Missed Approach Procedures in Advanced Air Mobility: Conceptual Exploration

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The High Density Vertiplex Sub-Project, as part of NASA's Advanced Air Mobility (AAM) Project, has been in collaboration with a team from Wisk Aero focusing on vertiport operations, procedures, and concept development. A particular area of focus has been on the development of missed approach scenarios and procedures that highlight the potential changes in the nearer- and further-term operational time frames. Such changes relate to topic areas such as airspace design, automation and autonomy, roles and responsibilities of actors and stakeholders, airspace management services and systems, as well as technologies specific to vertiport operations management. This paper presents the current state of joint concept development through the established collaboration and the application of elements in ongoing testing as part of NASA's High Density Vertiplex Sub-Project's research strategy.

I. Introduction

The Advanced Air Mobility (AAM) concept is helping to usher in 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. The AAM concept is a revolutionary and unique form of aviation in that it will be much more integrated into society with a large number of access points compared to current airports. Envisioned flights will be frequent and short duration using highly autonomous general aviation-sized vehicles (i.e., approximately 4 passengers) and be unpiloted. The associated AAM industry, regulatory authorities, and relevant stakeholders are deep in the early stages of development across a wide range of necessary topic elements from, for example, vehicle manufacturing and testing, aircraft certification, acoustics assessments, public acceptance, etc. In parallel, research is being conducted to support the needs of the AAM community in moving forward towards near-term operationalization as well as further-term research toward scalability and greater levels of autonomy.

In traditional Instrument Flight Rules (IFR) operations in today's National Airspace System (NAS), terminal area operations are closely managed through positive control and, in general, require many levels of procedures. Arrival operations are expected to adhere to published procedures and respond accordingly to air traffic control (ATC) instructions to ensure safety and efficiency of flow. However, even with that level of control, it is not uncommon for

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situations to arise where alternate procedures require additional needs for coordination and situational awareness given the many factors at play (e.g., vehicle performance, weather, gate availability, etc.). A specific example of a situation that occurs in that vein is that of a missed approach. In this situation, due to a number of potential reasons, an arrival aircraft operation will need to abort the approach, pull out of the pattern, and execute a procedure following specific instructions to safely abort the nominal approach and subsequently get sequenced back into the arrival flow after an available slot is either identified or created. Depending on the location and operating environment, a missed approach event can have significant impacts on overall operations with ripple effects that are felt in the system long after the initial event itself.

Although AAM will involve revolutionary vehicles and eventually highly advanced systems throughout the ecosystem, the fundamental aspects of arrival and departure operations at resource-constrained endpoints remains the same regardless: there are a finite number of available slots and landing spots that depend on a consistent and predictable flow of aircraft. Perturbations to that flow require additional measures to absorb it with minimal impact. Today, human ATC personnel manage the missed approach and resequencing. The high density of UAM operations will warrant more automated solutions for traffic flow management as a means to avoid high levels of human workload.

A great deal of research has been accomplished on this topic for traditional operations [1, 2]. There is a clear need to extend that research with a fresh perspective on applicability in AAM and addressing identified gaps with the capabilities unique to AAM. The driver for the distinction between missed approach situations in traditional operations versus AAM is that there are assumptions in AAM of additional airspace structures, infrastructure, roles/actors, and systems that are not seen in today's NAS. It is crucial to examine these cases with an expanded view that addresses the differences and includes alternatives in proper missed approaches handling, as well as eventually more significant off-nominal events (i.e., aircraft emergency landing operations, diversions to alternate landing locations).

II. NASA and Wisk Research Partnership

The highest localized traffic density and airspace management challenges are expected to exist within the vertiport operations area, which is akin to the terminal area down to the surface in traditional air operations. Future airspace management systems can potentially accommodate high-density traffic and large numbers of operations in nominal conditions. However, managing off-nominal situations in such an environment is expected to shape the resulting system. In this context, missed approaches are considered an off-nominal event that imparts a sudden change to the planned flights requiring the ecosystem to react immediately. The ability of the UAM ecosystem to respond to dynamic events is a major barrier to the AAM transportation concept. In that context, this paper will focus on the collaborative research and exploration being conducted through a partnership between NASA and Wisk to work through the handling of missed approach situations in a vertiport environment. Future work will include additional off-nominal events (e.g., aircraft in emergency conditions requiring immediate landing) in higher-density environments.

The efforts of the Wisk and NASA research teams on the topic of missed approaches are focused on how such situations can be handled given the operational environment, involved systems, and actors in the loop. However, there are some distinctions that are important to highlight with respect to the assumed environments that the teams are working toward. Wisk, given the need to operate in the mid-term of UAM development, is more immediately focused on earlier levels of UAM maturity, while NASA's HDV Sub-Project is focused on more advanced levels of UAM maturity. The distinctions are anticipated and meant to complement each other in providing insight into vertiport operations and procedures in the nearer and further term of AAM maturity. Wisk is a commercial industry company that is developing and testing autonomous electric vertical takeoff and landing (eVTOL) vehicles to safely carry passengers and provide services. In the collaboration with Boeing, the company has published a forward-looking concept of operations that sets the stage for a pathway to market [3] that coincides with the principles of operation for Wisk. The High Density Vertiplex (HDV) Sub-Project research aims to develop and evaluate a reference automation architecture that addresses scalable and efficient aircraft operations, flight and airspace management procedures, and vertiport operations in a further-term high density vertiplex environment.

III. Operational Environment

The operational environment of AAM will encompass a variety of areas: vertiports, UAM aircraft, airspace services, vertiport services, arrival and departure procedures, stakeholder roles and responsibilities.

1. Vertiports

While there are currently different interpretations of what constitutes a vertiport, Fig. 1 presents some distinctions and serves to highlight the facility to be assumed in reference to missed approaches.

