

The Vertiport Human Automation Teaming Toolbox (V-HATT) for the Design and Evaluation of Urban Air Mobility Infrastructure

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Future growth of Urban Air Mobility requires vertiport infrastructure where aircraft can depart and land for transporting passengers and cargo. There is a critical gap in tools needed for the design and operation of vertiports. The Vertiport Human Automation Teaming Toolbox addresses this gap for real-time human-in-the-loop simulations involving integrated arrival, surface, and departure operations. The toolbox enables exploration of the relationship of the human vertiport operator managing the flow of operations combined with decision support tool automation as a machine/artificial intelligence teaming agent. The simulation-based toolbox supports examining the effectiveness of various human-machine teaming strategies with differing degrees of automation. As future vertiports grow in capability and complexity, managing their operations will require innovative concepts that adapt to scale with operational complexity. The toolbox will assist researchers, operators, manufacturers, and infrastructure developers in understanding potential bottlenecks in vertiport capacity and the role of human-centered automation in alleviating them.

I. Introduction

The expanding interest and growth in Advanced Air Mobility (AAM), including Urban Air Mobility (UAM) and Regional Air Mobility (RAM), relies on having infrastructure, called a vertiport, in place for transporting passengers and cargo. Different aspects of vertiport design and operations have been addressed through industry developments, government and academic research studies, and regulatory guidance as described below. Nevertheless, gaps in knowledge and tools still need to be addressed. The Vertiport Human Automation Teaming Toolbox (V-HATT) is being developed to help fill these gaps.

These include tools for assessing the role of the human vertiport operator (VO) as part of human-automation teaming (HAT) and the tools needed to both integrate vertiport arrival, surface, and departure management as well as understand trades in vertiport design to optimize surface layout. We define the VO as the human responsible for managing the safe and efficient flow of arrival, surface, and departure traffic at a single vertiport location. In addition, we define the teaming agent as a broad term to reflect any automation related to VO functions and decision support tools (DSTs) for the Vertiport Operator. The Teaming Agent may execute single tasks, a group of tasks, or provide situational awareness for the human VO for task execution. The Vertiport Operator will always be virtual in V-HATT human-in-the-loop (HITL) simulations with no real-time view of the vertiport surface and surrounding airspace. For V-HATT, the pilot is representative of either a virtual or constructive pilot navigating to, around, and from the vertiport.

The goal for V-HATT is the development of a real-time HITL vertiport operations simulation platform for test of concepts of integrated arrival, surface movement, and departure AAM aircraft traffic flow management. The value proposition for V-HATT is to provide National Aeronautics and Space Administration (NASA), Original Equipment Manufacturers (OEMs), vertiport designers, municipalities, researchers, and others with the ability to:

- 1) Design the vertiport layout, airspace, and operational rules.
- 2) Validate simulated vertiport airspace, procedures, and use cases with a human VO in-the-loop assisted by DST automation.
- 3) Analyze vertiport performance and conduct workload analysis.

The Federal Aviation Administration (FAA) defines vertiports as “an area of land or a structure, used or intended to be used for electric, hydrogen, and hybrid vertical takeoff and landing (VTOL) landings and takeoffs and includes associated buildings and facilities” [1]. Vertiports represent the infrastructure for transportation of passengers and cargo [2]. Similarly, a vertiport has been defined as “an identifiable ground or elevated area, including any buildings, or facilities thereon, used for the vertical takeoff and landing of an aircraft” [3]. Within this vertiport construct, UAM will be enabled by extensive usage of autonomous systems both onboard the vehicle, on the ground at the vertiport and other locations, such as a facility used for operations by a Provider of Services for UAM (PSU). The role of vertiports in increasingly complex operations requires highly sophisticated capabilities for airside and surface traffic management [4].

FAA integrated vertiports as part of AAM infrastructure in its AAM 2028 Implementation Plan [5]. This included adequate parking for AAM aircraft for loading and unloading separate from the Touchdown and Liftoff (TLOF) areas, charging stations, weather stations (if the vertiport is remote from an airport), and other features such as security and maintenance. It is noted that a TLOF is a surface feature and the associated airspace above/around a TLOF is the Final Approach and Takeoff (FATO) area. The FATO is a protected airspace established to exclude obstructions.

Vertiports may use existing infrastructure such as commercial service airports, underutilized General Aviation (GA) airports, and heliports. According to the Plan, the FAA has completed research assessing hypothetical vertiport locations with conceptual layouts for a range of diverse scenarios and will be conducting simulation exercises and operational testing with AAM companies.

This paper is based on a NASA Small Business Innovative Research (SBIR) Phase I effort and builds on previous V-HATT development reports. An optimization-based scheduling algorithm for arrivals with strategic conflict management was integrated with a maneuver advisory algorithm to provide speed and holding advisories to meet the required time of arrival (RTA) [6]. Results suggested use of holding patterns can mitigate conflicts in high-density vertiport and terminal airspace operations. A proof-of-concept simulation employing arrival scheduling automation with a prototype V-HATT workstation highlighted human systems integration considerations [7]. These considerations included VO-DST workflow and design of configurable VO display interfaces.

The paper is organized into several major sections. First, a survey of vertiport design standards and guidance is presented. This is followed by a summary of some NASA, industry, and research efforts addressing vertiport design. Based on these efforts, gaps are identified in knowledge about vertiport design. Next, the V-HATT design is presented including assumptions and preliminary functions and tasks. Progress made in the design of the prototype human-machine/artificial intelligence (AI) interface is described with plans for further development.

II. Vertiport Physical Design Standards and Guidance

Government and industry guidance has been developed on vertiport design as part of UAM implementation. Some of this guidance has intersections relative to the VO human-machine/AI interface (HMI), although there needs to be more addressing of issues in human management with highly automated systems. Design standards and guidance for vertiports and heliports are listed in Table 1.

A notable difference in design guidance was found between ICAO Annex 14 for heliport design and FAA EB 105. Following EB 105, a vertiport would need to be more than double in size for the FATO and safety area for Lilium Jet eVTOL operations compared with ICAO Annex 14 [15].

An operational pinch point involves mixing traditional helicopters and eVTOLs because of the threat of helicopter downwash and outwash affecting eVTOL stability, which can be addressed with greater separation between TLOFs and parking pads. More specifically, eVTOLs are expected to have significantly higher disc loading (a ratio of total weight to the size of the rotors) which can lead to more severe downwash (higher downwash velocity). Helicopter downwash can extend downward 500 to 1,000 feet posing a hazard to parked light aircraft and turbulence for airborne aircraft. FATO-protected airspace extends 500 feet vertically and 4,000 feet laterally.

III. Vertiport Design Activities

Activities addressing vertiport design have been undertaken by NAS, industry, and academia. A summary of some of these efforts includes the following:

Table 1 Vertiport and heliport design standards and guidance.

