messages and alerts from the FM or the VAS and maintained both verbal and digital communication with the FM. The FM primarily communicated with GCSOs to coordinate take-off times, and to make updates to planned operations.
2) *Vertiport Manager* - The VM monitored traffic and managed vertipad status. Communications from the VM were sent digitally through the HDV Client interface to FMs and GCSOs. The FM was responsible for looking at the messages sent by the VM and responding accordingly within the context of the scenario.

Fleet Managers reported higher levels of situation awareness than VMs and GCSOs when it came to knowing what the other operators were doing in the environment. This could have been an artefact of the way the HDV FM role was designed because they mediated information between the VM and the GCSO, and they were the only operator that had two-way communication with both. Fleet Managers were unsure if this was a realistic depiction of their role because in some real-world situations a GCSO would need to be in direct contact with a VM.

Fleet Managers also experienced lower levels of workload in scenarios that required them to communicate verbally with the other operators, rather than communicating through the interface. Using an unfamiliar interface to communicate that required visual searching and button clicking, or interpreting messages with sometimes incomplete information could have been a source of frustration for FMs. By comparison, voice communications that were modeled after the present-day analog of "push-to-talk," were much easier to interpret and request for additional information if needed. However, relying solely on voice communications for fleet operations poses a hinderance to scalability. Users were supportive of the plan to eventually complete all communications digitally through the interface if voice communication was still available as an alternative. Designers of interface-based communication platforms must ensure that notifications are salient to the operators and persist long enough for them to respond. They should contain relevant information that is specific to the task the operator must complete and provide additional information once the task has been completed, or any follow-up steps that are required to complete the task.

2. Scheduling an operation

To schedule an operation, the FM was connected to individual flight crews for direct communications and operations management. The Fleet Manager defined an individual operation and assigned it to a specific flight crew through the Create Operation window (Fig. 8). This window allowed for the individual assignment of a slot and route for a given flight.

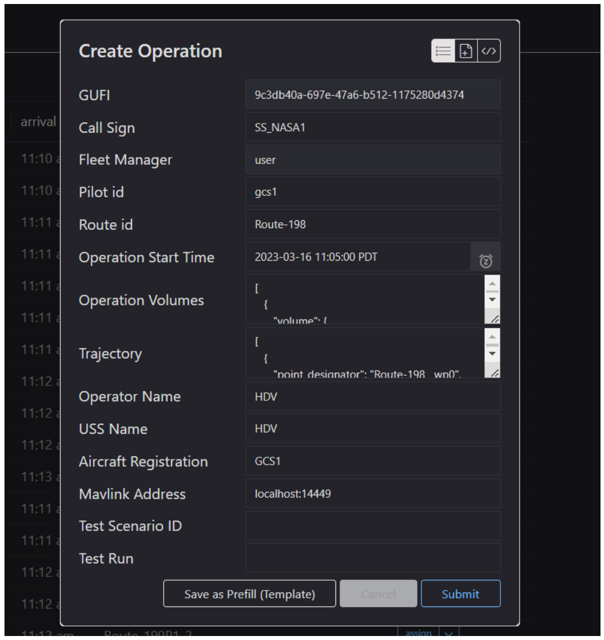


Fig. 8 The Create Operation window.

To schedule an operation, the flight crew used voice communication to call the FM and announce their callsign, requested route and requested takeoff time. From the schedule page, the FM visually searched for the desired route and departure time, clicked on the "assign" button and selected a pilot identification code. This caused the Create Operation window to pop-up with automatically generated information associated with the operation. The FM needed to manually input the callsign of the requested operation and occasionally edit the start time, then confirm the operation details (route identification, pilot identification, and start time) were correct. Once the information was entered, the Fleet Manager transmitted the package to the NPSU for acceptance, which was then sent to the flight crew for download and implementation as a flight plan to follow.

Fleet Managers experienced the highest rate of user error with the Create Operation window because the task of manual editing introduced the risk of inputting information incorrectly. There were also fields on the window that were not relevant to the user. A solution could be to remove fields from the form that are irrelevant to the FM and eliminate manual inputs. A flight crew could potentially prefill a form with their operation details and requested takeoff time, then send it to the FM who could approve it with a single button click.