A vertiport is a key element of transportation infrastructure designed for AAM vehicles to take-off and land. There will be many vertiport designs and they will be located in diverse geographic areas and in various classes of airspace. Services will be supplied to aircraft at vertiports (e.g., electric charging, cooling, etc.), and the surface and surrounding airspace will be closely monitored for safety assurance, configuration control, and resource management to include balancing of demand and capacity. Several variations of vertiport have been conceived that can be categorized by number of operations and level of on-site infrastructure. For example, a Vertistop may not have any services other than the Touch-down and Lift-Off (TLOF) area and means to access and disembark from the aircraft.

Fig. 1 Ground Infrastructure: Vertihubs, Vertiports, and Vertistops. (NASA HDV)

2. UAM Aircraft

To maximize vehicle performance and minimize operational costs, some UAM aircraft will be designed with autonomy in mind. The technology to enable autonomous aircraft has existed for some time in military applications and small unmanned aerial systems (sUAS). Onboard automation systems would include a Flight Management System (FMS) and Autopilot functions, as well as detect and avoid (DAA) systems to ensure well-clear, among many other functions. Other onboard autonomous systems would include autonomous contingency management systems, such as remote landing capability systems to enable safe emergency landings away from managed facilities (i.e., away from airports, vertiports). Onboard autonomous systems could also be used to ensure the TLOF is clear and safe to use during approach and landing. While the command and control (C2) links will be advanced compared to today's standards, some amount of fully autonomous flight capability is anticipated for the optimal integrated system. Integration and testing of the onboard autonomous systems in a relevant environment is an essential step towards the AAM vision. An example of UAM aircraft in development is provided in Fig. 2 below that shows Wisk's Generation 6 aircraft concept.

Fig. 2 Wisk's Generation 6 Aircraft. (Wisk)

3. Airspace Management Services

Airspace management services have traditionally been provided by government entities (ARTCC, TRACONs, Towers) or private towers (which follow ATO Tower Requirements) with humans complemented by various levels of system automation. Within the far-term AAM concept, airspace management services under an Extensible Traffic Management (xTM) concept may be offered by independent commercial third-party providers employing integrated and much more automated traffic management initiatives. These xTM systems can provide strategic traffic deconfliction, monitor vehicle conformance with respect to 4D trajectories, and greatly boost overall capacity of the

NAS. However, reacting to changes in flight plans and off-nominal situations is a major system integration challenge as information needs to flow seamlessly to an array of systems while maintaining situational awareness of the human participants. This encourages the transition from current day Air Traffic Services (ATS) to xTM, warranting a paradigm shift.

The types of services that will be available in support of AAM operations will likely evolve over time and the requirements for operator subscriptions will likely vary dependent on factors such as vehicle type and configuration, operation location, mission type, and others. One of the primary airspace services envisioned currently is the Provider of Services for UAM (PSU). This service provides support for operation planning, strategic deconfliction of flight paths, intent communication, messaging and notification, and maintaining the common operating picture. Additionally, there are other services that will provide airspace management support for weather, navigation, and communications services that are outside the scope of this paper.

4. Vertiport Services

Services supporting vertiport management will also likely evolve over time and may vary according to numerous factors. It is envisioned that many of these services and input data will be integrated with a system of systems to aid in vertiport resource management. This system is referred to as the Vertiport Automation System (VAS) that is an enabler for scalable density operations through the management of vertiport resources, scheduling and sequencing of vertiport resources and providing a means of coordination with external entities (e.g., Fleet Operators). Given the large number of operations from a relatively small location compared to large airports, vertiports will require a range of systems and functions to ensure safety of operations and required operational rates:

- Monitor the TLOFs and ensure their safety.
- Determine and communicate short- or long-term delays to incoming aircraft.
- Ensure safety and conformance of aircraft operating in vertiport environment.
- Establish situational awareness for the Vertiport Manager.
- Provide final authorization to land.

5. Arrival and Departure Procedures

Given that vertiports will more directly involve operations in the terminal area, they will have an associated set of procedures to impose structure and predictability for arrivals and departures. While UAM vehicles continue in their development and early testing cycles, the specifics on what the fully mature procedures and approach/departure characteristics will look like is currently in the early stages. However, there are assumptions that many of the features of traditional procedures and definitions will carry over in some form. Definitions of Initial Approach Fix (IAF), Intermediate Fix (IF), Precision Final Approach Fix (PFAF), and Missed Approach Point (MAP) are assumed to carry over to UAM and have importance to how operations are managed with respect to vertiports. Similarly, Approach and Departure Instrument Flight Procedures (IFPs) are assumed to help organize the prototyping and assessments.

6. Roles and Responsibilities

The execution and management of nominal operations as well of situations such as missed approaches in an AAM environment will involve a host of systems and human actors with complementary roles and responsibilities, some of which do not exist today. Below is a brief description of the roles and their assumed responsibilities with respect to the arrival and missed approach procedures that are the focus of this paper:

- *Fleet Manager:* Manages the strategic planning and resource management at the fleet operations level. Operations are scheduled, supervised, and managed in a supervisory capacity with communications and data exchanges with other actors (e.g., Vertiport Manager), as well as services for airspace management. It is assumed that fleets could include dozens of aircraft operating simultaneously.
- *Vertiport Manager:* With support from automation, services, and sensors the Vertiport Manager oversees operations at the vertiport including its surface and surrounding airspace. This position sets and manages the schedule in accordance with the capacity and resource constraints of the facility and in response to the environment and dynamic situations at the vertiport.
- *Flight Crews:* The team of individuals that manage individual aircraft that make up the fleet and oversee the execution of each flight.
- *Ground Crews:* The team of individuals that facilitate passenger and aircraft movements on the ground. Also responsible for flight line servicing of aircraft to include charging and inspections.