Issuing Organization	Guidance Title	Description	Guidance Classification
FAA	Engineering Brief (EB) 105 [1]	Interim guidance on vertiport design for VTOL capabilities	Vertiport design
FAA	AC 150/5390-2D, Heliport Design [8]	Notes on emerging VTOL aircraft performance compared to conventional helicopters or tiltrotors	Heliport design
Australian CASA	AC 139.V-01 v1.0 [9]	Guidance on vertiport physical characteristics, obstacle limitations, and visual aids	Vertiport design
EASA	Annex to ED Decision 2019/012/R [10]	Certification specifications for VFR heliports at aerodromes under Regulation (EU) 2018/1139	Heliport design
EASA	Prototype Technical Specifications for Vertiport Design [11]	For VFR vertiports operation with manned VTOL-capable aircraft in the enhanced category	Vertiport design
ICAO	Annex 14 – Volume II – Heliports Manual (Document 9261) [12, 13]	Heliports manual	Heliport design
ASTM	F3423/F3423M-22 [14]	Standard specification for vertiport design	Vertiport design

NASA Activities

Research by NASA includes High Density Vertiplex (HDV) that simulated multiple aircraft operating beyond visual line of sight (BVLOS) in-and-around the vertiport [4]. This project relied on a distributed graphics processing unit (GPU) simulation system originally developed for Uncrewed Aircraft System (UAS) Traffic Management (UTM) used in studying autonomous separation in a localized airspace.

A NASA survey of industry issues and concerns with UAM vertiports identified a range of considerations related to VO HMI workstation design requirements [16]. This included identifying the flight plan data needed by the VO in contrast to what data would be needed by the PSUs and vehicles operating out of a vertiport.

Industry Initiatives

Industry efforts in vertiport design include the following:

- Architecture Technology, Incorporated developed a Vertiport Traffic Automation System that accommodates low-density visual flight rules (VFR) operations in the near-term and can evolve to handle future high-density, autonomous operations at vertiports having close proximity [17]. This system uses an architecture that allows researchers to configure vertiports with various traffic patterns.
- Boeing’s Aurora Flight Sciences, working with Wisk Aero, developed an Advanced Teaming Sandbox that enables user testing of HMIs [18]. This system focuses on pilot interactions with aircraft autonomous systems.
- With expertise in ground infrastructure, Skyports designs, builds, and operates vertiports. This includes developing operational testbeds to determine optimal vertiport configurations [19]. Skyports has also partnered with Joby Aviation to develop a Living Lab passenger terminal for testing technologies and procedures [20]. The Living Lab is located at a Joby test site in California. A concern is that the cost of vertiport designs could increase if each municipality has varied unique requirements. Joby uses a remote-control tractor dolly around the front wheel for taxi.
- Overair signed a Memorandum of Understanding (MoU) with Dallas Fort Worth International Airport (DFW) to explore vertiport development and eVTOL aircraft operations within the DFW Metroplex [21]. A cross-functional working group will explore the infrastructure and policies needed to implement an integrated,

sustainable eVTOL program at DFW. This includes the operational procedures, including approach, landing, taxiing, charging, loading and unloading passengers, takeoff, departure, and safety protocols required for such a program. In addition, Overair is planning with the city of Arlington, TX to build a vertiport at the city's municipal airport and operate eVTOLs connecting to DFW and the Arlington entertainment district with its Six Flags Over Texas park, Hurricane Harbor, four pro sports teams, and shopping, dining, and live entertainment [22].

- The Blueprint for Autonomy, published by the Association for Uncrewed Vehicle Systems International (AUVSI), describes a future that methodically enables automation innovations for autonomous flight from today's small UAS already operating in the National Airspace System (NAS) to urban and regional air mobility. AUVSI envisions aircraft using auto-taxi capabilities at vertiports to optimize ground operations and safety and aircraft with skids (otherwise unable to taxi) use technology that integrates into the ground operating environment. Vertiport design should consider integrating TLOFs with the parking stand so that taxi operations are not required. The expansion of urban vertiports, combined with a new rule for BVLOS commercial operators, will facilitate the scaling of UAM operations using extensible traffic management (xTM) services for UAM aircraft [23].

Academic Research

Academic research studies guiding the definition of V-HATT capabilities included the following:

- Considerations in defining automated air traffic management requirements relative to the selection of vertiport locations, landing waypoints, and urban winds [24]. Results from modeling the landing simulations can support defining eVTOL requirements for vertiport-specific landing paths.
- Considerations for balancing the number of touchdown and liftoff (TLOF) pads with the number of gates key to achieving maximum aircraft throughput. This includes simultaneous paired arrivals or departures in contrast to independent approach and departure procedures. "Findings indicate the importance of balancing the number of touchdown and liftoff pads with the number of gates to achieve maximum aircraft throughput per vertiport footprint. Furthermore, simultaneous paired arrivals or departures provide significant throughput gains without the need for fully independent approach and departure procedures. The methodology and findings introduced in this paper support the development of concepts of operation to maximize throughput for a given vertiport footprint and demand scenario." [25]
- Relationship between vertiport design and parking pad throughput relative to pad operations and gate passenger loading and unloading [26]. A key result indicated that pad and gate processes have a threshold capacity beyond which delays increase exponentially.
- Considerations in arrival phase efficiency at vertiport and proposed a rolling-horizon optimization based scheduling algorithm to minimize eVTOL arrival delays. This study highlights the restricted resources of vertiports, high air traffic density, frequent flight maneuvers, and limited eVTOL battery energy as major constraints [27].
- Proposed a novel airspace design concept to manage air traffic of mixed eVTOL fleets (winged and wingless) and aims to minimize the makespan (landing completion time) for these vehicles at vertiports. The study introduces a heuristic approach combining insertion and local search (ILS) with mixed-integer linear programming (MILP) and time-advance (TA) scheduling methods to optimize the makespan of eVTOL fleets [28].
- Designing the structured airspace with concentric rings, each supporting a limited number of aircraft, to regulate the flow of landing traffic at a vertiport. The design uses a Markov Decision Process (MDP) based algorithm for sequencing and collision avoidance, allowing aircraft to self-organize and perform guidance while waiting to land [29].

IV. Gaps Driving the Need for V-HATT

Vertiports can be considered as bottlenecks in future mature UAM transportation networks, limiting traffic flow throughput rates and therefore impacting the business bottom line. Past studies have simulated and analyzed UAM route network design, vertiport siting, vertiport operational capacity, enroute airspace design, and related aspects. V-HATT is unique by virtue of its focus on the role of the human VO in partnership with machine teaming agents, as well as its integrated vertiport surface and terminal airspace management approach.

The vision for a vertiport is a high-density traffic environment, like most controlled airports, without requiring direct Air Traffic Control (ATC) services to manage traffic flow, like most heliports. As shown in Figure 1, the vertiport is a blend of heliports and airports when comparing throughput, infrastructure requirements, FAA oversight, and operations management. Vertiports will initially resemble heliports for near-term commercial operations. Over time, they will look more like airports as operations mature and safety concepts get validated. Initial commercial operations will involve a pilot onboard operating under today's rules (14 Code of Federal Regulation Part 91 or Part 135, or other applicable regulations). As part of its vision for an information-centric NAS, the FAA posed that infrastructure, including vertiports and remote sites, will need to evolve in pace with technology and commercial markets relative to the needs of the most demanding users or suppliers [30] including as part of its Implementation Plan for 2028 called Innovate 28 [31].

