Vertiport Management from Simulation to Flight: Continued Human Factors Assessment of Vertiport Operations

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The Urban Air Mobility concept envisions a new future for transportation in urban environments, primarily focused around vertiport operations. A vertiport refers to an identifiable ground or elevated area used for the vertical takeoff and landing of an aircraft. One critical role within vertiport operations that has been proposed but is under-researched is the vertiport manager. The vertiport manager is expected to manage the ground-to-air operations at the vertiport, but their precise responsibilities, tasks, and challenges are currently undefined. The goal of the High Density Vertiplex Subproject at NASA is to develop and test technologies, concepts, and architectures that will support the infrastructure needed for terminal environments around vertiports. Our previous work investigated ground control station operators performing simulated and live flight operations within a remote operations environment. In the current study, we extended from our previous work to explore the role of a vertiport manager. Specifically, we investigated five participants serving as a vertiport manager across both simulated and live flight operations. We performed multiple knowledge elicitation techniques, a thematic content analysis of qualitative data, and naturalistic observations to create a list of insights, design and training recommendations, and a simplified cognitive task diagram of the vertiport manager's primary task. Findings from this study are discussed within the context of the current debate on the degree to which this role should be automated. A third alternative is suggested to allow a human vertiport manager to be successful by teaming with increasingly autonomous systems, designing the role to improve safety and efficiency of Urban Air Mobility operations.

I. Introduction

Advancements in modern technologies enable new possibilities for adding additional aircraft classes and diverse missions to the National Airspace System (NAS). These advancements provide the ability to develop new concepts of aviation transportation operations, such as Urban Air Mobility (UAM). UAM envisions the large-scale use of small electric Vertical Take-Off and Landing (eVTOL) aircraft to transport goods and passengers within an urban environment [1]. To actualize the UAM vision, it is necessary to develop and research the physical, technological, and human infrastructure required. The physical infrastructure represents the construction of ground facilities known as vertiports that provide takeoff and landing zones while the digital infrastructure could represent a range of technologies

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from traffic management to communications [2]. Although the human infrastructure requirements have been theorized [3], this aspect of UAM infrastructure remains understudied. At NASA, the High Density Vertiplex (HDV) subproject is dedicated to the research and development of the Vertiport Automation System (VAS) and the required roles and infrastructure for high volume UAM operations, such as passenger transport or cargo delivery. One important aspect of this work is to identify the “human factors” associated with vertiport operations. Previous work focused on the initial prototypical build and analysis of a remote uncrewed aerial system (UAS) operations center to perform UAM operations [4]. The prototype led to a large-scale development of a usable and functional testing environment known as the ROAM (Remote Operations for Autonomous Missions) UAS Operations Center [5]. The next step was to test professional operators performing various representative UAM missions, both simulated and live, under normal visual line of sight and extended visual line of sight conditions [6, 7]. The present work is a continuation of prior research focusing on the human’s role within remote vertiport operations.

Vertiports are a necessary component to enable UAM operations. Vertiports are defined as an identifiable ground or elevated area, including buildings and facilities, used for the takeoff and landing of vertical take-off and landing aircraft [3, 8]. Yet, vertiports as a concept are not new. The United States has a long history of trying to implement vertiport operations into the NAS. Publications regarding the development and design of vertiport infrastructure can be traced back to 1967 [9]. During that time, vertiports were predicted to be fully operational and forecasted to handle five million yearly passengers by 1975. This prediction was predicated on increasing helicopter operations in the NAS. However, helicopters are expensive to operate with multiple points of failure, making them a less profitable vehicle for passenger transportation [10]. Over two decades, from the 1990’s to the 2000’s, there was a resurgence of interest in vertiports as technological advancements produced tilt-rotor aircraft that could cruise as a fixed-wing aircraft and perform a vertical take-off and landing [11, 12]. Recently, the development of electric vertical take-off and landing (eVTOL) aircraft that may be managed with increasing degrees of autonomy has reinvigorated efforts to design, develop, and actualize vertiport operations into the NAS. Unlike prior attempts, the electrification of the aircraft can make the aircraft safer and less costly to maintain, improving its viability as a long-term solution for passenger transportation (10). However, before these eVTOL aircraft can be seen flying over cities and houses, more research is required. Therefore, these operations currently only exist in a conceptual form until the data necessary for certification and regulation are collected.

The UAM concept of vertiport operations includes a variety of facilities and complexes not limited to vertiports. Two of the various facilities conceptualized within UAM operations are vertipads and vertiplexes. Vertipads represent the individual take-off and landing pads that may exist within a vertiport. A single vertiport can hold a large range of vertipads determined by the operational resources available. In a similar concept, vertiports are to a vertiplex as vertipads are to a vertiport. A vertiplex is a localized area that contains multiple vertiports that are generally considered to be interdependent. Although there are other facilities conceptualized within the UAM vision, only vertipads, vertiports, and vertiplexes are relevant for this work. For more details on the various facilities theorized for UAM operations, see [13].

