

Overview of an Exploratory, Multi-Pilot Simulation Study of Early eVTOL Operations at Non-Towered Vertiports

Kenneth H. Goodrich*

NASA Langley Research Center, Hampton, VA, 23681, USA

This paper provides a report out on an exploratory, multi-aircraft/multi-pilot, real-time simulation study conducted by NASA of early commercial powered-lift, Urban Air Mobility (UAM) operations at a non-towered vertiport. As used in this paper, vertiport refers to the primary ground and airspace elements facilitating the takeoff and landing of electric vertical takeoff and landing (eVTOL) aircraft with central emphasis on a vertipad, i.e. the physical touch-down and lift-off area and surrounding approach, departure, local pattern procedures. The study, known as the Piloted UML-2 ConOps Study (PUCS), had two high-level goals. The first goal was providing preliminary insights and observations relevant to the piloting and flight operations of early, commercial UAM operations aligned with the initial stage of the FAA's Advanced Air Mobility (AAM) Implementation Plan and the second level NASA's UAM Maturity Level (UML) scale. The second goal was evaluating a novel, medium-fidelity, extensible, many-pilot, real-time simulation capability known as the UAM Flyers developed by NASA. The Flyers are intended to allow rapid development, screening, evaluation, and demonstrations of potential Concepts of Operation (ConOps) for UAM flight operations and airspace management in a modular and low-cost, real-time, human-in-the-loop rapid simulation prototyping environment. For this study, ten Flyer cockpits were configured to evaluate flight operations through a non-towered vertiport with pilot interfaces and displays (external and in-cockpit) appropriate for operations under visual flight rules (VFR) and employing flight and communication procedures representative of current operations at non-towered airports. The presented results include an achieved operational tempo; durations of individual flight tasks for approaches and departures; off-nominal events and triggers; and pilot comments regarding potential procedural and technology improvements.

I. Introduction

Urban Air Mobility (UAM) enabled by advanced flight vehicles such as electric vertical takeoff and landing (eVTOL) aircraft is expected to provide new alternatives for accessible, rapid and sustainable transportation of people and goods to, from, and across urban, suburban, and other areas [1, 2]. While this vision of future UAM is compelling, significant development and evolution of aircraft and airspace technologies and operational procedures is likely needed to progress from the present state where eVTOL aircraft are mostly undergoing initial development and envisioned, high-density operations which are perhaps several decades in the future. As described by the FAA and NASA documents predicting possible development of UAM capabilities [3, 4], UAM will likely evolve through several significant stages, starting from an Initial stage employing present day regulations, airspace structures, procedures, and practices and progressing through Midterm and Mature stages, in-part involving increasingly integrated and tailored changes to airspace structures, flight and airspace operations, and relevant regulations.

To help facilitate and accelerate the expected development, several human-in-the loop studies of UAM operations have been conducted or are currently underway [e.g., 5]. As many prospective UAM operators (i.e. air carriers providing public transportation using UAM aircraft) intend to provide service to busy hub airports as soon as practical, most studies have focused on UAM integration in positively controlled terminal area airspace with an emphasis on

* Deputy Project Manager for Technology, Advanced Air Mobility Project, AIAA Associate Fellow.

busy Class B airports and metroplexes. Since Class B airspace is already heavily utilized and positively controlled by FAA air traffic controllers, the focus of studies in these areas has typically focused on assessing the impacts of UAM operations on controllers and current airspace users, primarily commercial transport airplanes.

As a compliment to studies of UAM integration in positively controlled airspace, the simulation study described in this paper, known as the Piloted UAM Maturity Level 2 (UML-2) [4] Concept of Operations (ConOps) Simulation or “PUCS” for short, focused on initial UAM operations outside of positively controlled airspace (i.e. operations in Class E or G airspace) as many vertiports (i.e. airport infrastructure dedicated to eVTOL operations), even in metropolitan areas, that are not located on, or close to, busy commercial airports may be outside (including below a shelf) positively controlled airspace. In such areas, the FAA currently does not provide tower-like services (e.g. sequencing and spacing) to so-called, private, “prior permission required” (PPR) facilities which many vertiports are likely to be. For background, 99% of current US heliports are PPR facilities[†]. In addition, unless traffic levels merit a control tower, many public-use facilities for small airplanes and helicopters safely operate without a control tower and associated services using well established procedures for “non-towered airports”[6].