3. Performing a nominal mission

To perform a nominal mission, the FM simply had to follow the steps to complete operation submission for between 1 and 5 vehicles (NASA1 – NASA5) who then flew their originally filed plan with no changes to the operation. The FM continuously monitored the flight missions from takeoff to landing, particularly looking for status updates such as 1) activated, 2) enroute, 3) cleared to land, and 4) landed. FMs could monitor flight status from the operations page, and flight positions from the map page. FMs ultimately preferred the map page as their primary tool for flight monitoring.

4. Performing a missed approach procedure

In the Missed Approach scenario, the FM scheduled three operations (NASA1 – NASA3) who all departed from Vertiport 1. Halfway through the operations NASA2 verbally announced an onboard emergency and requested expedited landing. The FM verbally commanded NASA1 to execute a missed approach holding pattern, and verbally commanded NASA2 to increase their speed. After issuing the verbal command, the FM opened the Missed Approach tab for the NASA1 operation, shown in Fig. 9, and clicked the "Initiate Missed Approach Procedure" button, which informed the PSU that the flight would deviate from the original flight plan and cancelled their arrival slot reservation. The NASA1 GCSO used a manual "jump to waypoint" command to enter the holding pattern. Once NASA1 was circling the holding pattern, the FM scheduled a slot for NASA1 to return to the approach flow by clicking the

"Generate Missed Approach" button. This automatically located an available schedule slot at the original TLOF. Once the FM approved and submitted the new arrival time, the slot was reserved. A notification appeared after the successful replanning of the operation that confirmed NASA1 received a new landing time in the vertiport schedule.

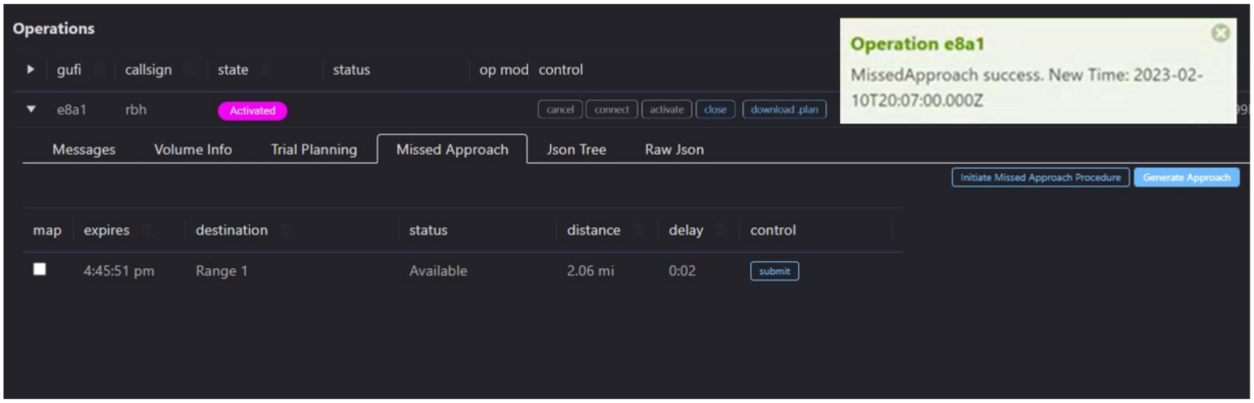


Fig 9. The Missed Approach tab within the drop down menu of an operation.

An important element of UAM operations is the inclusion of a PSU within any flight plan negotiations. In present-day operations, a missed approach maneuver is negotiated by a two-step process. Either a pilot or the tower verbally commands a missed approach, and either tower or pilot verbally confirms the procedure. For UAM, after the missed approach is commanded the original operation also needs to be modified through the PSU, otherwise the vehicle could be flagged as contingent (i.e., not following the expected original flight path). Furthermore, a new landing time slot at the TLOF needs to be arranged through the VAS. Therefore, performing a missed approach procedure must go beyond the traditional verbal agreement and recruit the airspace automation to provide the necessary clearances. For this reason, additional buttons were added to the FM Missed Approach tab called "Initiate Missed Approach Procedure," and "Generate Approach." These buttons informed the NPSU of the deviation from the original flight plan, and reserved a new arrival slot at the TLOF, respectively.