Research to develop vertiports capable for UAM eVTOL operations is in its infancy, yet there are many works describing the infrastructure, roles, and architecture necessary for arrival and departure operations (for overview see [14]). One critical role that is expected but under-researched is the vertiport manager (VM; [13, 15, 3]). The vertiport manager is tasked with “managing ground-to-air operations at the vertiport, ranging from landside management to monitoring vertiport airside surface conditions” [15]. However, specific determination on the precise tasks, responsibilities, and ultimate role of the vertiport manager is undefined. Additionally, as development towards vertiport operations continue, there is an active debate on whether the vertiport manager role should be filled by a human, should be shared between a human and an increasingly autonomous system, or if it should be fully automated. There is a dearth of research necessary to assist designers, engineers, and policy makers in deciding what role the vertiport manager will take.

In this paper, we explore the role of a vertiport manager within a remote operations environment across both simulated and live flight operations. Five participants monitored five vertipads across three representative vertiports in a vertiplex located at the NASA Langley City Environment for Range Testing Autonomous Integrated Navigation (CERTAIN) range. Participants were exposed to five operational scenarios designed to explore system and human performance across different levels of complexity and difficulty. Several knowledge elicitation techniques and cognitive interviews provided insights on the role of the vertiport manager.

II. Method

Following the method outlined in our previous work [16, 7], this study was exploratory in nature. We sacrificed experimental control to achieve a high degree of ecological validity by observing participants performing tasks in an operational environment. Therefore, the nature of this study was to explore and discover how these operations naturalistically occurred rather than to manipulate and generalize to overall theory. Details of the full data collection plan, testing procedures, vehicle specifications, simulation characteristics, and operation characteristics are described in [17, 18].

Apparatus & Materials

ROAM UAS Operations Center. The ROAM UAS Operations Center [5] is the remote facility that was used to conduct both simulated and live flight operations. For a full in-depth review of the ROAM operations center, see [5].

VM Workstation. The VM workstation was the primary information and interaction location for the VM [3]. The workstation was designed to keep the displays of information simple and in a consistent presentation format. VMs used three physical displays to monitor and manage their vertiports. The displays were presented on three separate monitors with a three-dimensional (3D) visual display of the vertiports on the left screen, a vertiport scheduler and interactive tool on the center screen, and the right screen containing time information, video feed of the vertiports, and an operational utility for data collection. Although participants followed the general setup as listed, they were encouraged to modify their display arrangements as necessary. These modifications resulted in slight changes to the size and layout of the displays but not to the content presented within each monitor.

Participants

Five participants were sampled from NASA's staff. Participants were selected to collect data from a range of professional backgrounds and experiences. Four of the five participants were experienced with UAS missions. Their experiences ranged from, but were not limited to, managing safety and risk of live UAS flight operations at NASA to performing operations in a commercial setting. The inexperienced participant was selected to elicit information on how a novice would interact as a VM. However, although the fifth participant was inexperienced with UAS operations, they held experience in human-system integration, and thus were able to provide a different but valuable insight. Participants did not receive any direct benefits for participating and all participation was voluntary. This research complied with the American Psychological Association Code of Ethics and received approval by the Institutional Review Board at NASA.

Operational Scenarios

Participants monitored and managed five vertipads at 60 operations per hour across five operational scenarios. Both simulated and live-flight operations used the same operational scenarios. Scenarios included up to three vehicles and three remote participants operating from ROAM under extended visual line of sight (EVLOS) conditions. EVLOS is a term used at NASA to describe the intermediary stage as flight operations transition from visual line of sight (VLOS), where all critical mission personnel are in the field, to beyond visual line of sight (BVLOS), where no critical mission personnel are in the field, excluding the vehicle servicing crew [19]. Under EVLOS conditions, field personnel are incrementally moved out of the field but maintain a pilot in the field that can take over control of the vehicle and serve as the pilot in command. For live flight operations the number of vehicles in simultaneous flight ranged between two to five while the remaining vehicles required for 60 operations per hour were simulated. Mission altitude for vehicles within these operations were limited to 350 feet above ground level.

Each operation was conducted using a vertiplex at the NASA Langley CERTAIN range. The vertiplex had three vertiports. Although there were three vertiports to manage, the operations prioritized vertiport one (VP1), with vertiport two (VP2) and vertiport six (VP6) requiring less management. VP1 consisted of three vertipads and was the primary vertiport for all incoming traffic, both simulated and live-flight. VP2 consisted of one vertipad but was not used for any incoming or outgoing traffic. VP6 consisted of one vertipad and was used for the takeoff of two live vehicles and a landing site for diverted traffic. The five operational scenarios are presented below.

Nominal Flight. Flight was executed per intended flight plan.

Missed Approach. A medical emergency on one vehicle required another vehicle to perform a missed approach maneuver. A missed approach is when, after an initial approach, a vehicle must perform a "loop" to return to the external airspace of a vertiport and attempt the approach again. A missed approach can occur for various reasons, such as a vertiport closure, a vertiport being occupied longer than expected by a previous arrival, or the need for expedited landing of another vehicle with an onboard emergency. The VM managed the schedule of vertipads to determine when a missed approach is possible. In this case, the action of a missed approach was issued because of a short closure of the vertiport by the VM.

Speed Change. A short closure of the vertiport by the VM required incoming vehicles to decrease their speed.

Divert. A long closure of a vertiport by the VM required incoming vehicles to land at a different vertiport than originally intended.