The development and conduct of PUCS was guided by two high-level goals. The first was providing preliminary insights and observations relevant to the piloting and flight operations of commercial Urban Air Mobility (UAM) operations consistent within the initial stage of the FAA’s Advanced Air Mobility (AAM) Implementation Plan[7] (which is similar to UML-2 on the NASA UML scale), and with a particular focus on assessing vertiport operations under current, visual flight rules (VFR)[8] combined with recommended procedures for non-towered airports adapted to eVTOL flight operations. Motivations behind this goal included assessing the throughput and limitations of these procedures and operations to provide benchmarks and insights to help inform future research.

The second goal was evaluating a novel, medium-fidelity, many-pilot, real-time simulation capability known as the UAM Flyers developed at NASA Langley[9]. The Flyers are intended to allow rapid development, screening, evaluation, and demonstrations of potential ConOps for UAM flight operations and airspace management in a modular and low-cost, real-time, human-in-the-loop, rapid simulation prototyping environment. As used in this study, ten Flyer cockpits were configured to evaluate flight operations in common environment, with pilot interfaces and displays (external and in-cockpit) appropriate for assessing VFR operations.

The remainder of the paper describes the configuration of the UAM Flyers; the flight and airspace operations procedures used in PUCS; the evaluation pilot cohort and preparation; and the primary findings and conclusions from the study.

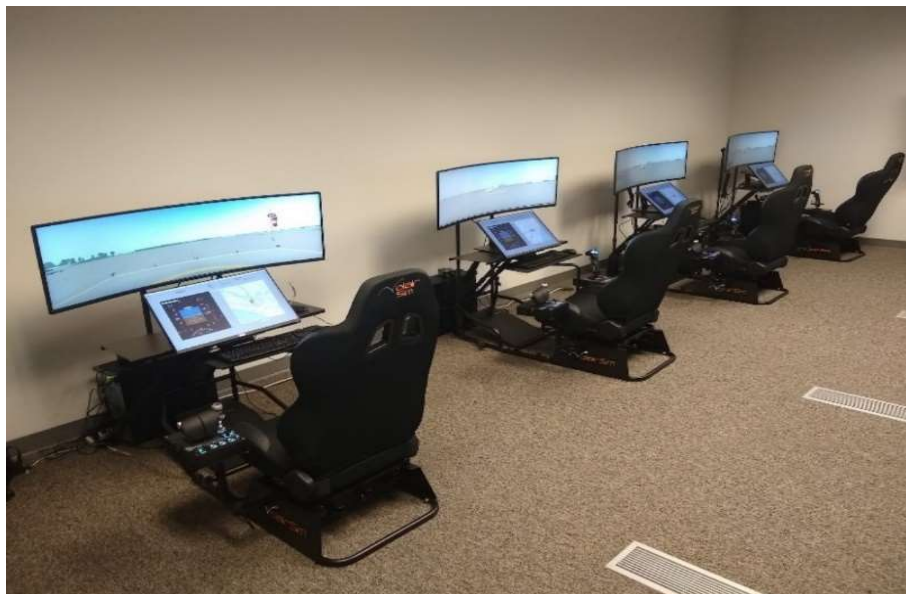


Fig. 1 Four flyer cockpits as used in PUCS

II. Flyer Description

Four of the Flyer cockpits used in PUCS are shown in Figure 1. An additional six cockpits were located in the same room, facing the opposite wall from those shown in the figure. All ten cockpits were connected via a local network to a simulation operator’s station located in the same room. The positioning of the cockpits was such that pilots were relatively isolated visually from one another. As can be seen in Figure 1, each cockpit had a pair of manual control inceptors consisting of a side-stick (3-axis) for the right hand and a

[†] <https://www.ainonline.com/aviation-news/business-aviation/2023-03-01/nations-heliports-normalize-deviance>



Fig. 2 External and cockpit displays

them easier to acquire visually. As shown in Figure 2, “ownship” is sitting on the vertiport surface and is number two in the departure queue while a third eVTOL is in translational hover nearing the vertipad for landing. The lower monitor depicted two multi-function displays inside the cockpit and is divided into a primary-flight display and a navigation display. The navigation display provided a moving-map depiction of the operating area including significant landmarks features, flight procedures, and Automatic Dependent Surveillance Broadcast (ADS-B) “In” traffic information which depicted the location of other ADS-B equipped traffic. In this study, all the UAM aircraft were modeled as ADS-B equipped and their relative locations displayed on the moving-map.