IV. Initial Autonomous Operations (IAO)

A. IAO Operational Environment

The operational environment for AAM in certain areas will likely be constrained due to urban settings and existing complex airspace structures in and around high-density airports. There may also be variability in the environment aspects, such as class of airspace, flight rules interoperability, weather patterns, air traffic flows, etc.; however, the full breadth of these factors is outside the scope of this paper. Instead, this paper will review the important operational environment characteristics relevant to the missed approach cases and discussion that will follow.

B. IAO Assumptions

This section conveys assumptions for the Initial Autonomous Operations (IAO) planned as the Mid-Term phase of Urban Air Mobility (UAM) growth for the 2028 timeframe. Overall assumptions are that there are a small number of vehicles being operated commercially and the number of operations-per-hour is well below maximum levels. This is due to several factors but is most significantly paced by the rate of integrated testing, operational experience, and limitations on various autonomous systems. Vehicles will be able to use Detect-and-Avoid (DAA) and other conflict management techniques to remain well clear of other UAM aircraft and traffic. This will be accomplished through ground-based/hybrid detect and avoid functionality, strategic traffic separation, and adequate procedures for off-nominal conditions.

Another assumption is that vertiports will have a procedural constraint that is only pertinent to the UAM aircraft and is similar, but not the same, to the Vertiport Volume (VPV) definition for farther term applications. The procedural constraint can be defined via Letters of Agreement (LOA) or Certificates of Authorization (COA) that would permit these specifically defined types of operations. Within this assumption, UAM vehicles arriving and/or departing the vertiport will use this constraint for a One-In-One-Out (OIOO) rule[12] adherence to ensure proper procedural separation in critical phases of flight. However, unless in an uncontrolled portion of airspace, ATC has the final authority over the operations flying in and out of that vertiport. The approach procedures will be connected to the UAM-specific IFR routes, where ATC will maintain their authority over safety of flight. However, in certain locations and situations, ATC may not be held responsible for providing separation services between arriving and departing UAM aircraft within the defined procedural constraint (subject to LOA/COA). Instead, a landing, for example, would be conducted at the operator's own risk similar to operations within airport non-movement areas today. The operator would leverage supporting systems and services to mitigate the assumed risk in accordance with the standards and requirements expected to be in place.

It is assumed that each vertiport is managed by a human vertiport manager (VM) with VAS support. The VM is responsible for the safe operations at the vertiport and will monitor operations in the vicinity of the vertiport. The VM can call for a suspension of operations if non-cooperative traffic was detected in the critical area of operations or issue delays to the aircraft scheduled time of arrival (STA) as needed. The VM/VAS will provide the “FATO Clear to Land” advisory, similar to a Fixed-Based Operator in airport non-movement areas. The VM/VAS can also close one, or all, FATOs at the vertiport if it is unsafe to operate on. Closures and delays are digitally communicated to the operators for subsequent risk mitigation. If sufficient infrastructure exists, the VAS may include sensors to aid in vertiport operations management such as cameras, machine vision, weather sensors, and airspace monitoring radar.

Vehicles may perform simple prescribed missed approaches in very low-density operations, which will be coordinated with the appropriate ATC facility and VM/VAS. Limiting the operations per hour will be needed to ensure well-clear and IFR/VFR separation requirements are maintained for IAO. In this context, missed approaches can be characterized by the number of other affected UAM aircraft. No more than 1 other UAM aircraft is assumed to be affected by another aircraft’s missed approach and that at least ~5 minutes of time will be available to adjust the affected aircraft’s trajectory.

Other assumptions include:

- Weather environment is clear of hazardous weather phenomena,
- Approaching vehicle is equipped with some level of onboard automation,
- Vehicle may be either onboard or remotely piloted by a Flight Crew/Operators,
- Vertiport has an established schedule with an assumed balance of demand and capacity, and

[12] This rule is synonymous to One-Aircraft-On-Runway rule commonly utilized by the Local Controllers as a safety-critical operational constraint. Due to flight profiles in these phases of flight for UAM aircraft being vertical and not horizontal as for fixed-wing aircraft, OIOO rule has to apply in three dimensions.

- Published procedures are in place to deliver operations from the enroute phase to the FATO with identified key waypoints and fixes.

The location of a vertiport will affect some aspects of the IAO operation. Traditional ATC will manage flights through the defined routes and provide landing authorizations into vertiports within Class-B, -C, -D. Vertiports in Class-G will make use of See-and-Avoid, Detect-and-Avoid, and Remain Well Clear from all traffic (cooperative and non-cooperative) on approaches and departures before entering the controlled environment.

V. Beyond IAO

The IAO discussion thus far has focused on nearer- to mid-term AAM operations and some of the assumptions underlying the concept. However, it is also useful to consider the further-term environment and associated concepts to ensure that there is a logical and natural bridge between the overall concept across time frames. The following section outlines some of the differences assumed and their contributions to missed approach handling.

A. Airspace

For the purposes of this paper, the airspace structures relevant for the missed approach discussion with respect to the vertiports' role in arrival operations will be presented. As described in the High-Density Automated Vertiport Concept of Operations [4], there are two key potentially concentric airspace structures envisioned surrounding the geographic location of a vertiport (see Fig. 3 and 4):

- *Vertiport Operations Area (VOA)*
  - Outer area of vertiport airspace where more than one aircraft can traverse it.
  - Includes most parts of the approach procedures (including Missed Approach).
  - Serves as the FATO-All-Clear and Resource Availability check.
  - Have established airspace fix-gates for airspace entry and exit.
  - Accustomed to the ATC-controlled airspace environment.
- *Vertiport Volume (VPV)*
  - Inner area of vertiport airspace.
  - Includes the very final part of the approach procedures where Missed Approach or balked landing can still be initiated.
  - *VPV Tier 1*: May only contain aircraft taking off or landing from the vertiport.
  - *VPV Tier 2:* May only contain aircraft taking off or landing from the FATO (i.e., OIOO rule).