Users reported the missed approach tool was easy to navigate and they had a high level of understanding of what was happening in the scenario. However, users were most confused about the process of using the Initiate Missed Approach Procedure and Generate Approach buttons, and why it was a task for the FM and not the GCSO. Many felt the GCSO should command the missed approach by coordinating with the VM directly, and the FM should only be informed. Also, combining a verbal missed approach command with two more button-click commands seemed heavily manual and burdensome to the FMs. Indeed, a procedure with too many button-clicks presents a target for increased automation. A GCSO would be more likely to use a single button that could perform all three scenario tasks that the FM was required to, 1) command a missed approach and send notifications to the VM and FM, 2) update the original flight plan by adding the predefined missed approach procedure, and 3) reserve a new arrival time slot at the TLOF. The VM would possibly need to approve this command from the GCSO, and the FM would simply be notified through the interface.

5. Performing a speed change procedure

There were two versions of the speed change scenario for the FM. In the earlier version, the FM scheduled NASA1 – NASA3 who all departed from Vertiport 1. Halfway through the operations the VM gave a short closure (30 seconds) to the NASA1 and NASA2 TLOFs due to wildlife crossing the area. The FM verbally commanded NASA1 and NASA2 to reduce their speed to 10 knots. By the time NASA1 and NASA2 arrived at the Vertiport 1, the TLOFs had reopened. In this version of the procedure the only way the FM could interact with the flight was through verbal commands, which highlighted the need to develop more tools to complete the speed change through the interface.

In the second iteration of the speed change scenario (shown in Fig. 10), the VM used a timeline to monitor the schedule of arrivals at Vertiport 1. The VM detected a conflict in which NASA1 and NASA2 had the same ETA and were competing for the same arrival slot. The VM clicked and dragged NASA2 to an open slot on the timeline, delaying the scheduled time of arrival by one minute. This action by the VM represented a proposed schedule change, meaning the VAS and NPSU temporarily reserved the slot pending approval by both the FM and the GCSO of NASA2. Once the slot was temporarily reserved, the FM received an orange notification on the operations page which directed the FM to approve the schedule change on the Schedule Mod[ification] tab. After the FM confirmed, a notification was sent to the GCSO via datalink asking for approval. After this final step in the approval chain, the original NASA2 operation was modified to slow down by one minute. With new times of arrival at the original waypoints, NASA2 automatically generated the speeds required to meet the new targets.