As all the cockpits were in the same room, “proximity speaking” (i.e. speaking out loud) was used to represent radio communication on a common frequency rather than implementing a more detailed simulation of typical aircraft

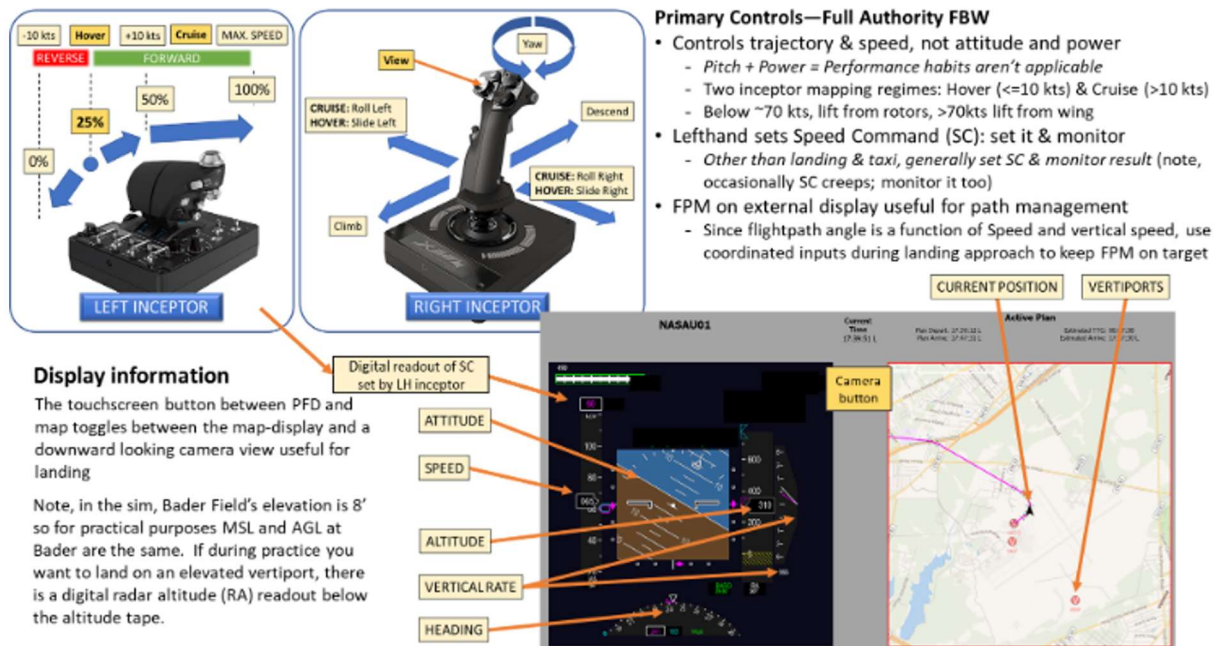


Fig. 3 Overview of cockpit displays and control inceptor command behavior

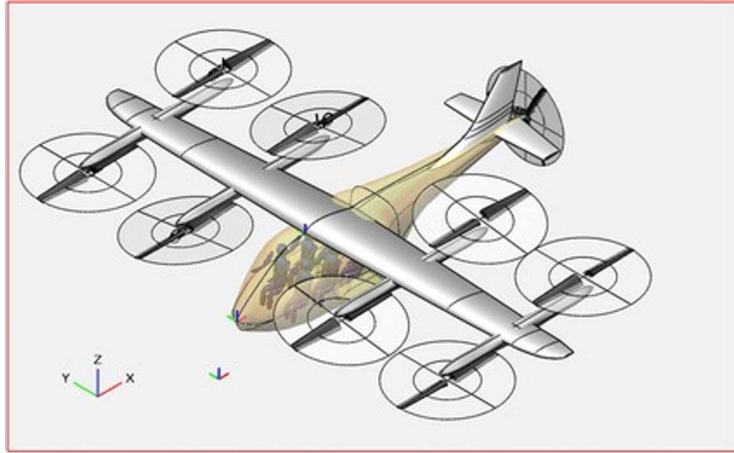


Fig. 4 Perspective view of eVTOL configuration [Ref. 10]