Combined: Missed Approach, Divert, & Speed Change. A long closure of a vertiport by the VM required incoming vehicles to land at a different vertiport, engage in a missed approach, and slow their speed. This scenario was the most complicated and was intended to simulate a worst-case scenario.

Vertiport Manager Task

The vertiport manager was responsible for several tasks including monitoring all incoming and outgoing traffic and managing the closure and opening of vertipads/vertiports. To complete these tasks, VMs had to monitor multiple streams of information such as but not limited to a 3D visual display of the vertiports, live video feeds of the vertiports, a vertiport scheduler, and communications from other actors within the operations. The actors included operators such as a fleet manager, ground control station operators (GCSO)s, and the vehicle service crew members on the vertiport. To help the vertiport manager interpret all of the inputs from these different places, the VAS was used to reduce the workload. The VAS gathered information coming into the vertiport and displayed it to the VM through the traffic management system known as xTM Client. Using the xTM Client, the VM could view the current schedule of the vertiport down to the individual pad level, could see the status of each vertipad (occupied, open, closed), and could issue a closure command to a vertipad.

Human Factors Data Collection

To understand the role of the VM within our operations, we conducted several knowledge elicitation techniques. First, participants were provided an open-ended digital questionnaire after each scenario. These questions asked "what went right?," "what went wrong?," and for general comments, with an open text box as the response option. Participants were asked to provide as much detail as possible about their experiences during these operations. In particular, participants were directed to consider the cognitive aspects of their experiences such as their goals, perceptions, and the challenges they faced within these operations.

Second, after all operations were completed for the data collection campaign, VM participants engaged in an After-Action Review (AAR) discussion with researcher team members. An AAR is a knowledge elicitation method which uses a discussion of an event to ultimately understand and improve performance [20]. AARs are traditionally performed by military organizations to improve task performance as a training exercise. In this study, we performed a modified AAR to discuss specific key events and insights gained from the vertiport operations. The goal of the AAR was to elicit knowledge from the participants to explore the VM's role within these operations. Participants were asked to engage in an open discussion on what they experienced and the cognitive aspects of their experience.

Finally, VM participants engaged in cognitive interviews with the researcher. During these interviews, participants were exposed to the critical decision method [21] and an applied cognitive task analysis (ACTA; [22]). Participants also engaged in a knowledge audit and simulation interview resulting in the creation of task diagram [23] presented in the latter part of Section III. These interviews lasted approximately two hours and did not follow any standardized structure or format. The intention for the interviews were to discover insights about the VM role rather than generalize to overall psychological theory.

III. Analysis

Thematic Content Analysis

We conducted a thematic content analysis to analyze participants' responses from the open-ended questionnaires. A thematic content analysis is a method for analyzing qualitative data that provides flexibility and structure to discover patterns within a data set [24]. The current data set consisted of 506 individual statements from the post-scenario questionnaire. Each statement was analyzed and coded. Coding comprised the following:

- All statements were coded into seven initial codes based on higher ordinal grouping qualities. These codes were used as an initial step in organizing and becoming familiar with the data. These codes were training, display design, procedural, information requirements, noticing errors, noticing nominal missions, and other.
- After the initial codes, each statement was re-coded into themes consisting of:
  - pictorial realism
  - situation awareness or sensemaking
  - designs for pre-attentive processing
  - maintaining attention
  - coordination
  - managing uncertainty

- noticing errors
- gulf of execution
- operational procedures
- mapped coding
- proximity compatibility principle
- multiple stages for vertiport
- developing mental models
- time demand
- role requirements
- naturalistic decision making
- noticing success
- limitations
- communications

- The aforementioned themes were constructed using the theoretical concept of macrocognition which encompasses the cognitive functions and processes most relevant to real-world tasks [25]. Macrocognition refers to the mental activities required to effectively complete a task or reach a goal in practical, natural settings. The key macrocognitive functions, such as decision making or sensemaking, define the objectives individuals aim to achieve. Meanwhile, the macrocognitive processes such as managing attention or handling uncertainty and risk outline the methods used to accomplish those functions.
- The purpose of this work was to gain insights and understanding about the role of a VM. Themes were analyzed and transformed into insights that are discussed below. Here an insight is defined as a non-obvious inference gained from existing data that can be used to improve understanding, problem solving, and innovation [26]. A sub-set of participant responses are presented to illustrate the insight generated. To see a similar coding method used to analyze qualitative data gained from commercial aviation pilots, see [27].

Insight 1: VMs need time to make decisions and time demand is a primary factor for vertiport management.

- Time demand and time pressure were one of the most frequently reported issues for the VMs (scenarios targeted 60 operations per hour). However, time demand was only an issue at the critical moment when the VM needed to act during an off-nominal event.
    - Ex: "[I] felt time pressure to get them all closed as soon as possible…"
    - Ex: "This role seems time sensitive especially in the case of a hazard on the vertipad…"

Insight 2: VMs require time progression information about an aircraft's mission state and their intent.