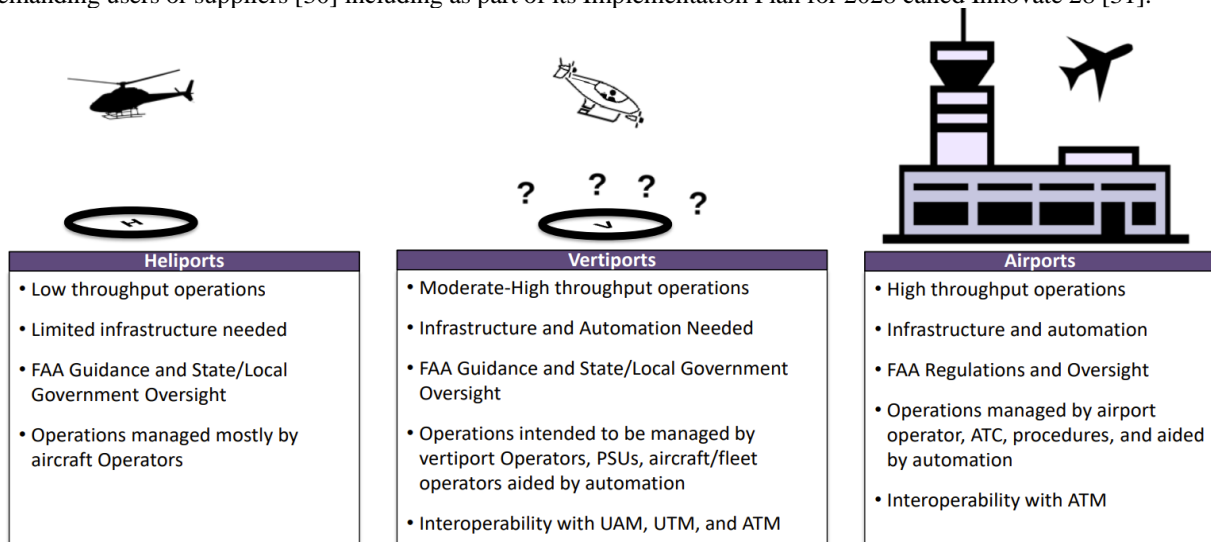


Fig. 1 Industry need for vertiport technology [32].

As the FAA defines operational constraints for managing the traffic and conflicts in and around the vertiport, V-HATT will be needed to enable the degree of automation required to manage UAM aircraft to meet those constraints under various operating conditions. Additionally, research must address a range of use cases and contingency management, such as for passenger transportation and freight deliveries.

A large city-center vertiport may have limited airspace approach paths because of buildings as well as merge points for arrival and departure routes with some being shared with other vertiports. Another vertiport in a nearby suburban area that is managed by the same PSU may have an open approach plate with few merge points. Additionally, operators may provide on-demand passenger and cargo delivery services with highly variable scheduling. Passengers might reserve seats in less than an hour timeframe as well as show up without advance notice. These issues lead to the need for a flexible system supported by vertiport operations.

Integration of management of arrivals, surface movements, and departures is critical to efficient operations. Once an aircraft lands on a TLOF, it needs to vacate the TLOF, making it available for the next arrival. Once an aircraft has unloaded/loaded passengers and cargo, it needs to vacate the parking pad to make it available for the next aircraft. Once an aircraft has taxied to a TLOF it must depart to make the TLOF available for the next departure.

V-HATT will provide an innovative capability for developing new vertiport configurations and operational concepts, enabling researchers to evaluate mitigations of choke points stifling throughput. This capability will be developed as a reconfigurable vertiport HMI that is attached to a simulation system for analysis of the operations. The simulations and trade studies outputs will provide important data and feedback and enable vertiport designers to determine optimal designs and operational concepts.

V. V-HATT Attributes and Assumptions

Key attributes highlighting the business importance and engineering utility of V-HATT include the following:

- 1) Focusing on human-DST automation teaming
- 2) Simulating off-nominal and contingency scenarios
- 3) Integrating arrival, surface, and departure traffic management
- 4) Including weather considerations that will impact vertiport operations
- 5) Considering a diversity of aircraft and business cases
- 6) Developing vertiport surface and airspace designs unique to local environments
- 7) Capturing and analyzing vertiport performance
- 8) Capturing and analyzing human factors data

The foundation for V-HATT in providing a real-time HITL testbed is framed by three Mission Phases that represent the flow of simulation planning, execution, and analysis. V-HATT capabilities were designed through the knowledge elicitation process. Information from this process was further decomposed for designing HITL simulations and organized into mission phases. The Pre-Mission phase includes setting up the simulation, adjusting teaming relationship parameters, designing the vertiport layout and airspace, defining operational rules, selecting weather conditions, and identifying potential off-nominal scenarios. The simulation engineer will be able to completely customize the simulation design for experimentation. This phase includes the design of surface resource management and arrival and departure airspace, configuring operational parameters such as weather and surface operations settings, and schedule and sequence planning using traffic algorithms and allocating tasks to automation or manual. V-HATT capabilities will mature as simulation and scenario development continues.

The Mission phase includes running the simulation with a HITL using the VO using automation through live virtual construction (LVC) to manage the flow of operations. The idea is that a human VO will have controls that allow for scheduling, sequencing, and controlling arrival, surface, and departure traffic to ensure high-throughput operations at the vertiport. Automation will play a key role in supporting the humans managing the flow of operations at the vertiport. This phase includes real-time management of surface resources, arrivals, and departures, and maintaining constant situational awareness.

The Post-Mission phase includes conducting analysis of human factors (e.g., VO workload), conducting bottleneck analysis, and comparing simulation configurations for trend analysis. Data analysis is key in the Post-Mission phase, allowing simulation engineers to examine the performance of the varying simulation conditions. This phase includes post-simulation data reduction and analysis for human factors and vertiport performance.

The Pre-Mission, Mission, and Post-Mission phases are depicted in Figure 2.



Fig. 2 Sequence of V-HATT phases.

The conceptual design for V-HATT started with knowledge elicitation with the participation of experts including those from industry and NASA. Identified needs were classified according to their mission phase and provided the foundation for defining functions and developing user stories. Off-nominal scenarios included unannounced arrival of helicopters and eVTOLs and unexpected requests for parking without advanced pre-coordination.

Assumptions underlying V-HATT development were made to communicate what V-HATT includes and does not include, identify how V-HATT is intended to be used, and bound design complexity. Assumptions included the following:

- 1) V-HATT will assist in airside traffic flow management but will not provide functionality or capabilities to support terminal or landside management such as passenger security, ticketing, baggage handling, or other supporting services.
- 2) V-HATT will support 2D vertiport surface layouts and will not allow a user to design a 3D vertiport layout with varying TLOFs and parking gates located at different verticals.