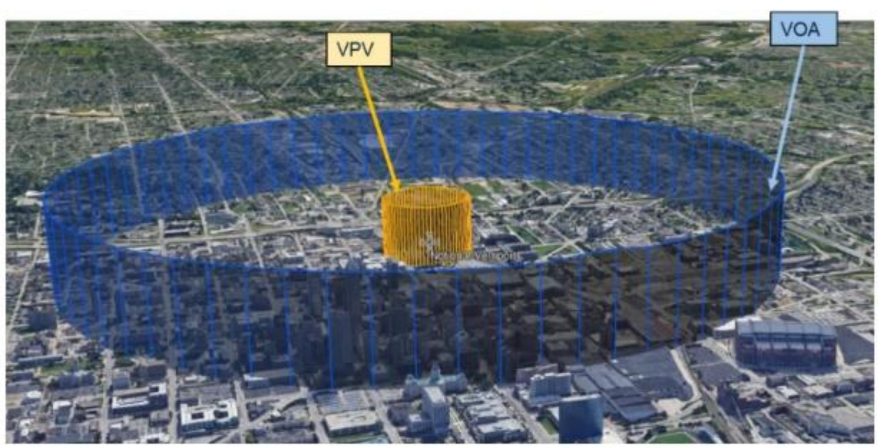

Fig. 3 Vertiport Operations Area (VOA) and Vertiport Volume (VPV) Airspace Structures (NASA HDV).

Being synonymous with the current airspace designations, VOA and VPV lateral dimensions will be based on the FATO location and the number of FATOs present rather than the vertiport as a whole. In other words, the center of FATO will coincide with the center of VPV and the center of VOA. However, this is only applicable to the vertiports with a single FATO. If there is more than one, each FATO has its respective VPV, while a VOA will be shared. Depending on the FATO spacing, the procedures in and out of the FATO will be designed appropriately to give enough separation at all phases of flight. In situations where both FATOs are closely spaced, proper standard operating procedures coupled with advanced airspace monitoring equipment (similar to Precision Runway Monitoring) shall be used to ensure safety in both VPV and VOA.

Understanding that these environments will be embedded within static airspace volumes designed for conventional aircraft operations, the shape, form, and dimensions of the VOA is likely to change or remain rigid to fit those static constraints. In other words, vertiports located close to the airports or in tight, unique urban areas might have a VOA (or even VPV) shaped to accommodate and co-exist with the nature of those environments.

Within NASA's HDV concept, two airspace structures were defined to scope the operational focus: VOA and VPV. However, to add an additional layer of safety for UAM operations within these airspace structures, the VPV may be further separated into two tiers: 1 and 2. VPV Tier 1 serves as the protection layer for the vertiports, where only operations in and out of that vertiport may enter that airspace. For example, single FATO vertiports may only have two aircraft in Tier 1 – one departing and one arriving; double FATO may have up to four, etc. VPV Tier 2 is designed to facilitate enforcement of the OIOO rule that ensures safety on the FATO and is synonymous with current safety regulations for runway operations. Figure 4 is a visual representation of the volumes and embedded procedures within VOA and VPV including the assumed patterns for sequencing.

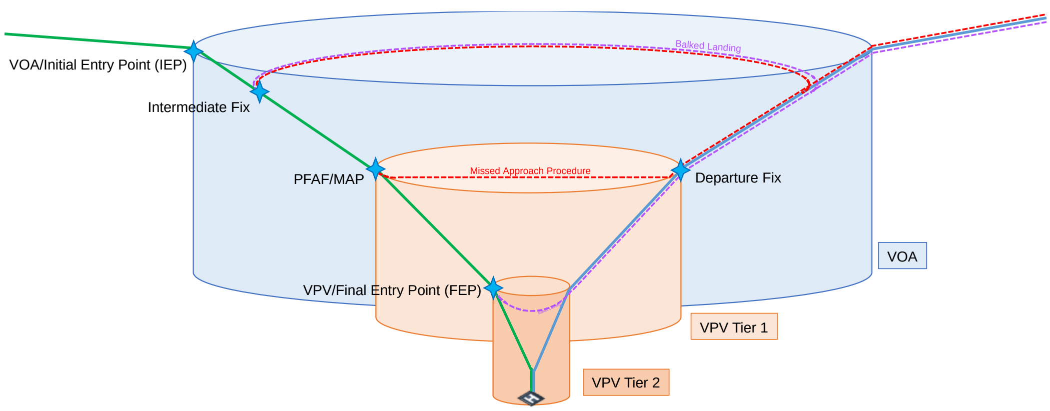

Fig. 4 Proposed airspace structure for the VOA and VPVs with associated procedures. (Wisk)

B. Beyond IAO Assumptions

This section conveys assumptions Beyond IAO envisioned as part of the further-term phase of UAM growth. The traffic density and rates of operations will be scaling more rapidly due to the development, growth, and trust in autonomous systems and technologies, such as autonomous DAA, integrated strategic/tactical traffic deconfliction systems, etc. A primary difference between Mid-Term and Far-Term is that increased capacity is realized through expanded use of automation, autonomous systems, and the integration of inter-operable services to manage airspace operations such as those referenced in terms of extensible Traffic Management (xTM) [5]. In this area, strategic xTM solutions are integrated to a level that the trajectories of multiple aircraft can be simultaneously and dynamically updated in response to off-nominal situations. Humans are observing automated traffic management systems with the ability to step in when and where necessary with the appropriate level of situation awareness and available response time.

VASs are expected to become more robust, enhanced by series of sensors in and around the vertiport continuously monitoring the vertiport surrounding traffic and VOA. The VAS will monitor:

- Systems to ensure nominal and off-nominal operations are performed safely, while being an integrated part of the xTM ecosystem.
- TLOFs and provide alerts to the xTM when hazards are detected.
- Conformance to ensure precise aircraft positioning within VOA with high-precision navigational solutions to complement or replace surveillance in GPS-denied areas.