- One important goal for the VM was to verify that the current operations were going as expected. By a glance, the VMs wanted to know what an aircraft was intending to do, what vertiport it was going to, what vertipad it was scheduled for, and where the aircraft was on its mission path including a timer of when it was expected to land.
    - Ex: "Visualization tools really desired to show [the] train of aircraft arriving at my vertiport"
    - Ex: "Having the approach / missed approach / [Standard Instrument Departure Routes] SID / [Standard Arrival Route] STAR plates would be helpful as a VM to predict flight path of the inbound and departing aircraft."
    - Ex: "The intersection of take-off and landing makes me need intent for both to ensure when they meet at the pad they do not collide."

Insight 3: *Role ambiguity and lack of training increased uncertainty and error*.

- VMs received a quick brief about their role, task, and responsibilities as set by prior concepts of operations for a vertiport manager [15]. However, the VMs were not explicitly trained on their role. The ambiguity of their role in the operations and lack of training contributed to errors in monitoring, response time, and the omission or commission of incorrect interactions with their displays.
    - Ex: "I lost track [of aircraft] while closing [the] pads but feel like I could improve in the future with practice."
    - Ex: "I do not feel comfortable calling [a mission abort], [I'm] not even sure if that is desired due to [the] complexity of testing and [the] desire for data..."
    - Ex: "I dragged down using the side scroller and realized that went too far down so I had to scroll back up -- caused some delay"

Insight 4: Trust and knowledge of the procedure helped the VMs manage uncertainty.

- The VMs relied on their knowledge of the procedures and intent of the aircraft to manage their uncertainty. For example, in one incident an aircraft was not descending as the VM expected it to do. But, when the VM realized the aircraft was performing a missed approach and intending to fly over the vertiport, they were able to determine if it was a threat requiring a closure of the vertiport or not.
    - Ex: "Knowing that [the aircraft's flight path] was following the procedure provided my confidence that it was not an issue for my incoming or departing traffic."

Insight 5: Procedures, checklists, and training are required for determining separation, safety, and decision making.

- The VM is primarily a safety role. Their ability to serve as a resiliency factor within vertiport operations is reliant on their ability to notice errors when they occur and make appropriate and effective decisions. To make these decisions, they require a series of procedures and/or checklists that serve as the criteria for decision making. Additionally, training to build the VM's expertise in the operations and procedures could facilitate better performance in noticing anomalies and making better decisions.
  - Ex: "[I need] procedures, numbers to call, people to contact in the event of unexpected/off-nominal occurrences"
  - Ex: [I] need a checklist for [the] VM to use (both opening and recurring) to make sure vertiport is safe for operations.
  - Ex: [I] need criteria for [the] VM to use to determine if the Vertiport/Vertipad should be closed.

Insight 6: Communication can support sensemaking for off-nominal events.

- When an off-nominal event occurred, the visual displays did not always provide information that could help a VM understand why it had occurred. VMs listened to the pilots' communications to improve their understanding of why the off-nominal events occurred and how the situation was going to unfold.
  - Ex: "NASA 2 did not show up on [my displays] so having the cameras and the communications helped with being able to understand what NASA 2 was doing"
  - Ex: "Communications provided [the] best [situation awareness] for indicating a change in the flight operation."
  - Ex: "For VM, listening to pilot communications and understanding who is doing what is important."

Insight 7: Communication between the VM and the GCSO can foster better coordination.

- VMs preferred the ability to communicate with a GCSO to coordinate mission efforts. In one scenario, a vehicle was set to land at a vertipad that had recently closed but was awaiting an imminent reopening. The GCSO engaged in a divert a few seconds before the vertipad reopened, an unnecessary action that would have been resolved through better communication.
  - Ex: "The lack of ability to communicate to GCSO led to an unnecessary divert."
  - Ex: "[I] need [the] ability to communicate [the] opening [of a vertiport] to [a] GCSO to let them know so that they can plan their mission accordingly."
  - Ex: "As VM, [it] would be nice to be able to communicate the reason for the closure with the pilots."

Insight 8: VMs want the ability to close all vertipads within a vertiport at once.

- In the current setup, each vertipad had to be closed sequentially. However, there may be events where an entire vertiport must be closed at once and this closure is urgent, creating the need for a "close-all" button.
  - Ex: "Is there any way to close the entire vertiport? If not, that should be something the VP manager should be able to do."
  - Ex: "I would want a button to close all vertipads at once."

Insight 9: Providing additional vertipad states can provide useful information to the VM.

- VMs requested more information about the vertipad states outside of open and closed. Providing the VMs with additional states for each vertipad may offer useful information to help facilitate their sensemaking, decision making, and planning among other macrocognitive activities.
  - Ex: "Vertiport statuses [are] more than binary: Pre-flight, Loading, Ready for Launch, Launching, Taxi Out, Taxi In, Landing, Unloading, Clear."
  - Ex: "It would be great to see that a vehicle has been moved off [of] the pad. This means the last position I can see should be off the pad."

Insight 10: Vertiport and airspace monitoring without an active role can increase boredom and make the task more difficult.

- VMs reported maintaining attention was difficult and boring when their task was to monitor a nominal operation with no interactions. The addition of audio communications allowed them to become more engaged in the operations. Additionally, including more active monitoring features, such as marking traffic, was desired.
  - Ex: "[The] VM role is hard to focus [on] with nothing to do."
  - Ex: "Without common voice channels to listen to during waiting periods, it was very boring leading to a very different experience with and without listening to all general voice communications."