based force and moment modeling of aerodynamic and propulsive forces acting on the aircraft at the instantaneous flight condition. As the open-loop flight dynamics of the simulated aircraft are highly-variable and unstable for some flight conditions, the aircraft simulation included a highly-augmented, manual flight control system (FCS) that was commanded through the left- and right-hand control inceptors as described in Figure 3. The FCS provided pilots with relatively simple and integrated control of the instantaneous flight path across the flight envelope. The FCS automatically managed transitions between powered-lift and wing-borne flight and is functionally representative of the highly integrated FCS capabilities present on powered-lift aircraft targeted to enter into commercial service in the next few years. No outer-loop, autopilot functionality was active in the study.

The simulated aircraft had a top speed of 130 kts, a cruise speed of 120 kts, a nominal approach speed of 90 kts and transitioned between wing-borne and powered-lift flight at approximately 70 kts. While power-required and battery state-of-charge parameters were modeled in the simulation, for simplicity the energy capacity and other battery properties were selected such that the simulated battery characteristics had essentially no direct impact on flight operations during the study. But, as explained later, the evaluation pilots were instructed to minimize their time spent in power-lift flight in recognition of likely, practical battery limitations.

Modeling of winds, turbulence, and other weather considerations such as clouds and reduced or broken visibility were not included in this exploratory study.

III. Vertiport Environment and Flight Procedures

The simulated, operational environment and flight procedures evaluated in PUCS are described in this section. While operational UAM air-taxi flights are nominally expected to shuttle passengers or cargo between vertiport pairs (i.e. origin and destination vertiports), in order to effectively double the attainable vertiport traffic with ten pilot stations, a single vertiport was simulated in PUCS with flights originating from and returning to the same vertiport by following departure and arrival procedures connected by a brief (~5 minute) cruise loop. This closed-circuit had the advantage of providing a more naturalistic flight experience for the evaluation pilots as it allowed them to conduct complete flights from takeoff to landing and including representative surface operations and self-management of takeoff and landing operations.

The basic layout of the operational area around the vertiport is shown in Figure 5. Geographically, the simulated area corresponds to Atlantic City New Jersey with the vertiport located on Bader Field, a now closed general aviation airport (formerly designated AIY). While the external visuals corresponded to the Atlantic City area (as rendered using X-Plane for the external visuals), other than providing external ground references for visual flight, the specific details of the Atlantic City area were not important to the study.

The vertiport simulated in the study used a small portion of the tarmac at AIY, as shown in Figure 6 from the perspective of a landing aircraft. The vertiport had a single, square, 50' x 50' vertipad marked out by yellow perimeter lines and typical helipad markings in the center. An extended, hold-short line was set back 50' from the edge of the vertipad. Taxiway lines provided surface guidance to enter and exit the vertipad and formed a closed circuit on the

radios. While not simulating aircraft radios removes some of the issues associated with crowded radio channels (e.g. stepped-on transmissions and frequency sharing with other vertiports), the evaluation pilots generally felt the proximity speaking was sufficient for the exploratory goal of the evaluation. Figure 3 provides more details on the pilot displays and manual control inceptors.

A common aircraft simulation model was used for all cockpits and was based on a modified version of the NASA "Lift + Cruise" reference model developed by the NASA Revolutionary Vertical Lift Project [10] and shown in Figure 4. The aircraft was simulated using typical 6 degree-of-freedom differential equations of motion with table-