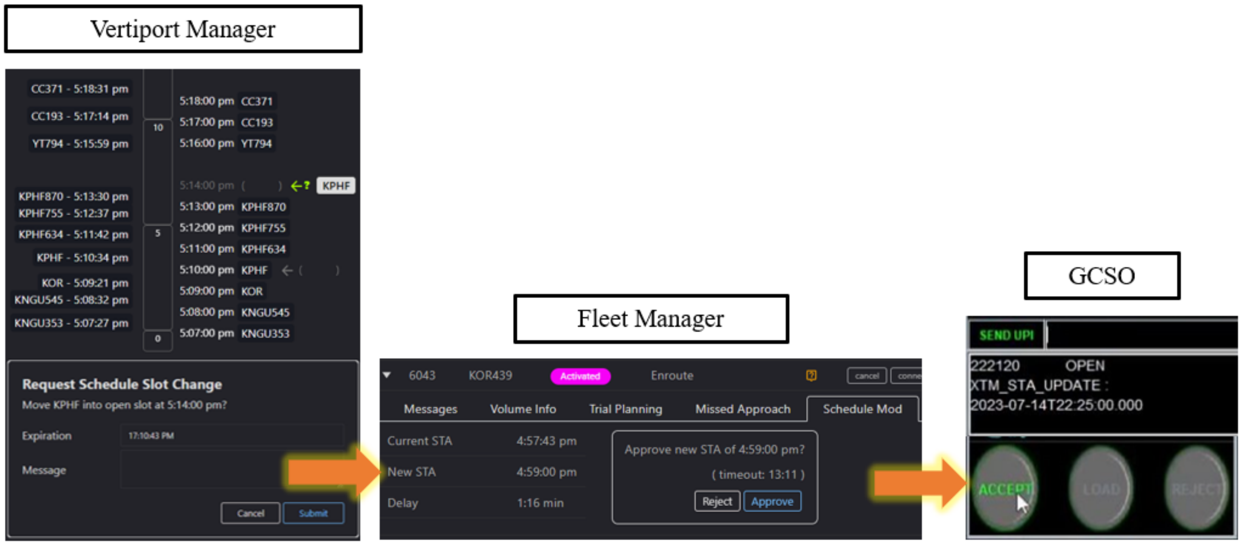


Fig. 10 Process of schedule change approval from VM to FM to GCSO

Users reacted positively to viewing the vertiport schedule in a timeline format and using the timeline to make scheduling adjustments. Although performing a speed change entirely through the interface was a technological leap above the earlier version (voice communication only, no clearance through the NPSU), Fleet Managers expressed discomfort with the format of the Schedule Mod tab. They did not have enough insight into what they approved. Altering the schedule of one flight could have larger impacts on the overall fleet schedule, and FMs wanted to see that. A solution could be to have another timeline for the FM to see their scheduled flights and open slots which could allow them to assess if making a schedule change would be beneficial or not.

6. Performing a divert procedure

In the Divert scenario, the FM scheduled NASA1 – NASA3 who all departed from Vertiport 1. Halfway through the operations the VM gave a moderate closure (3 minutes) to Vertiport 1, which revoked the accepted arrival status of NASA1 and NASA2. When the vertiport closed, the FM was notified to replan the affected operations through a red pop-up notification in the corner of the operations page (Fig. 11), and a red warning triangle in the “op mod” column.

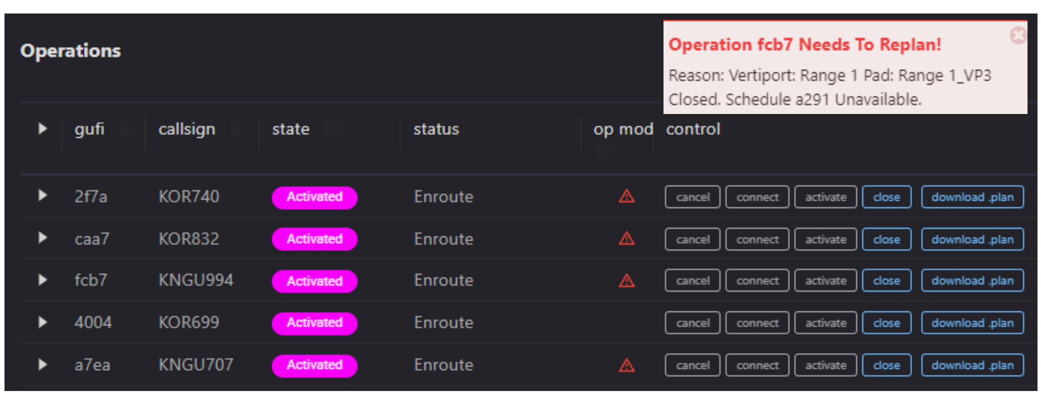


Fig. 11 Operations page with required replan notifications

To resolve the replan directive, the FM opened the drop-down menu within the operation and navigated to the Trial Planning tab. Within the Trial Planning tab, the FM generated three new route options and arrival times to an alternate landing location (Vertiport 6) for NASA1 and NASA2. The FM submitted their reroute selection which reserved the arrival slot and forwarded the update to the GCSOs. A green pop-up notification confirmed the operation had been successfully modified. Once the NASA1 and NASA2 GCSOs received the update, they downloaded and executed the new flight plans.

Like the Speed Change scenario, the Divert scenario had two different versions of the FM interface. In the earlier version, nominal routes were short (approximately seven minutes duration), so reroute planning time horizons were even shorter (approximately 30 seconds). For this reason, users were instructed to pick a reroute option as quickly as possible, rather than review the options and decide for themselves. However, as shown in Fig. 12, the trial planning tool was designed to present the user with multiple options and their associated trade-off factors. The information contained within each option is the expiration time (i.e., the time through which the option remains valid), destination, status (e.g., available, expired, or accepted), duration (i.e., the amount of time in minutes it will take to reach the destination from the first waypoint of the route), and distance in kilometers.