- Ex: “It would be good to mark traffic I am observing or have observed, good to know if there is traffic that is new that I didn’t have a chance to get info on”

Insight 11: Understanding ground movements were of equal or greater priority to understanding air movements

- Low awareness for ground movements, personnel, and grounded aircrafts were one of the primary concerns for the VMs.
  - Ex: “I would want to "confirm pad is clear" prior to arriving aircraft beginning descent OR transitioning OR before last point for missed approach.”
  - Ex: “[I had] no [Situation Awareness] on ground movements…”
  - Ex: “Pads need to be cleared after landing ASAP…”

Insight 12: Different phases of the operation had different informational requirements, potential hazards, and response options to conflicts.

- Vertiport operations have different phases that can be categorized by factors such as spatial location to the vertiport, temporal demands of mission, and the state of the mission to list a few. Based on the vehicle’s location within each phase of operation, the VM will sample different information and anticipate different hazards.
  - Ex: “I relied heavily on [my video feed], as well as [my 3D visual display] to make decisions whether I should be concerned about tie ups during landing and takeoff.”

Insight 13: Monitoring and noticing both spatial and time separation is integral for vertiport operations.

- Two of the most important tasks reported by the VMs were to maintain an awareness of both spatial and temporal separation between the aircraft.
  - Ex: “[The] 3D visual markers in [my 3D display] with procedure visual aids were very helpful for me to see [if] another vertiport departure was within my vertiport airspace.”
  - Ex: “[The 3D display’s] ground circles as a function of time in addition to the altitude bars would be helpful to verify separation is good or bad when observing.”
  - Ex: “It should be easy binary to know if separation based on time is being reached or not.”

Task Diagram

In this section, we present a simplified cognitive task diagram of the role of the vertiport manager. A task diagram is one tool within the applied cognitive task analysis toolbox that provides an overview of the task, identifies the cognitively complex aspects of the task, and can be used to frame the rest of the analysis [23]. The cognitive task diagram was created as a representation of the information discovered from the knowledge elicitation techniques used during the cognitive interviews and naturalistic observations made during operations. This diagram represents the first model of the primary task for a VM and can be used by designers to help implement this role in an increasingly autonomous system.

This task diagram is focused on the cognitive aspects of the VM’s primary role in monitoring their vertiport and airspace represented by the oval symbol at the top of the diagram. There are other tasks that a VM may be responsible for such as the management of ground units, management of air units, and approval of clearances for arrivals and departures. These additional tasks are represented in the top right box and fall outside the scope of this simplified task diagram. The diagram represents a closed-loop system with important decision nodes requiring awareness and action. In the situation of an off-nominal event, the VM must manage and resolve the conflict while also continuing to monitor other agents within their airspace and vertiport, represented by the dotted gray box outlining the off-nominal situation. Each stage of this diagram is discussed in detail below.