- 3) Aircraft taxiing capabilities will include powered ground taxi, hover taxi, and tugs. V-HATT will not consider air taxiing (that is, flying to a separated facility in close proximity).
- 4) Vertiport terminal airspace traffic situational awareness will include inbound, outbound, nearby, and overflight air traffic which provides for a more realistic operational environment.
- 5) The V-HATT vertiport operator only manages arrival, surface, and departure traffic for a single vertiport (1:1).
- 6) There will be no locations, points, or fixes in the terminal airspace where eVTOL hovering will be required due to energy management concerns.
- 7) The vertiport operator may optionally be responsible for terminal airspace management including scheduling and sequencing air traffic. Aircraft separation will be the responsibility of the pilot.
- 8) The vertiport operator will provide taxi directions to the pilot/aircraft after arrival on the TLOF and the pilot/aircraft will be responsible for separating itself from other aircraft and vehicles on the vertiport surface during taxi.
- 9) The vertiport operator will issue the equivalent of “clearances” to arriving, taxiing, and departing aircraft.
- 10) The fleet operator or pilot is responsible for selecting an initial vertiport surface reservation time slot in advance of arrival at the vertiport (this is assumed through pre-loaded schedules for the vertiport prior to initiating simulation).
- 11) The vertiport operator will have a pre-built schedule upon starting operations and may adjust the schedule as the day progresses. Non-scheduled aircraft may request to land at the vertiport in which case the vertiport operator will add those aircraft to the schedule if able.
- 12) The vertiport will not be co-located on an airport.
- 13) At least one TLOF will be designed to accommodate the largest design aircraft anticipated for operations.
- 14) The vertiport operator will not coordinate en route traffic with a PSU or Air Traffic Control (ATC) during routine operations. It is assumed that a Letter of Agreement (LOA) exists between local ATC facilities, as is required by local vertiport airspace.

VI. V-HATT Functions and Tasks

The goal of the Pre-Mission phase is to set the parameters for a HITL simulation based on V-HATT functions and tasks, as listed in Table 2.

Table 2 Pre-Mission functions and tasks.

Functions	Tasks
1.0 Surface Design Modeler	<ul style="list-style-type: none"> • Select desired vertiport location on geospatial map • Create an object • Create different areas on the vertiport surface • Adjust object size and shape attributes • Adjust object position and spacing • Assign object performance attributes
2.0 Arrival and Departure Airspace Design Modeler	<ul style="list-style-type: none"> • Create an object • Visualize local airspace • Visualize local ground environment • Visualize historical weather data
3.0 Adjust object position and spacing	<ul style="list-style-type: none"> • Adjust fix and surface slope angle (e.g., 8:1 - 8 degrees horizontal for every 1 degree vertical) • Adjust fix and surface length, width, and height limitations (e.g., 4,000 ft longitudinal distance) • Place a metering gate at a point along a fix or at the beginning or end of a fix • Place a decision point at a point along a fix or at the beginning or end of a fix • Create a holding pattern • Create a navigation obstacle that may not exist in the local geography • Create arrival and departure surfaces to match above fixes

4.0 Operational Parameter Configuration	
4.1 Weather Settings	<ul style="list-style-type: none"> • Search historical weather data (loaded per geographic location setting) • Select weather conditions for vertiport operations simulation based on historical day • Load selected weather conditions into vertiport simulation via desired formats
4.2 Surface Operations Settings	<ul style="list-style-type: none"> • Define initial vertiport resource availability (open or closed) • Define planned outages for vertiport resources (closed for certain amount of time)
4.3 Arrival and Departure Operations Settings	<ul style="list-style-type: none"> • Define initial vertiport airspace fix preference based on selected weather conditions for the simulation
4.4 Off-Nominal Scenarios	<ul style="list-style-type: none"> • Define off-nominal scenarios • Assign probability to off-nominal scenarios • Assign specific times where off-nominal events are triggered in simulation
4.5 Fleet Operator and Aircraft	<ul style="list-style-type: none"> • Create and define aircraft (to be piloted by pseudo and artificial pilots) • Define aircraft performance (as defined by aircraft performance models) • Define fleet operators • Allocate select vertiport resources to fleet operators
4.6 Define vertiport operating model (scheduled, on-demand, hybrid approach)	<ul style="list-style-type: none"> • Select whether vertiport will operate: <ul style="list-style-type: none"> ○ Only according to a pre-defined schedule (must have scheduled with vertiport before departing origin vertiport) ○ Only accepting on-demand aircraft (maintains no schedule in advance, cannot schedule until aircraft is close to vertiport) ○ With a hybrid approach - some aircraft will be scheduled in advance and some will request landing on-demand, ad hoc • En route arrival and departure traffic demand model based on known distribution <ul style="list-style-type: none"> ○ Arrivals will be pre-determined before running the simulation ○ Arrivals may be based on an uploaded schedule or based on a known distribution (such as Poisson distribution)
5.0 Sequence/Queue Planning	
5.1 Arrival Sequencing	<ul style="list-style-type: none"> • Define prioritization weighting and objectives: <ul style="list-style-type: none"> ○ Remaining battery ○ Emergency level ○ Current prioritized delay • Define schedule freeze horizon and arrival separation criteria: <ul style="list-style-type: none"> ○ Number of aircraft at any time window should within the terminal airspace capacity ○ The RTA of any two aircraft should have a minimum temporal separation ○ The RTA should consider the dynamics of aircraft and remaining energy • Define sequencing/queuing algorithm: <ul style="list-style-type: none"> ○ Optimization based algorithm to minimize in-air delay while keep the above constraints
5.2 Departure Sequencing	<ul style="list-style-type: none"> • Define prioritization weighting and objectives: <ul style="list-style-type: none"> ○ Emergency level ○ Current prioritized delay • Define schedule freeze horizon and departure separation criteria: <ul style="list-style-type: none"> ○ The number of aircraft in high-performance layer (outside the terminal airspace) should within the pre-defined capacity ○ One TLOF should only allow one departure at a time interval ○ Departure time should consider the approaching aircraft

	<ul style="list-style-type: none"> ○ Departure time should be later than the earliest departure time, which considering the charging time and passengers boarding time ● Define sequencing/queuing algorithm: <ul style="list-style-type: none"> ○ Optimization based algorithm to minimize ground delay while keep the above constraints
6.0 Task Allocation	<ul style="list-style-type: none"> ● Assign Arrival Vertiport Operator Tasks as Manual or Automated ● Assign Surface Vertiport Operator Tasks as Manual or Automated ● Assign Departure Vertiport Operator Tasks as Manual or Automated ● Generate “Plays” - represent a delegation scheme for operators to give authority to automation to perform a set of tasks

The goal of the Mission phase is to run the HITL simulation using LVC capabilities organized by functions and tasks shown in Table 3 and mission interface requirements shown in Table 4.

Table 3 Mission functions and tasks.