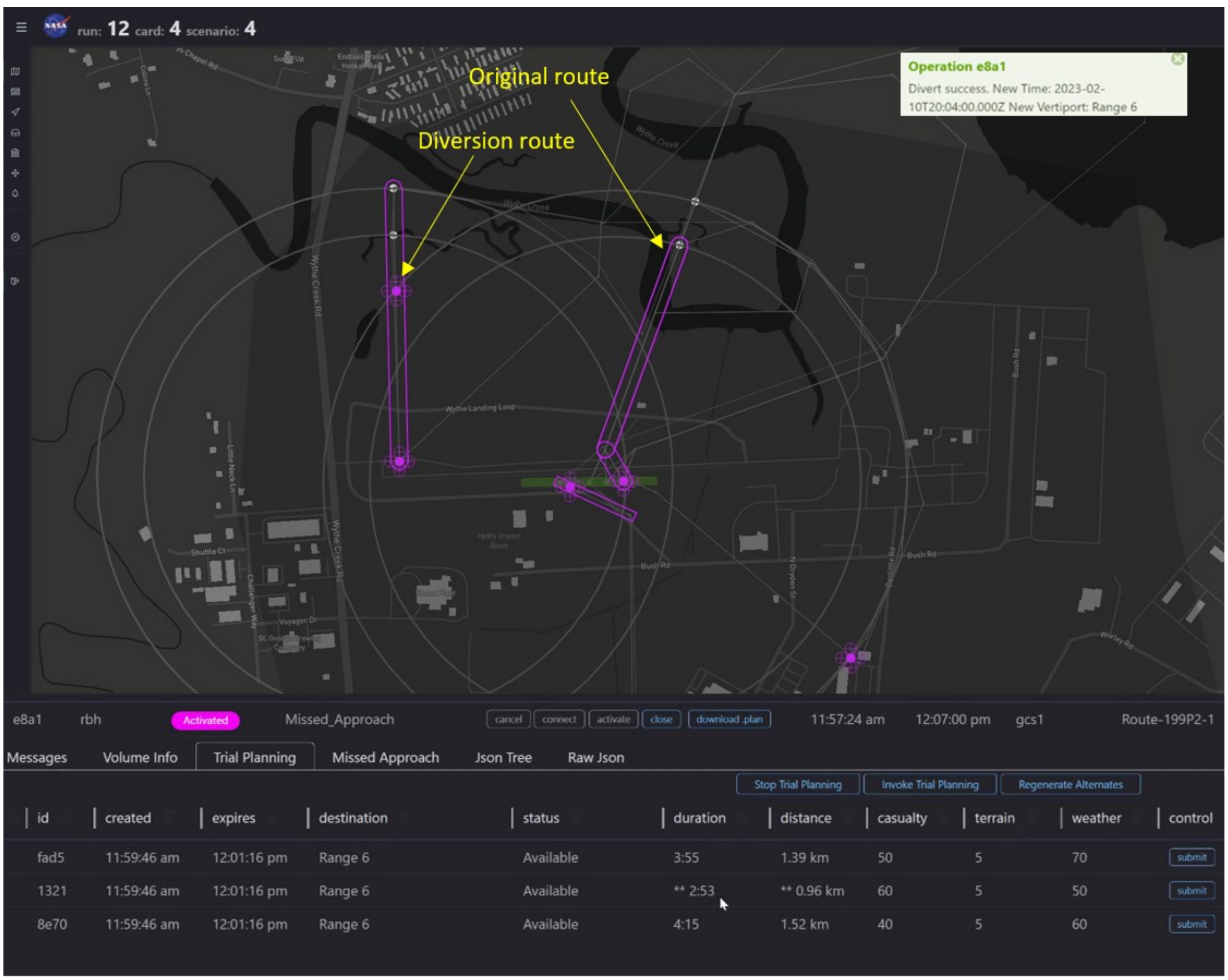


Fig. 12 The map and old version of trial planner during a divert procedure

Three other loosely defined factors were included in the reroute option information. They were casualty, terrain, and weather. These three factors were intended to represent inputs from supplemental data service providers (SDSPs) that could inform the user of the safety or potential hazards of a given route. What was not included in the earlier version of the trial planner was a way to interpret the numerical factors associated with casualty, terrain, and weather. A user would not necessarily know if a reroute option with a weather factor of 70 was any better or worse than a factor of 50, and if it was worse, how much worse? It was clear from testing with the early version of the trial planner that changes were needed to make it more usable. First, planning time horizons needed to be longer to allow the user to fully explore all the options before deciding. Second, differences between trade-off factors that were relevant needed to be more salient to the user.