UAM aircraft are expected to fly within defined airspace volumes, like corridors, interfacing directly with xTM providers or ATC, depending on the environment. These environments will be integrated with VOAs to ensure a smooth transition between phases of flight and safe handling of missed approaches. VOA and VPV airspaces will be constructed around the vertiports and integrated with existing airspace structures. These airspaces will be managed as part of the xTM ecosystem either by VAS, PSU, or a synergy of both for common situationally aware decision making and action by the interconnected stakeholders.

The VM, with support from the VAS with its integrated systems and services, is responsible for the safe operations at the vertiport and will monitor operations in and around the vertiport surface as well as within the VOA with the ability to manage traffic in that airspace. In that regard, the VM/VAS will provide the final approval to land. Vehicles will perform missed approaches in accordance with set procedures but will ultimately remain within the VOA as it will be sized to contain such procedures.

The location of the vertiport may affect some aspects of the IAO operation. However, it is assumed that the synergy between xTM and VOA/VPV airspace will be high to allow seamless transition of UAM aircraft within constrained Terminal environments with low to no impact on legacy ATC procedures and systems. Traditional ATC will be made aware of the operations and coordinated with in case of off-nominal situations that may not be contained within xTM.

VI. Nominal Approach Scenario

Before discussing the case of a missed approach in an AAM environment, it is important to first set the stage through a brief overview of what a nominal approach and landing sequence at a vertiport might look like and the assumptions in place as foundations of the scenario. Within this work the vertiport capacity is treated as a test condition or goal since the resulting ultimate capacity will be driven from off-nominal conditions yet to be tested.

It is critical to note that the actual nominal approach procedure (with fixes and IFPs) or landing sequence for IAO and Beyond IAO is very similar. The main difference will be in the airspace structures that are in place for that phase. At IAO, the operational airspace is either ATC-controlled or uncontrolled, where vertiports only provide guidance instructions. Beyond IAO, vertiports have dedicated airspace pockets (VOA/VPV) where more control can be assumed over the course of operations and traffic management.

Figure 5 presents a visual walkthrough of a standard UAM landing sequence under nominal conditions. A subsequent report will provide a detailed description of the procedure involved in the landing.

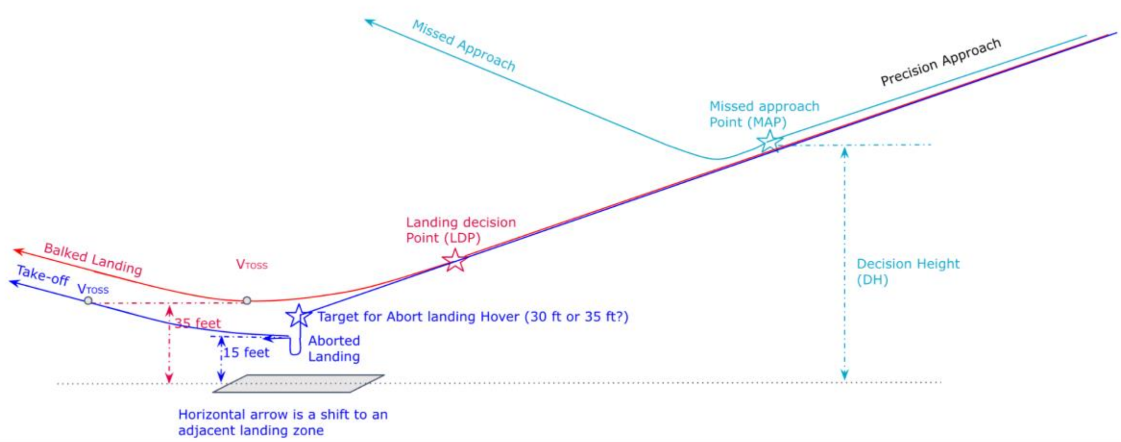

Fig. 5 Nominal approach and landing at vertiport. (Wisk)

VII. Missed Approach Scenario

Missed Approaches are a common occurrence in conventional operations and shall be applicable to anticipated UAM operations as well. The procedure with subsequent go around is usually preceded by a triggering event, potentially by the assigned vertipad for arrival being occupied, and the occupying vehicle not being able to clear the vertipad in time to safely accommodate the arrival.

At IAO, this procedure will be between the ATC, aircraft, and VAS if applicable. If an event is identified by the aircraft, ATC will be notified of the missed approach and asked for a clearance to either divert or make a second approach to the vertiport if VAS may allocate another slot. If the event is identified by the VAS, it will provide an advisory for a missed approach to the aircraft, after which, the same sequence of events will be completed. Slot reallocation can be pre-planned as shown in Fig. 6.

Arrival Time	Departure Location	Aircraft Designation
1106 AM EST	Vertihub A	Callsign E
1105 AM EST	RESERVE	RESERVE
1104 AM EST	Vertiport 1	Callsign D
1103 AM EST	Vertistop A	Callsign C
1102 AM EST	RESERVE	RESERVE
1101 AM EST	Vertiport B	Callsign B
1100 AM EST	Vertiport A	Callsign A

Arrival Time	Departure Location	Aircraft Designation
1106 AM EST	Vertihub A	Callsign E
1105 AM EST	RESERVE	RESERVE
1104 AM EST	Vertiport 1	Callsign D
1103 AM EST	Vertistop A	Callsign C
1102 AM EST	MISSED APPROACH	Callsign A
1101 AM EST	Vertiport B	Callsign B
1100 AM EST	~~Vertiport A~~	~~Callsign A~~

Fig. 6 Slot re-allocation for missed approach via vertiport scheduling.

Beyond IAO, the missed approach procedure shall be designed as part of the published vertiport approach procedures with associated instructions that prompt the aircraft to stay within the VOA boundary. As with missed approaches today, an aircraft can be queued back into the flow of traffic almost immediately or proceed to a fix and hold until an appropriate slot arises. Since the VAS has already allocated arrival slots for all aircraft, slot reallocation shall not be prolonged if communicated and addressed properly between the VAS and PSU.