Functions	Tasks
1.0 Arrival Traffic Flow Management	<ul style="list-style-type: none"> ● Accept or reject inbound traffic (based on current capacity vs. demand) ● Assign aircraft arrival queue position ● Assign arrival aircraft to arrival fixes ● Schedule arrival aircraft to arrival metering gate(s) ● Assign arrival aircraft to a holding pattern ● Command aircraft to maintain separation ● Issue landing clearance
2.0 Surface Traffic Flow Management	<ul style="list-style-type: none"> ● Assign arrival TLOF ● Schedule arrival TLOF ● Issue taxi (surface movement) clearance ● Adjust vertiport surface resource availability ● Schedule vertiport surface resources ● Assign departure TLOF ● Schedule departure TLOF ● Estimate Departure Time
3.0 Departure Traffic Flow Management	<ul style="list-style-type: none"> ● Assign aircraft departure queue position ● Assign departure aircraft to departure fixes ● Issue departure clearance
4.0 Data Capture and Management	<ul style="list-style-type: none"> ● Record a simulation such that the simulation can be loaded and ran again with the same operational conditions and aircraft movements ● Load a pre-configured simulation run for future testing so that a scenario may be tested among multiple subjects ● Record all the relevant vertiport performance metrics such as vertiport throughput rates, vertiport demand vs. capacity, number of conflicts (segmented by arrival, surface, and departure), number of alerts generated for the vertiport operator, amount of in-air delay used, separation and holding commands issued to arrival aircraft, accepted and rejected inbound air traffic, and any other performance metrics determined by the vertiport operator ● Structure data such that different scenarios and different subjects can be evaluated against a consistent set of performance metrics ● Generate a report post-simulation for the vertiport performance metrics desired

Table 4 Mission interface requirements.

Functions	Interface Requirements
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<p>1.0 Airspace and Weather Situational Awareness Interface</p>	
<p>1.1 Airspace</p>	<ul style="list-style-type: none"> • Aircraft information: <ul style="list-style-type: none"> ○ View position of aircraft in terminal airspace ○ View intent of aircraft in terminal airspace ○ View aircraft information (e.g., type, identification (ID), tail number, velocity, position, origin, health status) ○ View aircraft queue / priority and sequence ○ View Estimated Time of Arrival (ETA) vs. Scheduled Time of Arrival (STA) ○ View Estimated Time of Departure (ETD) vs. Scheduled Time of Departure (STD) ○ View important dependency information such as: <ul style="list-style-type: none"> • If aircraft has received appropriate clearances • If aircraft is compliant with metering gate or TLOF schedule(s) • If aircraft are maintaining sufficient separation ○ View arrival / departure TLOF ○ Aircraft separation commands • Airspace information: <ul style="list-style-type: none"> ○ View terminal airspace routes (e.g., vertiport fixes, VFR sectional chart, U.S. helicopter chart) ○ View holding patterns ○ View nearby airspace (e.g., controlled, Temporary Flight Restrictions (TFRs), Special Use Airspace (SUA), Military Operations Area (MOA)) ○ View nearby Notice to Air Missions (NOTAMs) ○ View transient traffic passing through or near vertiport airspace <ul style="list-style-type: none"> • View airspace congestion as a function of fix / holding pattern capacity
<p>1.2 Weather</p>	<ul style="list-style-type: none"> • View the following surface information (both current and forecast): <ul style="list-style-type: none"> ○ Visibility ○ Winds (gusts, turbulence, shear) ○ Outside Air Temperature (OAT) and Dew Point ○ Air Pressure ○ Weather cameras (if applicable) • View the following terminal airspace information (both current and forecast): <ul style="list-style-type: none"> ○ Visibility ○ Winds (gusts, turbulence, shear) ○ Temperature ○ Cloud ceiling ○ Severe weather (rain, hail, snow, icing) • View the following en route airspace information: <ul style="list-style-type: none"> ○ View severe weather (rain, hail, snow, icing) ○ View Pilot Reports (PIREPs) and Significant Meteorological Information (SIGMETs) or other alternative to pilot reporting • View the preferred TLOFs for arrival and departure based on current wind conditions
<p>2.0 Surface Situational Awareness Interface</p>	<ul style="list-style-type: none"> • Aircraft information: <ul style="list-style-type: none"> ○ View position of aircraft on the vertiport surface ○ View aircraft taxi clearance instructions ○ View assigned parking pads including duration of parking ○ View assigned staging areas including duration of staging ○ View ETA vs. STA ○ View ETD vs. STD ○ View aircraft information (e.g., type, ID, tail number, velocity, position, origin, health status) ○ View aircraft departure queue / priority and sequence

	<ul style="list-style-type: none"> ○ View arrival / departure TLOF ○ View important dependency information such as: <ul style="list-style-type: none"> • If aircraft has received appropriate clearances • If aircraft is compliant with TLOF and vertiport resource schedule(s) • If aircraft are maintaining sufficient separation • Surface information: <ul style="list-style-type: none"> ○ View current occupation or vertiport resources ○ View vertiport resource status ○ View position of GSE on the surface ○ View surface congestion as a function of surface capacity
3.0 Scheduler Interface	<ul style="list-style-type: none"> • Arrival Schedule Interface • Surface Schedule Interface • Departure Schedule Interface • Integrated Schedule Interface • Forecast Conditions Interface
4.0 Communications Interface	<ul style="list-style-type: none"> • The Vertiport Operator shall be able to execute VHF radio communications with pseudo pilots • The Vertiport Operator shall be able to execute message-based communications with artificial pilots (send messages) • The Vertiport Operator shall be able to send a batch message to artificial pilots with command information • Pilots should be able to communicate the following information to the Vertiport Operator <ul style="list-style-type: none"> ○ Position ○ Velocity ○ Carrying passengers (PAX) or cargo ○ Remaining fuel / energy ○ Operational status (nominal or emergency) ○ Tail Number ○ Origin ○ Destination ○ Clearance readbacks ○ Go around / missed approach ○ Traffic following • Vertiport Operator should be able to communicate the following information to pilots <ul style="list-style-type: none"> ○ Arrival <ul style="list-style-type: none"> • Fix(es) assignment and schedule • TLOF assignment and schedule • Separation commands • Landing clearance ○ Surface <ul style="list-style-type: none"> • Taxi clearance • Vertiport resource assignment and schedule ○ Departure <ul style="list-style-type: none"> • Fix(es) assignment • Departure clearance
5.0 Simulation Execution Monitor	<ul style="list-style-type: none"> • Load the simulation and deploy to human work stations • Start the simulation • Play and pause the simulation • Stop the simulation • Introduce unexpected “constructive”, artificial pilots/aircraft, into the simulation either transiting the airspace or intending to land at the vertiport

	<ul style="list-style-type: none"> • Prompt the vertiport operator to answer surveys and/or questionnaires (e.g., Instantaneous Self-Assessment)
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The functions and tasks for the Post-Mission phase are shown in Table 5.

Table 5 Post-Mission functions and tasks.