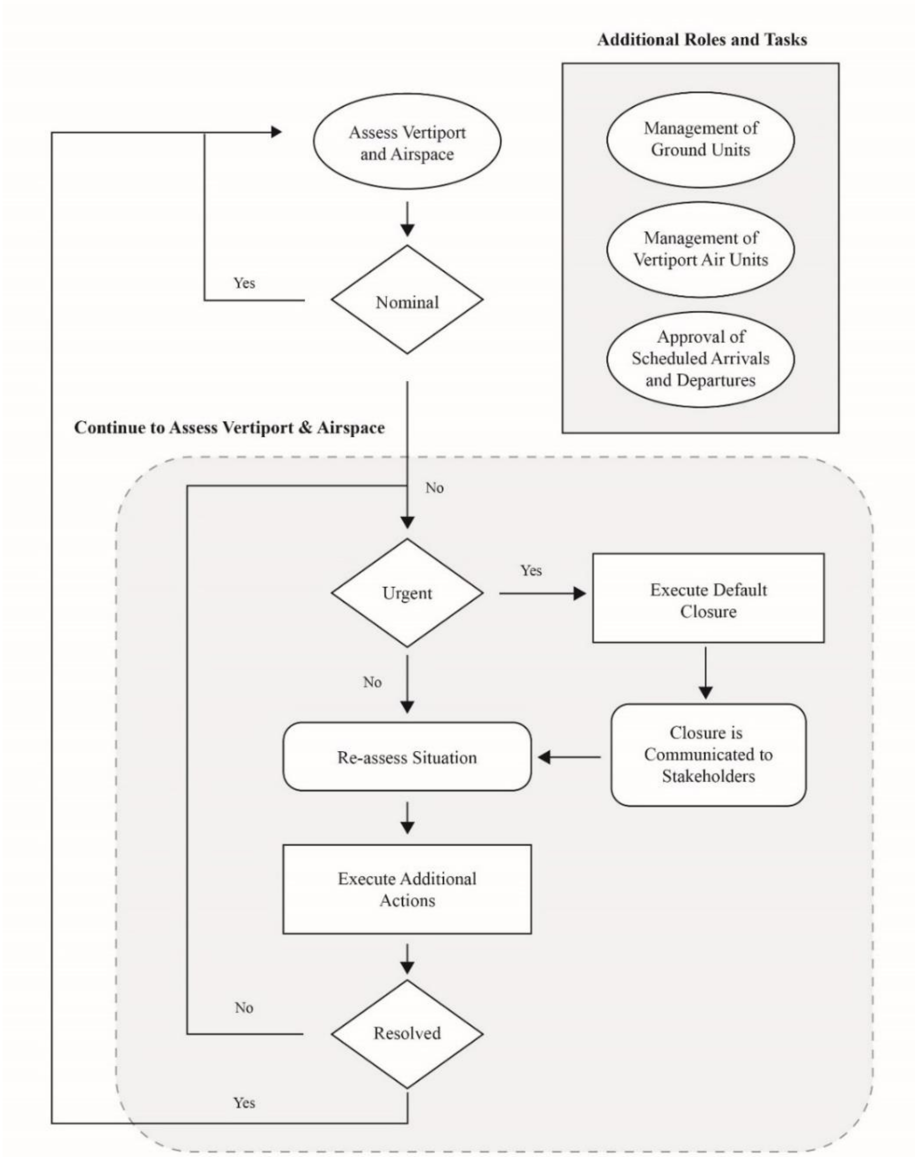

Fig. 1 Simplified task diagram of the primary cognitive task of assessing the vertiport and airspace

Assess Vertiport and Airspace. During this stage, the VM is assessing both the state and intent of all ground and air movements within their vertiport. This includes scheduled arrival and departure information, the state of each vertipad, and the intent of the vehicles and ground crew. To accomplish this, the VM requires informational feeds of vertipad state, health, and clearance. For our study, VMs highly preferred the visual camera feeds. Visual clarity of the vertipads is important and should include both the taxi and parking locations for the vehicle. However, it is unknown what level of clarity is required. Additionally, VMs suggested design implementations such as providing the VM with a spatial map of the ground area with each vehicle tracked as one potential solution to improve their awareness of ground movements. For air movements, both time and spatial separation are the two most important cues. A three-dimensional map of the vertiport provided VMs with critical information for spatial separation. Another display VMs requested was a display to determine temporal separation. This display would provide a visual graphical flow of incoming and outgoing traffic that a VM could glance at and determine temporal distances. The goal of the VMs during this phase was to monitor and ensure that all missions and movements were within their expected threshold. If they noticed and assessed a vehicle or event that was off nominal, then they moved to the next decision node.

Decision on the urgency of the off-nominal situation. After the VM has determined that an event is off nominal, they perform two important judgements of the potential severity of the conflict and the time demand for their response. If the VM has more time to respond or the potential consequence for the off-nominal event is low, then the VM can find ways to resolve the conflict without interfering with the flow of traffic into or out of the vertiport. However, if the VM has a short time to respond or the potential consequence is severe, then the VM does not have time to evaluate and assess other options and must have a default closure procedure and action that can allow for swift and efficient execution. As the severity of the conflict increases, the decision to execute a default closure increase. As time urgency increases, the decision to execute a default closure increase. As severity of conflict and time urgency increases, the decision to execute a default closure increase. The goal of the VMs during this phase was to accurately understand the urgency of the off-nominal event and if the urgency crossed a threshold, then execute a default closure.

Execute default closure. The default closure should be a procedure designed to serve as an emergency stop response. In the event that a time sensitive and highly hazardous event is occurring, the VM cannot be expected to perform complicated or intricate mental operations. Therefore, the default closure should be a simple design such as a single action button with a confirmation slider. More research is needed to understand the limits and requirements for such a function. For example, the time to respond value required of the default closure button would be a function of the speed limit inside the vertiport airspace, crew response time, and time-to-event of the potential conflict. Additionally, distinctions between a default closure for a vertipad versus a vertiport should be investigated to evaluate the effects on efficiency and safety. The goal of the VM during this phase would be to close the vertiport as quickly as possible to prevent further conflicts and rapidly move into the deconfliction phase. After the default closure is enacted and the vertiport closed, the closure of the vertiport needs to be communicated to any agent that may be affected by that closure.

Communicate default closure. The default delay should be communicated to all agents that may be affected by the default closure. This could include the ground crew, the pilot in command, the pilots that may be diverted or asked to adjust their flight plan, a fleet manager, and could extend to all pilots in the vertiplex. This response could be automated and contain a variety of information but at a minimum should include information that the vertiport is closed and how much time that vertiport is set to be closed for. A longer default closure time is recommended to allow the VM to safely deconflict the vertiport before reopening. During the closure time, the VM would have the bandwidth to re-assess the situation. The goal of the VM during this phase would be to ensure communication of the default closure to all stakeholders of the incident.