In the second iteration of the trial planning tool (Fig. 13) a few design changes were made to address the previous issues. Connectivity between the trial planner and the map was increased to display reroute options in cyan blue to make them stand out from the background. Checkboxes were added next to each route that when checked could bold the route. The duration column was changed to delay (i.e., the difference in minutes between the original ETA and the proposed new ETA), with positive delay indicating a longer route and negative delay indicating a shorter route relative to the original. The casualty column was changed to ground risk to deter the association of casualty with loss of human life, and the terrain column was changed to battery after feedback from many users that battery reserves was priority information to have easy access to. Finally, the numerical trade-off factors were exchanged for color coded icons.

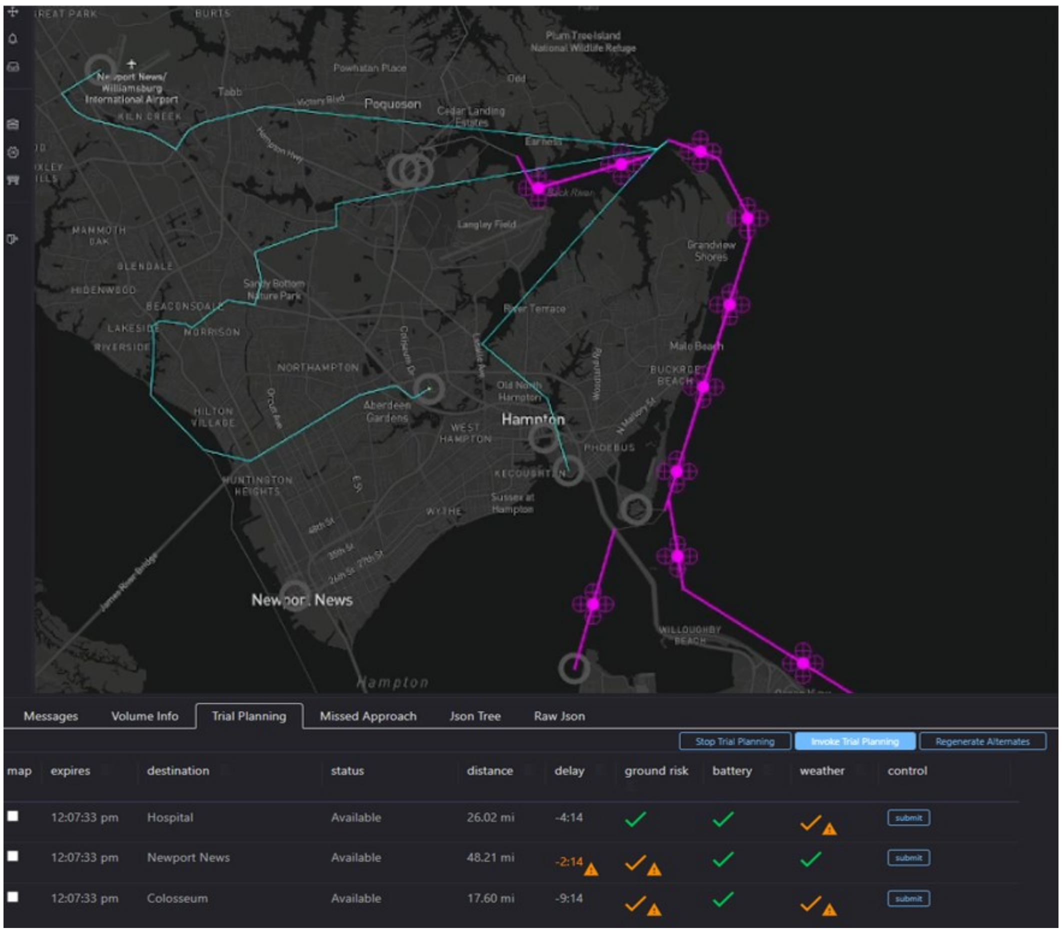


Fig. 13 The map and new version of trial planner during a divert procedure

The binary color-coding system of the check mark icons was intended to convey to the users that a route option factor was either acceptable – well within safety limits (green), or acceptable – approaching limits of the safety threshold (orange). No unacceptable options were presented to the users. A warning triangle displayed next to the orange check marks to prompt the user to examine that option, and hovering the mouse over a warning triangle would cause a pop-up text box to appear with details about the level of risk. The delay column was also color coded with orange highlighting the delay with the least amount of benefit in terms of time. For positive delays, the largest absolute value was highlighted, and for negative delays the smallest absolute value was highlighted.