Functions	Tasks
1.0 Human Factors Analysis	
1.1 Quantitative Measures	<ul style="list-style-type: none"> • Instantaneous Self-Assessment (ISA) for subjective workload every 2-3 minutes using a 5-point workload rating scale • Post-scenario using NASA Task Load Index (TLX) <ul style="list-style-type: none"> ○ Average workload ○ Peak workload • Activity measures <ul style="list-style-type: none"> ○ Data inputs by keyboard and mouse (counts) ○ Voice communications: landing clearance, taxi to parking pads (counts) • Error Measures <ul style="list-style-type: none"> ○ Operator mistakes ○ Operator forgets ○ Operator distraction ○ Error rate as a function of workload • Situational Awareness Rating Technique (SART) • Human-Automation Trust
1.2 Final Subjective Semi-Structured Interviews	<ul style="list-style-type: none"> • Purpose is to solicit overall likes/dislikes, suggestions/recommendations, and other information after each subject completes all scenario runs
1.3 Data Analysis	<ul style="list-style-type: none"> • Workload Data Analysis <ul style="list-style-type: none"> ○ Counts of activity measures over time ○ Correlate ISA and TLX workload measures with activity measures ○ Comparison across different simulation runs, e.g., multiple subjects/vertiport operators going through the same scenario ○ Comparison across different scenarios, e.g., multiple subjects/vertiport operators going through multiple scenarios
1.4 Visualization	<ul style="list-style-type: none"> • NASA TLX • Timeline graph with workload overlaid with activity measures • Table of correlations <ul style="list-style-type: none"> ○ Correlate ISA with TLX measures ○ Correlate ISA measures with activity measures ○ Correlate TLX measures with activity measures
2.0 Vertiport Performance Analysis	
2.1 Measures	<ul style="list-style-type: none"> • Safety <ul style="list-style-type: none"> ○ Loss of separation (LOS) events <ul style="list-style-type: none"> • Loss of separation events resolved vs. unresolved • Time to resolve (for resolved LOS events) • Go around events (% of arrival operations) ○ Concurrent and simultaneous landing and/or takeoff operations ○ Clearance success rate (provided necessary clearances in time vs. did not) ○ Efficiency <ul style="list-style-type: none"> ○ Arrival <ul style="list-style-type: none"> • Arrival TLOF occupancy statistics • Arrival TLOF utilization (scheduled vs. occupied) • Arrival delay statistics (on-time arrivals vs. delayed)

	<ul style="list-style-type: none"> • Arrival acceptance rate (accepted vs. rejected) • Holding rate (no holding vs. holding required) • Number of arrival alerts generated ○ Surface <ul style="list-style-type: none"> • Taxi time statistics • Parking time statistics • Clearance-to-action time statistics • Schedule change statistics (quantity of schedule changes required) <ul style="list-style-type: none"> • Parking gate turns per hour • Number of surface alerts generated ○ Departure <ul style="list-style-type: none"> • Departure TLOF occupancy statistics • Departure TLOF utilization (scheduled vs. occupied) • Departure delay statistics (on-time departures vs. delayed) • Number of departure alerts generated • Capacity <ul style="list-style-type: none"> ○ Throughput statistics (operation is counted as a discrete landing or takeoff) <ul style="list-style-type: none"> • Vertiport arrival rate (VAR) • Vertiport departure rate (VDR) ○ Surface capacity over time
2.2 Analysis	<ul style="list-style-type: none"> • Vertiport performance measures should be comparable within the three primary constructs (Safety, Efficiency, and Capacity) and across these measure domains <ul style="list-style-type: none"> ○ As example, Efficiency metrics of Arrival Delay and Arrival TLOF Occupancy should be comparable ○ As example, Safety metric Go Around Events should be comparable to Capacity metric Vertiport Arrival Rate (VAR) • Vertiport performance measures should be comparable against Human Factors measures <ul style="list-style-type: none"> ○ As example, Efficiency metric Holding Rate should be comparable to ISA workload assessments ○ There are some metrics that will vary over time (temporal) which can be compared to time-marked in-simulation human factors assessments (such as ISA or activity measures) ○ Other metrics will be the result of the entire simulation (one set of values / statistics) that can be compared to post-simulation human factors assessments (such as NASA TLX or SART)

These results support conducting bottleneck analysis and comparing simulation runs for different vertiport configurations to look at possible trends in throughput and other performance metrics. Data analysis and interpretation are key in the Post-Mission phase to support examining how performance varies with different simulation conditions.

These functions and system requirements together represent the foundation for V-HATT that uses an initial system architecture combined with an initial user interface design and airspace configuration supports the definition of use cases to evaluate different vertiport design approaches as described in the following sections.

VII. Initial V-HATT System Architecture

The initial V-HATT system architecture, shown in Figure 3, consists of multiple software components. These include the following:

- Client-side application programming interfaces (APIs) and baseline vertiport operations interface
- Server-side state machine implementation
- Airspace route editing capability
- Vertiport editor interface
- Baseline aircraft simulation
- Aircraft control system for human and automated maneuver control
- Integrated arrival, surface, and departure scheduling algorithms

VIII. Initial User Interface Prototype Design

The initial prototype design of the V-HATT user interface, shown in Figure 4, consists of multiple displays to support VO information requirements. Starting at the top-left is a surface traffic situation display showing current aircraft locations against a background of six parking gates, two TLOFs (one for arrivals and the other for departures), and associated taxi routes. At the top-right is an airside situation display showing arrivals out to three miles from the vertiport using a background of geo-located rings demarking operational flow areas including a holding ring. Immediately below the airside situation display is a tabular window containing additional information on arrivals. The bottom display shows arrival and departure flow ribbons providing information about sequencing and spacing based on arrival scheduler automation.

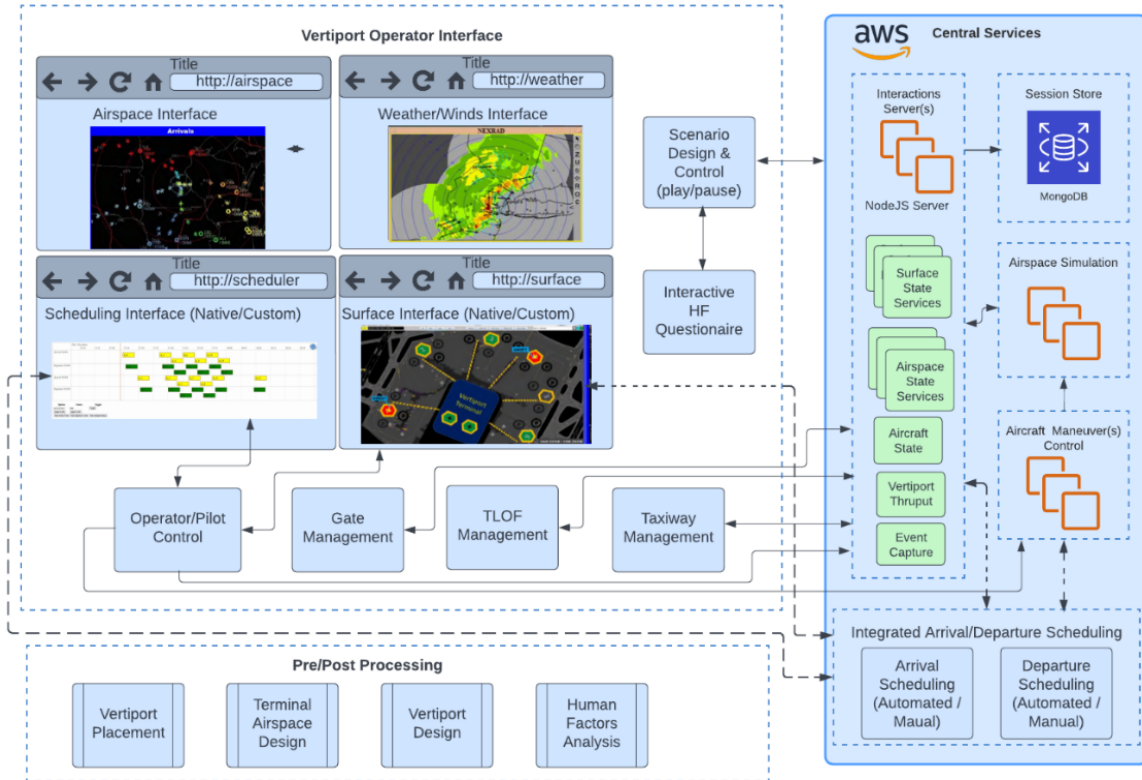


Fig. 3 Initial system architecture.