A missed approach can be initiated by the VM, FM via PSU, aircraft, or aircraft operator for any reason. However, the reason for a missed approach shall be recorded by the advising entity for a further analysis and potential aviation safety reporting. In most cases, the decision around missed approach will be either by the aircraft (or pilot if piloted) or by the VM.

Based on the assumptions outlined regarding missed approaches, the following is a sample scenario that can be used to build from for further exploration and refinement of the concept and procedures: Before the aircraft enters the VOA, the VM and VAS are passively monitoring the aircraft progress to arrive as they approach the airspace arrival gate (fix) on time. Once the aircraft arrives at that fix and enters the VOA, the VM and VAS begin active monitoring of the aircraft as it progresses through the approach procedure. At the same time, the VAS confirms that the FATO is clear to land and that the estimated Touchdown Time still matches the scheduled slot. As the aircraft continues along its approach within the VOA, an off-nominal event happens due to:

- Severe or quickly changing hazardous weather conditions.
- Unstabilized approach where the aircraft cannot maintain a clear path.
- The aircraft cannot maintain a controlled path to the touchdown zone.
- Unexpected debris on the FATO.
- FATO or VPV incursion.
- Landing authorization has not been received or has been canceled.
- Wildlife in the VPV or on the FATO.
- UAS in the VPV or on the FATO.

It is important to note that missed approach procedures shall be initiated within the VOA portion of the approach up until the VPV entrance before the aircraft has fully transitioned from wingborne to rotorborne flight. VPV Tier 1 entry point shall coincide with the point to execute the missed approach - Missed Approach Point (MAP) - which could also coincide with a half transition point for most eVTOL aircraft. If the aforementioned off-nominal event happens as the aircraft enters the VPV Tier 2, a balked landing procedure will be performed. In either case, the current scheduled arrival slot at the vertiport becomes invalid and requires rescheduling or alternative actions.

The following decision scenarios shall be made rapidly and consider the event that triggered the rejected landing. If the event has a brief longevity, another approach attempt may be made. If the event has a lengthy longevity, the aircraft will likely divert to an alternate vertiport. In either case, a collaborative decision-making process shall involve VAS, PSU, and the Fleet Manager and/or aircraft operator depending on the time horizons. The resulting decision will be informed by the following criteria:

1. If another slot can be allocated at the arrival vertiport by the VAS within a reasonable time frame, an aircraft shall perform a circling approach and make another approach attempt.
2. If the slot is allocated by the PSU further in the traffic flow that will impose less time than the calculated diversion, then the aircraft shall be assigned that slot and make another approach attempt.

3. If the slot is not allocated in the traffic flow or if the allocated slot will impose more time than the calculated diversion and exceed aircraft endurance limits, then the aircraft shall divert to the pre-planned alternate vertiport in coordination with the PSU and VAS responsible for the alternate vertiport to ensure accommodation.

Scenarios 1 and 2 will likely keep the aircraft within the VOA or within the corridor airspace where no impact on traffic will be imposed. Scenario 3 will require use one of the airspace exit gates using defined procedures, and obtain a new 4D trajectory authorization from PSU to the pre-planned alternate vertiport.

As VAS and PSU have continuous exchange of data and information, slot reallocation may happen immediately with proper instructions and coordination. In certain situations, the VAS may impose a localized constraint similar to a Traffic Management Initiative, where speed restrictions are imposed on the arriving aircraft by the Fleet Manager in response to PSU messaging based on the VAS-PSU exchanges. Other traffic management techniques facilitated by digital data exchanges may be applied depending on the situation to ensure that the flow of traffic remains orderly and safe. For example, the PSU may facilitate the reroute of Missed Approach aircraft to more downstream schedule slots or to an alternate vertiport in accordance with a decision-making process -manual or automated- that accounts for safety and efficiency.

VIII. NASA Prototyping and Assessment

As the concepts of UAM and AAM more broadly are further developed and refined, it is important for capabilities and test environments to be instantiated to provide deeper insight and understanding of the many complexities and interactions to be considered in a representative environment. NASA's HDV Sub-Project is dedicated to the development and testing of a reference automation architecture to enable scalable operations at higher levels of density with a focus on vertiports and their terminal areas. In support of its objectives, the HDV team has 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. In addition to the airspace and vertiport management systems incorporated into the testing environment, surrogate sUAS with onboard automation are employed to facilitate the performance of rapid prototyping and high-fidelity assessments of an end-to-end UAM Ecosystem rapidly and at low-cost [6-10]. The intent, however, is to scale the airspace design and procedural time horizons to align with the larger eVTOL aircraft flight characteristics as they become more readily available for integrated testing.

In support of its goals and objectives, HDV has been in execution of a series of scheduled work packages that builds in complexity and density of operations as the ecosystem under test is expanded. Each HDV schedule work package, lasting approximately 14 months, builds upon the previous UAM Ecosystem prototype. HDV testing includes human+hardware+in+the+loop (HHITL) simulation combined with follow-on live vehicle flight testing in a spiral development approach. The HDV team has been developing reference systems and incorporating technologies to test through large-scale simulation first, followed by flight tests that build upon the simulation work while integrating onboard vehicle systems in a live test environment. In 2023, as part of its Scalable Autonomous Operations work package, HDV unveiled version 1.0 of a VAS that provides the newly introduced Vertiport Manager (VM) role/position the ability to manage certain aspects of the vertiport, such as Final Approach and Take Off (FATO) closures and arrival delays. The actions of the VM through a user interface connected with the VAS are communicated externally for ingestion by other integrated components such as the Fleet Management system for alerting and response.