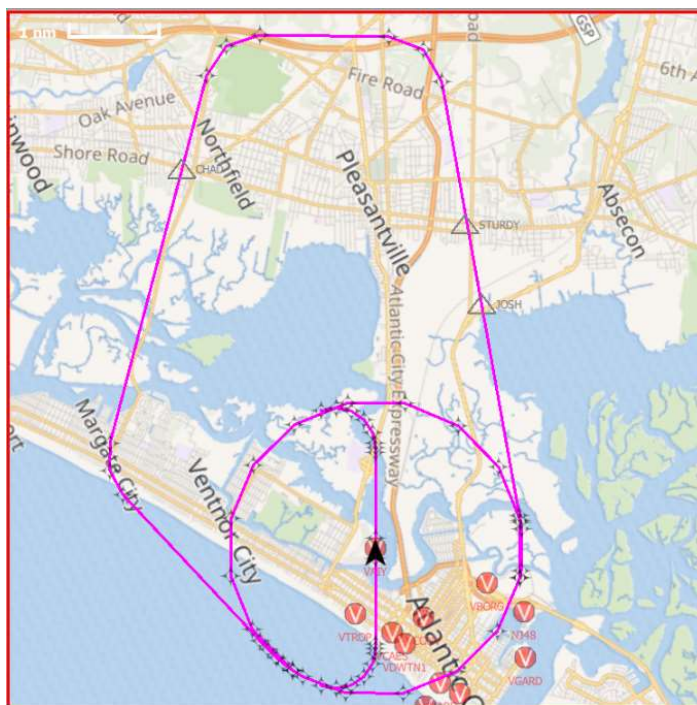


Fig. 5 Map view of simulated operating area

PUCS, all operations were conducted in the northwest configuration, with departures toward the top of Figure 5. The deproach procedures had slopes of 6.0 degrees (i.e. the approach glideslope and departure climb-out angles). The radius of the “outer-ring” of the pattern was 1.6 nm and could be flown at 120 kts with the resulting turn rate being less than a standard rate turn (<3 degrees/second). The curved, radius-to-fix, transition segments between the deproach procedures and outer ring were designed to result in a standard rate turn when flown at 90 kts. For flights departing the pattern for the cruise circuit, rather than following the left-hand turn at the end of the departure segment, pilots would head direct to the waypoint “JOSH” and intercept the cruise route there. Pattern altitude (i.e., the altitude of the outer ring) was 700’ above mean sea level (MSL) while the cruise-route altitude was 1000’ MSL. The vertipad altitude was 8’ MSL.

During familiarization sessions, pilots were encouraged to use the following general flight procedures:

- 1) Stay behind the hold-short line while verifying the status of the pad and approach path. Pilots were instructed to visually assess traffic in the vicinity while also monitoring for standardized, Common Traffic Advisory Frequency (CTAF), self-announcements vocalized by the other pilots. The CTAF self-announcements followed the guidelines described in reference 6.
- 2) After verifying the pad and approach path were clear, pilots would announce their taxiing to the pad while ground taxiing to the pad and lining up for departure.
- 3) From the pad, pilots self-announced takeoff and initiated a vertical ascent at maximum rate (~500 fpm). When passing through 50’ above ground level (AGL), they would command forward flight at 90 kts and follow the departure path. (The flight control system managed the acceleration and outbound transition from thrust- to wing-borne flight.)
- 4) Upon reaching the end of the departure path, if departing the pattern, accelerate to 120 kts and make a slight right turn to go direct JOSH.
- 5) While maintaining appropriate spacing from other traffic, fly the cruise loop nominally at 120 kts with adjustments as needed for spacing.
- 6) When passing through the waypoint at Margate City, self-announce an intention to enter the pattern for landing.
- 7) Descend to pattern altitude of 700’ AGL and just prior to turning on the transition segment to the approach procedure slow to 90 kts.
- 8) At the end of the transition segment, roll wings-level, and self-announce being on final approach.

vertipad surface. The lengths of the taxi paths leading to and from the hold-short line and the vertipad were each approximately 100 feet long. For PUCS, after landing on the vertipad, pilots would follow the taxi line off the pad, across the hold-short line, and around to the end of the queue of any aircraft waiting to depart. As the simulated aircraft had fixed, wheeled landing gear, ground taxiing was used for surface operations.

In actual operations, after landing, aircraft would likely taxi to a gate or other parking area to deplane and board passengers, as well as recharge for the next flight. As there was no need to simulate these activities in PUCS, the simple closed taxi-loop was considered sufficient.