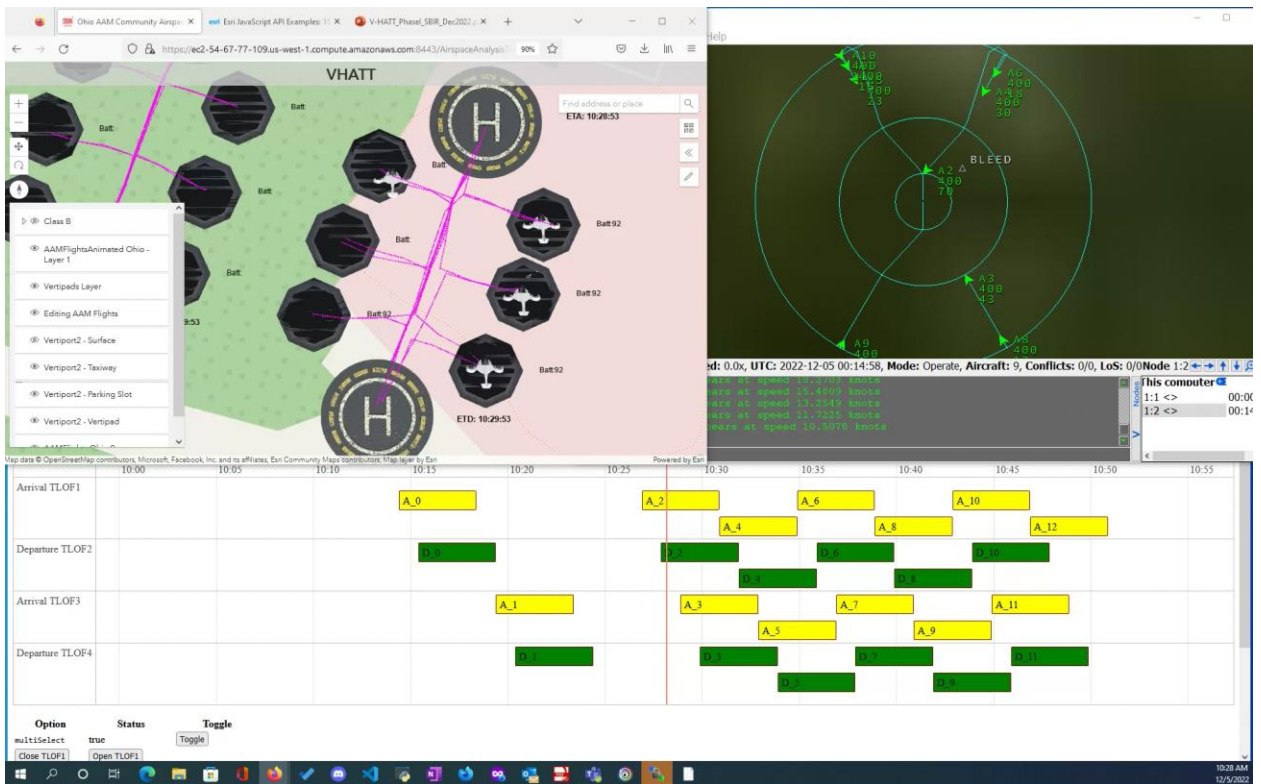


Fig. 4 Initial Prototype VO Display Design [7].

IX. Use Cases

Arrivals

The preliminary use case for arrivals has the user goal that an arriving aircraft pilot requests to land at the vertiport. The expected outcome is that the arriving pilot successfully lands at the vertiport. The main flow of the arrival use case consists of the following information.

- [Arriving Pilot] communicates to [Vertiport Operator] at designated location (first call point) they are en-route to land at the vertiport
 - [Vertiport Operator] checks to see if [Arriving Pilot] is on the schedule or is an on-demand arrival
 - IF SCHEDULED: [Vertiport Operator] checks to see if [Arriving Pilot] is on track to meet their scheduled vertiport resource times
 - IF NOT SCHEDULED, NOT ON SCHEDULE, OR VERTIPORT RESOURCES ARE UNAVAILABLE: [Vertiport Operator] looks at vertiport resource availability and uses the Vertiport Resource Scheduler to schedule and/or reschedule [Arriving Pilot]
 - IF [Arriving Pilot] DOES NOT LIKE THE RESOURCE ALLOCATION: [Arriving Pilot] may either request alternative vertiport resources or cancels arrival request (Loop until satisfactory results for both Arriving Pilot and Vertiport Operator).
- Vertiport Resource Scheduler
 - [Vertiport Operator] looks at the combined Arrival TLOF, Parking Gate, and Departure TLOF schedule for the vertiport and continuously updates surface schedule (TLOFs and Gates) based on flow of arrivals, surface movements, and departures
 - [Vertiport Operator] then ensures compliance with both the arrival and departure air traffic sequences generated by the Arrival Sequencer and Departure Sequencer
 - [Vertiport Operator] lastly adjusts the vertiport resource schedules as is necessary based on evolving conditions
- Vertiport Arrival Sequencer