To provide a comprehensive and representative test environment, the HDV Sub-Project leverages multiple NASA facilities that are inter-connected across the United States at NASA Langley Research Center (LaRC) in Virginia and NASA Ames Research Center (ARC) in California. Figure 7 illustrates the HDV testing environment that includes the Remote Operations for Autonomous Missions (ROAM) sUAS control lab at NASA LaRC. ROAM is configured with 6 configurable workstations that can be used for ground control station operators, vertiport managers, range safety officers, flight test directors, etc, and can control either simulated or live aircraft. An expansive reconfigurable forward video wall provides integrated situational awareness for the team. The systems integration and validation lab (SIVL) at NASA LaRC generates 6-degree of freedom (6DOF) simulations of representative sUAS aircraft that are integrated with the actual aircraft hardware and software used for flight testing. Onboard autonomous systems are also integrated in testing such as the Integrated Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS) for Detect and Avoid (DAA) functionality and Safe2Ditch autonomous contingency management systems.

The Airspace Operations Laboratory (AOL) at NASA ARC is used to provide Fleet Management (FM) functionality and serves as a Flight Operations Center (FOC). Control and management of simulated Multi-Aircraft Control Systems (MACS) aircraft are also supported from the AOL, which supplies the targeted traffic densities and scenario complexities necessary to test specific concept elements addressed in each scheduled work package. The

Autonomous Vehicles Applications Lab (AVAL) at NASA ARC serves to support trial planning system development and overall test quality monitoring.

HDV flight testing is performed at the City Environment Range Testing for Autonomous Integrated Navigation (CERTAIN) at NASA LaRC. Up to 5 simultaneous physical aircraft can be operated and integrated with higher density simulated aircraft to fully assess the UAM Ecosystem prototype. Flight testing planned for 2023 will employ a mix of extended and beyond visual line of sight (EVLOS and BVLOS) operations. During simulation and flight testing, all teams at the distributed facilities have real-time views of the operations and data exchanges via the many visualizations that have been developed. Figure 8 provides an illustration of a Vertiport Manager display that displays the vertiport locations and their associated approach and departure routes with highlighted symbology. The display viewpoint is fully adjustable to provide views from user-selected viewpoints. This provides situational awareness of where the aircraft are within a vertiport operations area and their trajectory conformance. Additions to provide 4D symbology for conformance monitoring is planned.

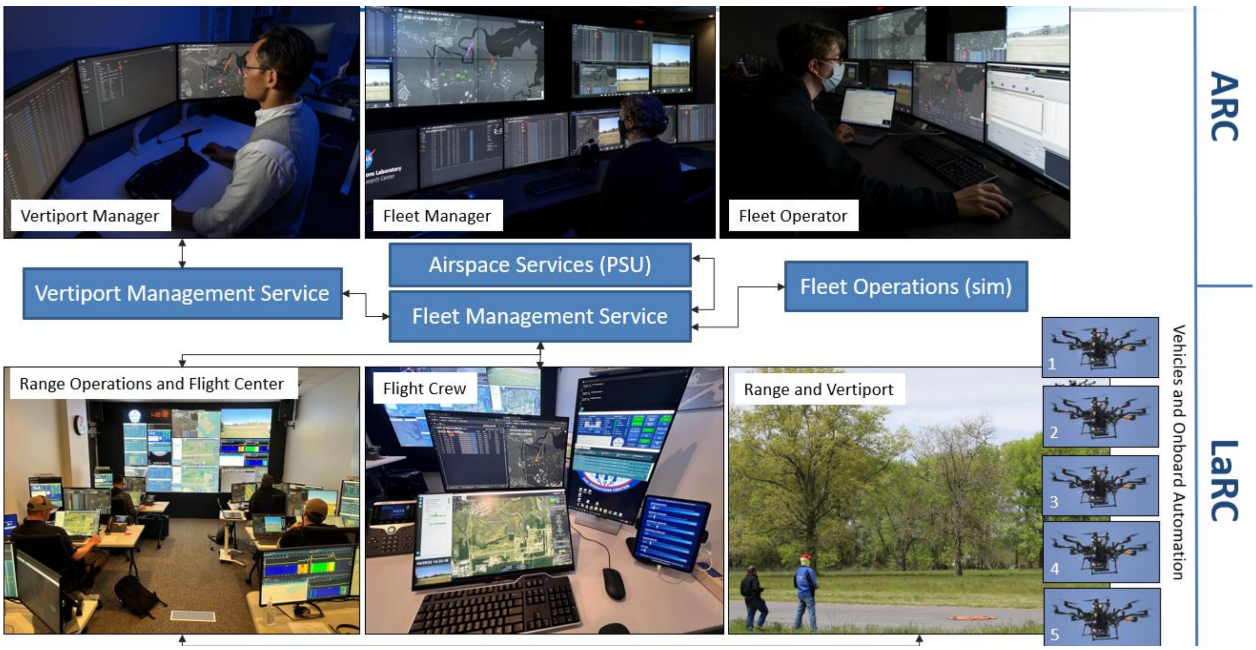

Fig. 7 High Density Vertiplex Sub-Project UAM Ecosystem prototyping and assessment.

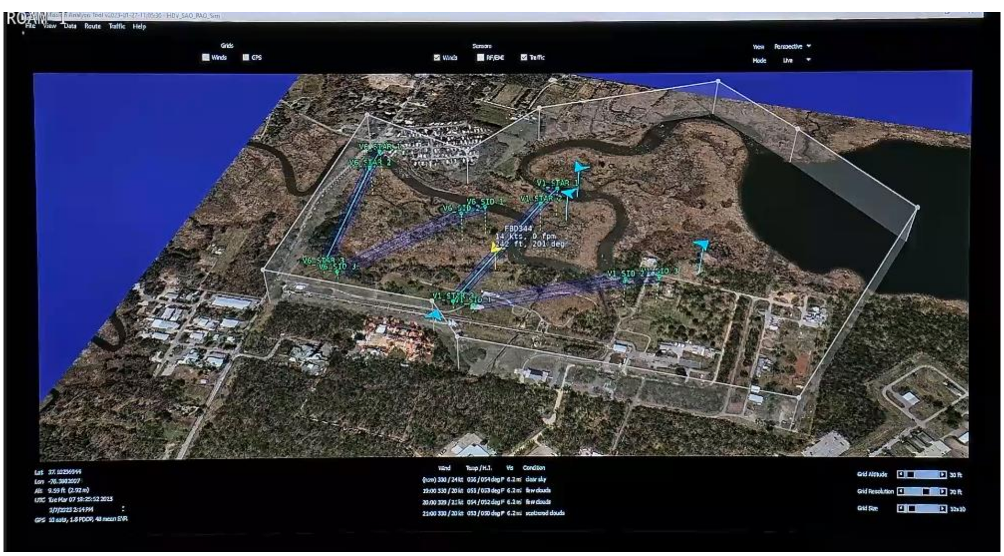

Fig. 8 Example of Vertiport Manager display developed for HDV testing.