Terminal area flight procedures based on the concepts described in Ref. 10 were developed for the vertipad. While these concepts are designed to be consistent with the requirements of instrument operations, for the visual operations of PUCS they provided advisory information visible on the pilot’s displays to help enhance the predictability of operations. The “deproach procedures” (i.e. integrated, approach or departure procedures) supported operations in a either a northwest or southeast direction. For



Fig. 6 View of vertipad, hold short line, taxi lines, and departure queue as viewed from a landing aircraft

- 9) During the approach maintain 90 kts until reaching 300' AGL. Pilots were instructed to assess and monitor the availability of the vertipad for landing during this phase of the approach.
- 10) At 300' AGL, referred to as the deceleration decision point (DDP), pilots were asked to make the following decision:
 - a) If the vertipad was occupied, a go-around was to be initiated rather than transitioning to powered lift flight. This was done to reduce the probability of either having to hover in powered-lift mode while waiting for the pad to clear or initiating an energy intensive go-around after transitioning to powered-lift flight. If a go-around was performed, pilots were instructed to climb back to pattern altitude (700'), fly an offset to the right so as not to over fly the vertipad or departure queue, and fly a closed-pattern while resequencing themselves for another approach and landing.
 - b) Alternatively, if at the DDP, the pad was clear for landing, pilots were to reduce the commanded speed from 90 kts to 30 kts. As the aircraft slowed through about 70 kts, the flight control system automatically managed the transition from wing-borne to thrust-borne flight. (Note, since the DDP was based on barometric altitude, referring to it as the deceleration decision altitude would be more descriptive, but the term DDP was used in the study).
- 11) Approaching the pad, pilots would continue to visually manage their arrival to the pad, aiming to hover above it at approximately 20' and with no forward speed.
- 12) Once over the pad, pilots would descend to touch down. Once on the ground, they would follow the taxi line off the pad while self-announcing that they were exiting it.
- 13) Pilots would complete a flight by following the taxi line either back to the departure hold-short line or to the end of the queue of aircraft waiting to depart. Note, as is typical of most heliports, the vertipad was assumed to be a private, PPR facility and as such, no outside or non-participating traffic was included in the study. Future studies could consider the possibility of non-participating traffic (either airplanes, helicopters, or other eVTOLs) potentially flying in proximity to the vertipad.

Pilots typically tended to modify some of the specifics of the landing procedure (steps 10, 11, and 12) based on the training and practice sessions with the goal of developing a technique consistent with performing safe, accurate, and timely landings on the vertipad. Pilots were also instructed to minimize, as much as practical, the time spent in powered-lift mode (e.g. speed below 70 kts) in recognition of the high-energy consumption and possible battery temperature limitations that may be present in this lift mode. During takeoff, from the time the wheels left the surface until achieving wing-borne flight, aircraft typically spent 20 seconds in powered lift. During approach and landing (e.g. Step 10b through wheel touchdown in Step 12), powered-lift mode was typically active for between 60 to 80 seconds.

IV. Evaluation Pilots and Training

Ten pilots participated in at least one familiarization session and the final data collection session. Initially, it was desired that pilots participating in the data collection session have a minimum of a private pilot certificate, with a commercial or higher rating being preferred to better reflect the qualifications and experience expected of commercial, eVTOL air-taxi pilots during initial operations. Due to last moment conflicts, the final pilot cohort for the data collection session consisted of six commercial or air-transport pilots (including five, full-time, NASA pilots from across the agency), two private pilots, and two certified under Part 107 as remote pilots for small, unmanned aircraft.

All pilots participated in at least one familiarization session before the data collection session. The first portion of these sessions involved familiarization and practice sufficient for them to become reasonably proficient in the operation of an individual aircraft. The more experienced pilots achieved proficiency operating the aircraft relatively quickly, typically less than 30 minutes. While the less experienced pilots also quickly gained basic proficiency, as can be seen in the results section, their performance of flight tasks was typically more variable. The second portion of a familiarization session focused on group practice of airport operations through and around the vertiport environment in order to become proficient with the overall flight and airspace procedures. Based on interactions and discussions during these sessions, refinements were also made to the operational procedures and test scenarios. These refinements are described in the following section.