- [Vertiport Operator] first assigns a priority to [Arriving Pilot] based on prioritization logic
- [Vertiport Operator] then assigns the appropriate arrival fix to the assigned TLOF for the [Arriving Pilot]
- [Vertiport Operator] finally schedules the [Arriving Pilot] to the appropriate metering gate(s) as is applicable (in the absence of metering gates, the Arrival TLOF schedule is used)
 - IF THE [Arriving Pilot] WOULD ARRIVE TOO EARLY OR TOO LATE: [Vertiport Operator] would first look to see if arriving early or late would impact schedule, and if so, would either attempt to delay or speed up the [Arriving Pilot] or re-sequence the [Arriving Pilot]
 - IF THE [Arriving Pilot] CANNOT BE DELAYED OR RESEQUENCED: [Vertiport Operator] will try to reschedule the inbound aircraft with the Vertiport Resource Scheduler flow
 - IF THE [Arriving Pilot] CANNOT BE RESCHEDULED: [Vertiport Operator] will reject inbound traffic and reroute to alternative vertiport
- [Vertiport Operator] communicates to [Arriving Pilot] the arrival TLOF and the approach in use to the designated TLOF
- [Arriving Pilot] reads back arrival TLOF and approach to use for designated TLOF
- [Vertiport Operator] then continuously monitors for [Arriving Pilot] conformance with the sequence and schedule
 - IF THE [Arriving Pilot] CANNOT MAINTAIN SEQUENCE OR SCHEDULE: [Vertiport Operator] will execute the Vertiport Arrival Sequencer flow if the schedule or sequence deviation impacts other flight operations (execution of the Vertiport Arrival Sequencer flow may trigger Vertiport Resource Scheduler updates as well if the sequence and speed adjustments alone cannot solve the problem)
 - The [Vertiport Operator] will communicate any updates to arrival fix, airspeed, and arrival TLOF to the [Arriving Pilot] as is needed
 - The [Arriving Pilot] will read back and acknowledge any instructions provided
- When the [Arriving Pilot] reaches the Final Approach Fix (FAF), the [Vertiport Operator] ensures the arrival TLOF is clear of aircraft and obstacles, then issues a landing clearance to the [Arriving Pilot]
 - IF ARRIVAL TLOF IS NOT AVAILABLE: The [Vertiport Operator] will execute the Vertiport Resource Scheduler flow to first look for alternative arrival TLOFs, then moving to the Vertiport Arrival Sequencer flow
- [Arriving Pilot] reads back landing clearance to [Vertiport Operator]
- [Arriving Pilot] lands at designated arrival TLOF

Surface Movement

The preliminary use case for surface movement has the user goal that an aircraft on the surface needs to move from Point A (origin) to Point B (destination). The expected outcome is that the pilot successfully maneuvers the aircraft from Point A to Point B on the vertiport surface. The main flow of the surface movement use case consists of the following information.

- [Pilot] communicates to [Vertiport Operator] requesting surface movement from Point A to Point B
- [Vertiport Operator] looks for existing vertiport surface reservations (e.g., TLOFs and Gates) for surface taxiing
 - IF [Pilot] REQUESTS TO TAXI TO A SURFACE RESOURCE WITHOUT A PRIOR RESERVATION: [Vertiport Operator] will execute the Vertiport Resource Scheduler flow to schedule the appropriate resources to taxi
- [Vertiport Operator] will look for the optimized taxi route from Point A to Point B and see if that route is available and clear of surface traffic
 - IF THERE IS A SURFACE CONFLICT: [Vertiport Operator] will look for alternative taxi routes that are clear of surface traffic and conflicts
 - IF THERE ARE NO ALTERNATIVE TAXI ROUTES: [Vertiport Operator] will look to see if Best Taxi Route is available later, if not the [Vertiport Operator] will adjust resource reservations via the Vertiport Resource Scheduler
- The [Vertiport Operator] will provide a safe surface taxi advisory to the [Pilot] which may involve a temporary movement to a holding area to clear another reserved vertiport resource
- [Pilot] reads back surface taxi advisory
- [Vertiport Operator] continuously monitors [Pilot] taxiing and surface resource availability and adjust resource schedule with the Vertiport Resource Scheduler flow

- [Pilot] arrives at Point B

Departure

The preliminary use case for departure has the user goal that the departing pilot seeks to depart from the origin vertiport to a destination vertiport. The expected outcome is that the departing pilot successfully departs from the vertiport. The main flow of the departure use case consists of the following information.

- [Departing Pilot] communicates to [Vertiport Operator] requesting departure from the vertiport
- Vertiport Departure Sequencer
 - [Vertiport Operator] first assigns a priority to [Departing Pilot] based on prioritization logic
 - [Vertiport Operator] then assigns the appropriate departure fix to the assigned TLOF for the [Departing Pilot]
 - IF [Departing Pilot] CANNOT MAKE DEPARTURE SCHEDULE: [Vertiport Operator] would first look to see if departing early or late would impact schedule, and if so, would attempt to re-sequence the [Departing Pilot]
 - IF THE [Departing Pilot] CANNOT BE RESEQUENCED: [Vertiport Operator] will try to make schedule adjustments via the Vertiport Resource Scheduler flow
 - [Vertiport Operator] communicates to [Departing Pilot] the departure TLOF and the departure fix
 - The [Departing Pilot] will read back and acknowledge any instructions provided
- [Vertiport Operator] then continuously monitors for [Departing Pilot] conformance with the sequence and schedule
 - IF THE [Departing Pilot] CANNOT MAINTAIN SEQUENCE OR SCHEDULE: [Vertiport Operator] will execute the Vertiport Departure Sequencer flow if the schedule or sequence deviation impacts other flight operations
 - IF THERE ARE CONFLICTS AT THE DEPARTURE TLOF OR ARRIVING TRAFFIC: [Vertiport Operator] will try to make schedule adjustments via the Vertiport Resource Scheduler flow
 - The [Vertiport Operator] will communicate any updates to departure fix to the [Departing Pilot] as is needed
 - The [Departing Pilot] will read back and acknowledge any instructions provided
- When the [Departing Pilot] reaches the Departure TLOF, the [Vertiport Operator] then issues a departure clearance to the [Departing Pilot]
- [Departing Pilot] reads back departure clearance to [Vertiport Operator]
- [Departing Pilot] departs from the vertiport on departure fix

Further development of the use cases will provide an important framework for maturing V-HATT functions and system requirements.

X. Discussion and Future Plans

FAA Office of Airports (ARP) and the Airport Technology Research and Development Branch (ATR) as part of a multi-year project supported the development of EB 105, Vertiport Design [1] and are currently undertaking simulation exercises and operational testing with AAM companies with the intent to develop a performance-based Advisory Circular by 2025 [33]. These tests address landing precision, approach/departure profiles, rotorwash/downwash impacts, and aircraft taxiing. Results from these tests may guide future V-HATT development, as appropriate.

Future visions of AAM and UAM pose a critical role for vertiports in efficiently transporting passengers and cargo. The scaling of vertiports in capability and complexity will be enabled with innovative concepts to simulate and evaluate the relationships for how different designs affect vertiport throughput and VO human factors.

V-HATT provides the capability to assess and understand potential bottlenecks in vertiport capacity and consider the role of the human VO. This tool will assist researchers, operators, manufacturers, and infrastructure developers in developing standards and guidance associated with vertiport design and operations. Prior V-HATT papers have addressed gaps, defined system requirements and the software architecture, and selection/design of the vertiport for use cases.

Future research intends to examine HAT for the VO using an automated teaming agent. A more capable V-HATT workstation will integrate mature versions of different services. V-HATT will then enable in-depth studies comparing multi-faceted relationships between vertiport designs, arrival-surface-departure throughput performance, and human factors. Development of surface resource scheduling between TLOFs and gates will pair with arrival and departure

sequences. Taxiing will be accomplished on a per request basis ensuring the aircraft has a reservation at the intended taxi destination.

Future research could address the interoperability and typical architecture of operational services, functions, and capabilities among the various stakeholders, including the VO, fleet managers, flight crews, PSUs, and secondary service providers such as weather service providers.

Research is needed on the relationships between traffic volume and airspace complexity with communications between pilots and EWR terminal and tower controllers.

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