Users reported favorable views of how the trial planner tool worked. There was an increase in confidence and decision-making power when the planning time horizon was lengthened. The question arose again whether it was realistic that an FM would need to bother rerouting a single flight, or if the GCSO would be responsible for doing their own trial planning. Ultimately, there could be a situation when a group of flights need to divert, in which case an

FM would be in a good position to do so. A natural progression for the interface would be to add a multi-trial plan tool which enables an FM to select multiple flights and simultaneously trial plan all of them. This could require increased automation, replacing most of the decision-making process with a single best, algorithmically derived solution.

V. Discussion

What is a Fleet Manager? Sometimes fleet management is not well defined. Today, in traditional aviation the specific role of FM does not exist, yet some parallels can be drawn between existing aviation and navigation service provider roles. The HDV Concept of Operations [15] uses the term "Fleet Operator" to encompass the entire airline and its operations ranging from ground services, to boarding, to flight planning, as well as dispatch responsibilities. The Wisk Aero Concept of Operations [16] provides more details for their envisioned Fleet Manager role, as one that will perform services much like a traditional dispatcher. Notably, a Wisk Fleet Manager might also undertake system level planning of the entire fleet based on forecasted passenger demand and capacity at vertiports, much like a traffic flow manager at an Air Traffic Control System Command Center (ATCSCC) would do. However, specific Fleet Manager capabilities and responsibilities are still fuzzy and further definition is needed.

The HDV subproject defined Fleet Manager as an operator who will manage multiple departures and arrivals at a vertiport, and indeed, the FM scheduled, dispatched, and even replanned multiple operations. However, an FM is not necessarily envisioned to deal with singular operations as they did in the HDV scenarios. This keeps us closer to the 1:1, operator to aircraft paradigm than we wish to be. Rather they will probably need to replan multiple operations simultaneously, shifting banks of operations from one resource to another over longer periods of time, and managing the impact to the overall schedule and to the customer. This would place the FM into more of a flow management role and would require more sophisticated tools and scenarios to test the concept. The FM exploration could be framed by whether it is feasible for a FM to use extant traffic management tools such as ground stopping or airspace flow programs (AFP)? Furthermore, how would customers respond?

We learned through interviews with FM interface users that the impact of off-nominal situations on air carrier customers is not well understood by the current instantiation of the HDV ecosystem. When a flight is diverted away from the original destination it is presumed that the air taxi company will still be responsible for getting the passenger to the desired destination. This could include coordination with ground services to arrange transportation. Therefore, much more information should be provided to the FM regarding ground infrastructure at alternate destinations.

One question that has been left unanswered is what will the specific responsibilities of the FM be over different phases of flight? We tested FM monitoring end-to-end with a small number of flights. One can imagine as that number increases there will be a strain on the situation awareness the FM is able to maintain. Furthermore, takeoff and landing are widely known as the most critical and complex times of the entire operation, so it might not be feasible for an FM to monitor multiple operations engaged in heterogeneous phases of flight. How could this impact the role of the FM? A few potential answers could be that there would be specialized FMs for each phase of flight, such that a single FM monitors operations in takeoff status only, then will hand off to an enroute FM who will hand off to a terminal FM. Another possibility could be that an FM would be responsible for a particular route or corridor and would only monitor operations along that section, but this could easily limit the number of operations a single FM could handle. Whatever the solution, it is clear that the present studies of fleet management for HDV have only scratched the surface of the FMs potential.