Reassess situation. If an off-nominal event occurred but was not urgent or if it was urgent but a default closure was executed, then the VM will reassess the situation to understand the nature of the incident. In some cases, this process could be swift and effortless, allowing the VM to move to the action stage. Expert VMs who hold a well-developed mental model of vertiport operations may be able to “make sense” of the off-nominal situation much faster than more novice VMs. Yet, in other cases, this process may require time, effort, and attention. In the latter scenario the VM has increased risk of becoming overloaded, specifically if the vertiport remained open as their primary task of monitoring the vertiport and airspace has not ceased. This increased workload and potential for missing other critical information would also occur if the VM was managing multiple vertiports outside of the one they closed for this event. In either case, the reassessment of the current off-nominal event must be simplified to not interfere with the primary task. Another solution suggested by the participants would be to pass off management of additional vertiports during this stage. Further research is necessary to support the VM during this phase. The goals of the VMs during this phase were to develop an understanding of the current off-nominal event and to plan a course of action to deconflict the situation. To accomplish this goal, they must sample information about the nature of the incident, air traffic, ground traffic, and the health and state of the vertipads within the vertiport. This information forms an expectation that they then use to develop a contingency plan or adhere to a procedural contingency plan already developed for the current incident. After assessing, or during the process of assessing, the VM will need to take additional actions.

Execute Additional Actions. The additional actions a VM takes is dependent upon the resources they are responsible for managing and the state of those resources. If the incident is more urgent, then the VM may need to directly interact and communicate with pilots. If, however, the incident is less urgent, the VM may wish to communicate their assessment of the event to a fleet manager or other agent who could manage the resolution. A few actions the VM may take are calling for a divert, a missed approach, an immediate landing, a hold, or communicating the current state of the incident to stakeholders. Alternatively, the VM may seek to communicate with the pilot or ground units to get more information about the state of the incident. More research is required to understand the breadth of incidents that a VM may face and what design elements may help facilitate quick and efficient response options. The goal of the

VMs during this phase was to either take actions to resolve the conflict or take actions to prepare for eventually resolving the conflict.

Conflict Resolution. The final decision node for this cognitive task is to estimate and determine if the conflict was resolved. If not, then the VM must reassess the situation and take additional actions to resolve the conflict. If so, then the VM returns to assessing the vertiport and airspace for nominal operations.

IV. General Discussion

The purpose of this work was to explore the role of a vertiport manager, a novel position that until this point has only been conceptualized and never studied. Five participants served as a vertiport manager across a total of 46 operations consisting of five scenarios in both a simulated and live flight capacity. Knowledge elicitation techniques and methods provided a wealth of data that were represented in terms of insights and a simplified cognitive task diagram. Overall, the insights and task diagram provide an initial understanding into the role of a vertiport manager.

For designers intending to fully automate the VM position, this paper can serve as a foundation to expand from to discover which functions and processes will need to be replaced. For example, at a minimum, the autonomous system will need to assess nominal mission status for stakeholder vehicles, notice anomalies, and execute and communicate vertipad closures. Additionally, this paper can provide insights into some of the layers of resiliency that would be lost without a human in the loop. A human VM provides many resilient elements which increase the safety and efficiency of the operations that would be difficult to automate such as their adaptability, ability to anticipate future events, and their ability to coordinate to resolve conflicts before they occur. For designers intending to rely on a human in the role, Section III can provide some key information necessary for the actualization of vertiport operations. However, a human VM will also face limitations such as their ability to manage their attention over time and resource limitations on the number of aircraft they can manage. In particular, during an off-nominal event, the VM is most vulnerable to missing information while they are deconflicting and resolving the current conflict. For a human VM, time demand is critical and during those few but urgent situations, it will be even more important to have an effective display design and effective procedures to minimize risk. Using technology to automate specific functions and work with a human VM may serve as a useful path to mitigate against the aforementioned risks. A few design and training recommendations discovered during this study are presented below.

Design & Training Recommendations

Design. Based on our study, VMs are presented with a large amount of information, therefore, the display should simplify the information. Simplification and design improvements can be made by applying the following:

- **Mapped coding**. Displays should have the same information mapped similarly across different displays or functions. VMs in this study had multiple displays such as a 3D visual display of the vertiports, a vertiport scheduler, manager, an interactive tool, a timer, video feeds of the vertiports, and an operational utility for data collection purposes. Similar information was presented across the different displays as each display provided a different function. But some information was not presented using the same mapping across the displays causing a higher mental demand for processing, confusion, and longer response times. For example, a vehicle was presented with a specific identification number on one display, but another displayed the same vehicle using a different identification number. In another example, graphics of vertipads and vertiports were presented on one display becoming useful cues the VM used to navigate the map. On a second display that contained a map of the same area but from a different viewpoint, there were no graphics of the vertiports or vertipads, removing that cue and leading them to create a new strategy to navigate that display. Consistency in the mapping of information across different displays can improve the scanning efficiency of the human and facilitate automaticity reducing the cognitive load on the human (SEEV model, [28]; Automaticity, [29]). Three examples for the need for mapped coding reported by participants are presented below.
    - Ex: “[I am] spending a lot of time [scanning] between the three situational tools trying to figure out which vehicle is which because the vehicle IDs do not match between the three systems.”
    - Ex: “Terrain [in the 3D display] should match [my] camera view, [it] makes determining vertiports/vertipads on [the 3D display] difficult.”
    - Ex: “I also noticed that the start/end times are listed in standard time but it is listed in military time in the "Update Vertipad's Status" popup menu, so I got a bit confused there.”
- **Pictorial realism**. Displays should represent information as the human mind would conceptualize that information. For example, a good design of pictorial realism is a thermometer. As temperature rises, the

indicator also rises. When the temperature falls, the indicator also falls in conjunction with the human's abstraction of such concepts. Similarly, designers should consider how the human conceptualizes the information that is being presented and match the display to that abstraction. In the current study, the participants desired a "waterfall-like" display that showed a listing of arriving aircraft, time to arrival, and spatial distance in a way that matched their conceptualization of the information. An example of the need for pictorial realism reported by participants is presented below.