The HDV Client display, shown in Fig. 9, is another example of a real-time interface that was developed to provide specific capabilities to support the Fleet Manager, Vertiport Manager, and the Ground Control Station Operator in configurations respective of the participant roles. The client interface generally displays the vehicle location in real time through updated position reports from simulated and live aircraft. The magenta lines on the map display represent the trajectories that the vehicles are intending 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 VPV and VOA concentric circle airspace structures (in grey). An Operations table is also available that displays each of the operations in the system with details such as the state (e.g., Active or Closed), departure and arrival times, and flight phase/status. Each row of the Operations table provides the appropriately scoped user the ability to expand and interact with that operation depending on the user role. A follow-up publication is planned that will describe this system in greater detail.

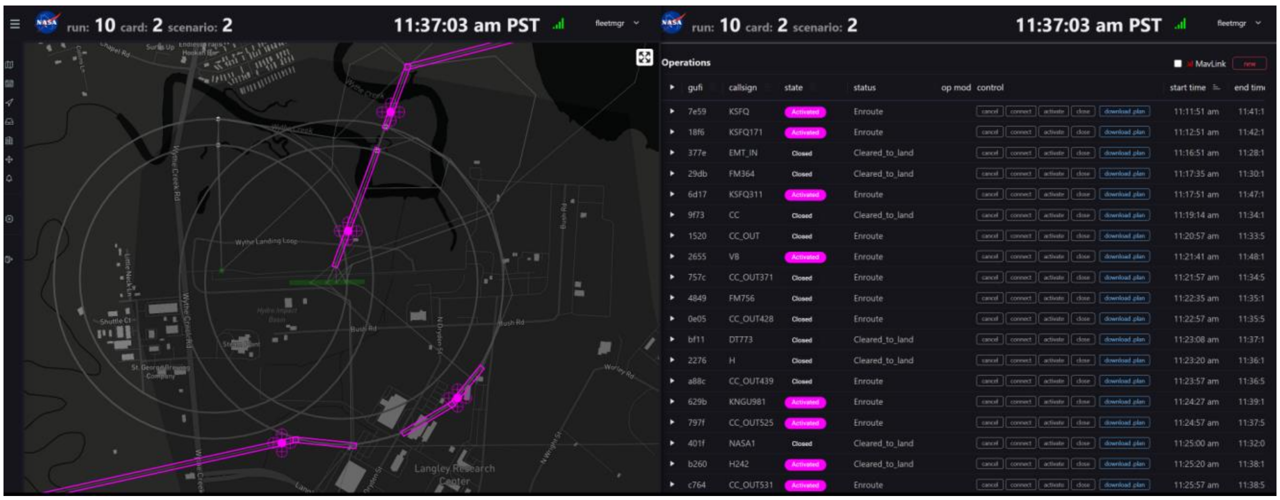

Fig. 9 HDV Client display developed to support research and testing.

With respect to the focus on the missed approach concept and procedures as part of the NASA HDV and Wisk collaboration, the test environment described provides a flexible framework in which to implement and test mutual areas of interest. The flexibility provides an opportunity to examine the differences in perspectives as well as the timeframes envisioned from the nearer-term IAO to the further-term Beyond IAO where HDV has been focused. The messages and information exchanges needed to support nominal vertiport terminal area operations as well as missed approach and divert procedures can be tested from an architectural standpoint as well as a human factors standpoint where the display of relevant information to participant roles can be assessed as part of a comprehensive view of scenarios that play out in real-time through simulation and live flight testing with surrogate aircraft and dedicated flight crews. As part of the current work package, missed approach procedures and divert scenarios are under test based on a further-term view. Results of that work will be published in subsequent venues pending completion of HDV testing.

IX. Conclusion

The Advanced Air Mobility (AAM) concept is helping to usher in a new age in aviation that holds potential to change the way people commute, cargo is transported, public good missions are carried out, and many other aspects affecting the daily lives of people across the globe. This is a revolutionary and unique form of aviation that will be much more integrated into society with numerous access points compared to current airports. The envisioned AAM/UAM Ecosystem will include: 1) Vertiport Automation Systems, 2) Onboard Autonomous Systems, 3) Ground Control and Fleet Management Systems, and 4) Airspace Management Systems. Human interaction with the UAM Ecosystem will evolve as technology evolves, is tested, and is fully integrated into the overall system. The ability of the UAM Ecosystem to respond to changes in plans and off-nominal situations is a primary challenge. Human roles will evolve from being in the loop to being on the loop. How the disparate elements integrate and communicate with each other and how the human participants interact with the system is a major area of research, development, and testing at NASA and Industry. Results from HDV rapid prototyping and assessment of the UAM Ecosystem will help shape future research and accelerate the timeline towards actual implementation. The

Wisk/NASA collaboration provides a unique opportunity to evaluate both nearer-term Initial Autonomous Operations as well as the Future-Centric Operations that leverages the experience and perspectives of each organization. The results of this collaboration, however, are not intended to advance the interests of each organization but are instead intended to contribute to the larger conversation in AAM and benefit the community as a whole.

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