VI. Concluding remarks

The HDV subproject successfully prototyped an extensible Fleet Manager position that has been tested in a variety of simulated and live scenarios across multiple NASA centers. It is a unique interface that can be used to conduct research on the future of AAM. Several additional technologies from NASA and industry have been integrated into the HDV UAM ecosystem to conduct system level demonstrations. Over the course of studying the Fleet Manager interface, we learned a great deal about how users interacted with the partially automated systems while they communicated with us the information requirements for more advanced automation. There is a lot left to explore, but there is great value in expanding our knowledge of the FM role within a reference UAM automation architecture.

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References

[1] T. Prevot, P.U. Lee, T. Callantine, J. Mercer, J. Homola, N. M. Smith, E. Palmer, "Human-in-the-loop evaluation of NextGen concepts in the Airspace Operations Laboratory." *AIAA Modeling and Simulation Technologies Conference*, 2010, pp.7

[2] B. K. Buck, E. T. Chancey, M. S. Politowicz, J. R. Unverricht and S. C. Geuther, "A remote vehicle operations center's role in collecting human factors data," in *AIAA SciTech*, National Harbor, MD, 2023.

[3] A. I. Tiwari, C. V. Ramirez, J. Homola, B. Hutchinson, B. Petty, L. Glaab, "Initial development and integration of a vertiport automation system for advanced air mobility operations," in AIAA Aviation Forum, 2023.

[4] M. S. Politowicx, E. T. Chancey, B. K. Buck, J. R. Unverricht and B. J. Petty, "MPATH (Measuring Performance for Autonomy Teaming with Humans) Ground Control Station: Design Approach and Initial Usability Results," in *AIAA SciTech 2023 Forum*, National Harbor, MD, 2023.

[5] M. Consiglio, C. Munoz, G. Hagen, A. Narkawacz, S. Balachandran, "ICAROUS: Integrated configurable algorithmns for reliable operations of unmanned systems," in *2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC)*, 2016.

[6] L. J. Glaab, P. C. Glaab, P. C. Lusk, B. J. Petty, R. W. Beard, C. V. Dolph and R. G. McSwain, "Safe2Ditch autonomous crash management system for small unmanned aerial systems: Concept definition and flight test results," NASA TM-2018-220110, 2018.

[7] G. S. Hodell, Q. V. Dao, J. R. Homola, M. T. Goodyear, S. N. Kalush, S. Swaroop, and J. Yoona, "Usability evaluation of fleet management interface for high density vertiplex environments," in *AIAA 2022 Digital Avionics Systems Conference (DASC)*, Portsmouth, VA, 2022.

[8] A. Suzuki, Q. V. Dao, "A flight replanning tool for terminal area urban air mobility operations," in AIAA 41st Digital Avionics Systems Conference, 2022.

[9] L. J. Glaab, M. A. Johnson, R. G. McSwain, S. C. Geuther, Q. V. Dao, J. R. Homola, "The High density vertiplex advanced onboard automation overview," in AIAA 41st Digital Avionics Systems Conference, 2022.

[10] R. G. McSwain, "High Density Vertiplex Flight Test Report Advanced Onboard Automation," NASA Technical Memorandum-20220016890. Langley Research Center, Hampton, Virginia.

[11] C. J. Petty, J. R. Unverricht, B. K. Buck, L. J. Glaab, Q. V. Dao, J. R. Homola, "High Density Vertiplex: Scalable Autonomous Operations Prototype Assessment Simulation," in *AIAA SciTech 2024*, Orlando, Florida, accepted.

[12] S. G. Hart, L. E. Staveland, "Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research," in *Advances in Psychology*, North-Holland, 1988, pp. 139-183.

[13] R. M. Taylor, "Situational Awareness Rating Technique (SART): The development of a tool for aircrew systems design," in *AGARD Conference Proceedings No. 478, Situational Awareness in Aerospace Operations*, Copenhagen, 1990.

[14] J. R. Lewis, "Psychometric evaluation of the post-study system usability questionnaire: The PSSUQ," *Proceedings of the Human Factors Society 36th annual meeting*, Boca Raton, FL, 1992.

[15] Northeast UAS Airspace Integration Research Alliance (NUAIR), "High-density automated vertiport concept of operations," 2021.

[16] Wisk, "Concept of operations for uncrewed urban air mobility," 2022. https://wisk.aero/wp-content/uploads/2022/09/Concept-of-Operations-for-Uncrewed-Urban-Air-Mobility.pdf