  - Ex: "Each shared resource, approach, and pad points should have an easy time-based visualization aid. Waterfall like display example provided in notes."

- **Proximity compatibility principle**. To perform the role of vertiport management, the VMs had to integrate multiple sources of information for the same task. The proximity compatibility principle states that "displays relevant to a common task or mental operation (close task or mental proximity) should be rendered close together in perceptual space (close display proximity)" [30]. VMs reported many instances desiring information to be more closely spatially related. Three examples of the need for the proximity compatibility principle reported by participants are presented below.
  - Ex: "You can add [a] vertipad schedule within [the] vertiport tab data fields, and also each pad should have the countdown until the NEXT scheduled event."
  - Ex: "A take-off time should be visible on close in view of vertipad."
  - Ex: "I would suggest combining features from [the vertiport scheduler map] and [the 3D display] into one tool."
- **Interactivity**. Many studies have documented the human's ability to monitor a system that is performing nominally (vigilance [31]; complacency [32, 33]). Without any ability to interact, control, or become active in the role, the human may become a passive monitor. Within the aviation domain, an air traffic controller represents a close analog to what a vertiport manager is envisioned to be. One study showed that when an air traffic controller engages in passive monitoring under high traffic conditions, they demonstrate longer response times to detect potential conflicts, requiring almost double the amount time [34]. For VMs, the existing time sensitivity creates a greater potential risk by longer processing times of potential conflicts, indicating the necessity to keep the VM active. Specific examples of the need for interactivity reported by the participants can be found within Insight 10.
- **Pre-attentive processing**. Because of the high temporal demand and large amount of information being presented, designers should use salient principles that can communicate important information without much effort. Participants requested the ability to "at a glance" sample important information such as nominal status of a vehicle. By using designs that can leverage pre-attentive features, designers can provide critical key information at a glance without requiring much mental effort. Four examples of the need for the pre-attentive features reported by participants are presented below.
  - Ex: "Different aircraft should have different visual markers for their operational or intent graphics."
  - Ex: "[I] want [the] flight path shown when selecting [an] aircraft."
  - Ex: "I am really not tracking weather [;] I need an easy weather go/no-go [built]into the vertipad display."
  - Ex: "I need a visual alert to notify [me when] crew and operators are not in places they are scheduled/approved."

Training. The role and requirements of a VM are currently notional. However, there are a few training and procedural needs that were discovered and will be critical for VM to perform successfully. First, the VM will require a checklist and list of procedures they can refer to for both nominal and off-nominal operations. Although the criticality of off-nominal events does not provide much time for the VM to react, limitations in human memory should be accounted for by providing externalized documentation for responses to conflicts. However, that is not to indicate training to be unimportant. The VM should still be trained, experienced, and knowledgeable of these procedures with demonstrated ability to act accordingly, specifically within a time sensitive situation. Second, the VM should be trained to be effective when performing deconfliction, communication, and coordination efforts as that is where their true value lies. By reinforcing the strengths of the human-in-the-loop, you can better improve the resiliency that human provides the system.

Limitations and Future Directions

This work represents the first step towards understanding and documenting the role of a human vertiport manager performing their job during UAM missions. However, it is not the last. Research using a wider range of anticipated end-users under a large variety of conditions, missions, and environments is needed to replicate and generalize these findings. Much is unknown regarding the environment and role of the vertiport manager. For example, phase of flight is a common term used to describe the different stages a pilot and aircraft can take through their mission ranging from taxi and departure to approach and landing [15]. These stages are important as informational requirements and potential conflicts shift and change depending on the phase of flight one is in. It is apparent that a vertiport manager has a similar concept for their missions and that their stages are not equivalent to that of phases of flight. Yet, it is unknown what shape or form the VMs' operational structure or stages can be categorized into. Additionally, the findings in this work are bound to adapt and change as we move closer to actualizing UAM operations in everyday life. Advancements in technology, industrial demands, and procedural regulations will affect the ultimate shape of what a VM becomes outside of what is conceptualized through the operations at NASA. Never-the-less, it is critical to continue the work of studying this role and these operations to move the aviation world closer towards implementing the envisioned UAM future. Controlled experimental studies replicating and extending these results are required for that next step.

V. Conclusion

Vertiport management will be a critical role as the UAM vision is actualized. This work provided many insights, design and training recommendations, and a simplified task diagram of the vertiport manager's primary task. A strength of this work is that each recommendation, insight, and model were not only theorized but created using data collected by participants performing real vertiport management operations within both a simulated and live flight environment. This work only scratches the surface of what the vertiport manager's role will be during future UAM operations. But for designers, researchers, and leaders of industry, this work can provide a strong foundation to build the infrastructure required to make the UAM vision a reality. As the ongoing debate considering whether to fully-automate the vertiport manager role continues, findings presented in this work can help describe what could be gained or lost in either condition as well as provide recommendations on how to implement a third option, one where the human and automation can work together to accomplish the task.

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