V. Evaluation Scenario Development

For this initial exploratory evaluation, the evaluation scenarios focused on nominal flight operations without additional complexity or off-nominal situation elements being intentionally introduced. For example, as mentioned earlier, non-participating traffic was not included and all aircraft had the same performance, which simplified flight operations. Furthermore, no complicating weather factors like winds, turbulence, or areas of reduced visibility (e.g. broken clouds) were included. The simulated operations occurred in airspace that did not require communication with or instructions from air traffic control (i.e., class G or E airspace), although as mentioned earlier, vocalization and monitoring of standardized, CTAF self-announcements for a non-towered airport were performed. Finally, no intentional, off-nominal situation elements, such as an aircraft declaring an emergency or being unexpectedly delayed while occupying the vertipad were included. Future studies should consider inclusion of such elements. That said, simply having ten human pilots simultaneously participating in the simulation introduced a significant degree of variability into the flight operations. While this variability made rigid control or repeatability of specific situations impractical, it afforded the opportunity to observe more naturalistic, interactions between the pilots and aircraft during the scenario.

The initial plan for the study was to start scenarios from an initial condition that had one aircraft on the vertipad ready for takeoff, and the other nine aircraft queued up behind the departure hold-short line. As the aircraft on the vertipad departed, the pilot of the first aircraft in the departure queue was instructed to wait for a specified time interval (each pilot was supplied a digital timer) and then, if there were no aircraft on final approach (as there could be once an aircraft had completed a circuit), they could taxi to, and depart from, the vertipad. These actions correspond to Steps 1 and 2 of the flight procedures described earlier. A minimum specified time interval between takeoffs was to be imposed to establish a nominal spacing interval between aircraft in order to provide a degree of control over the tempo of flight operations. Once in flight, pilots were requested to obtain and maintain the requested time interval from the preceding aircraft. Initially, it was planned that three scenarios with minimum takeoff/spacing intervals of 120, 90, and 60 seconds respectively would be evaluated as a control variable to assess changes in task performance and pilot workload as the overall tempo of operations was increased. A “scenario” consisted of operating at the target tempo for 30 minutes after the first aircraft completed its initial circuit and had landed back at the vertiport as this event nominally indicated the vertiport was in a steady operating condition in terms of having simultaneous arrival and departure demand.

During the final practice session, which was the first opportunity to evaluate the proposed tempos with all 10 pilot stations occupied, it was found that the 60 second interval between takeoffs resulted in spacing between arriving aircraft too close for routine interleaving of landing and departing aircraft as there was insufficient time after an aircraft landed for the next departing aircraft to taxi to the vertipad and takeoff without typically creating a conflict with the next landing aircraft since it was typically already beyond the DDP. The inability to routinely alternate takeoffs and landings resulted in “strings” of consecutive aircraft landing with relatively little judgement or decision making needed by the departing pilots to assess whether they could depart prior the end of a string. Ultimately, with the 60 second interval, the interaction and decision making between pilots was relatively uninteresting and the decision was made to exclude it from the final data collection section.

The 120 second spacing interval was found to be overly conservative in that there was generally plenty of time between successive arriving aircraft for the aircraft at the head of the departure queue to depart before the next arriving aircraft had completed its turn onto the final approach segment (i.e. Step 8). Again, pilot decision making was relatively simple and while the 120 second interval was run during the data collection session, the results are not included in this paper.

The 90 second interval between takeoffs was found to result in operations that challenged pilot coordination and decision making in the context of non-towered operations and seemed to be representative of a high, but generally sustainable tempo. Based on pilot feedback during the final practice session, rather than requiring a minimum 90 second interval between successive takeoffs, a more flexible, and more operationally representative procedure was instituted. In place of the 90 second interval, once the first aircraft to depart had completed its initial circuit and landing, departing pilots could transition from Step 1 to 2 without delay if they judged they could complete their takeoff prior to any aircraft on final reaching the DDP. Once in flight, they would manage their speed to obtain what they perceived as being approximately 90 seconds in-trail from any preceding takeoff.

A description of operational events, event times, pilot comments, and observations by the author during the scenario as conducted using the procedure described above are summarized in the next section. Pilot comments were obtained during a group interview conducted immediately after the completion of the scenario.

VI. Summary of Results

Table 1 provides a record of vertiport operation times (i.e. takeoff and landing times). Table 2 provides event times for takeoffs, corresponding to Steps 2 and 3 (initiation of taxi over the hold-short line and wheels leaving the vertipad). Table 3 provides times from the final approach fix to wheel contact with the vertipad, along with the altitude and time corresponding to the speed command change at the DDP (Step 10b). Time intervals of interest and high-level summary analysis are also included in the tables. Event times are given in seconds referenced to the initialization of the simulation. Since the scenario formally began when the first aircraft to depart completed its first landing, the initial event in Table 1 is the time of that landing (as a target of opportunity, Table 3 includes data from the approach to that initial landing).

Considering the overall tempo of operations, as shown in Table 1, 36 operations were performed in the 30 minute window (the first landing is not included in this count). This pace equates to tempo of 72 vertiport operations per hour or an average of 50 seconds per operation. As noted in Tables 1 and 3, two approaches resulted in go-arounds which slightly reduced the number of vertiport operations. It is recognized that two go-arounds in a 30 minute period is objectionably high and suggests the tempo of the operations was aggressive, but the go-arounds also provided the opportunity to assess the ability of the pilots to recover from off-nominal, albeit routine contingencies.

The cause of the first go-around (by tail #10) was an unstable approach that appeared to be initiated by the pilot inadvertently setting the commanded speed in the transition speed range (~60-75 kts). Pilots were advised to avoid sustained flight in this range as the handling of the aircraft was deficient in this speed range. The throttle quadrants used in the Flyer cockpits likely contributed to the event as they move smoothly and easily while having essentially no static friction or breakout force. These characteristics made it relatively easy to make inadvertent inputs if the pilot left their hand on the throttle, which is a common technique on approach. Finally, the pilot of tail #10 was one of the Part 107 remote pilots and their limited experience may have been a contributing factor.

The first go-around indirectly contributed to the second (by tail #4) as tail #10 flew a closed traffic pattern, creating a spacing challenge for the pilots where the cruise-loop and traffic pattern merge (near Ventnor City in Figure 5). Using situation awareness provided by the moving map, the merge was performed with safe spacing (i.e. all aircraft comfortably remained well-clear). However, it resulted in the stream of arriving aircraft having less than the targeted, 90 second interval. Tail #9 was first in the departure queue as these aircraft conducted their final approaches and after waiting for two aircraft to land (#3 and #10), #9 attempted to depart while #4 was on final. At the DPP the pilot of #4 (also one of the Part 107 remote pilots) recognized that the vertipad was occupied and self-announced they were going around. The go-around was conducted per Step 10a and #9 delayed their takeoff to ensure spacing from #4.

To better understand the sequence of events leading up to the second go-around, several observations on techniques developed by the pilots are needed. In the interest of operating at what they perceived to be near a high, but safe and sustainable tempo, the pilots developed modifications to Steps 2 and 10. During the final practice session, they felt not allowing departures if an inbound aircraft had reached the final approach fix was overly conservative. Alternatively, the pilots found that an expedited takeoff could safely be performed if the in-bound aircraft had not yet started to over-fly the water separating Bader Field from the resort strip (see Figure 5). The moving map allowed the position of inbound aircraft to be assessed. The need to conduct such an expedited departure is noted as having high

Table 1 Vertiport operation times

Operation Number	Event Type	Aircraft Tail Number	Time (secs.)	Delta Time (secs.)	Notes
1	Landing	1	642	NA	
2	Takeoff	8	673	31	
3	Landing	2	739	66	
4	Takeoff	9	765	26	
5	Landing	3	817	52	
6	Takeoff	10	857	40	(Go around on first approach)
7	Landing	4	923	66	
8	Takeoff	1	957	34	
9	Landing	5	981	24	
10	Takeoff	2	1037	56	
11	Landing	6	1087	50	
12	Takeoff	3	1123	36	
13	Landing	7	1196	73	
14	Takeoff	4	1233	37	(Go around on first approach)
15	Landing	8	1271	38	
16	Takeoff	5	1327	56	
17	Landing	9	1384	57	
18	Takeoff	6	1423	39	
19	Takeoff	7	1502	79	Takeoff delay for go-around by #10
20	Landing	1	1586	84	
21	Takeoff	8	1613	27	
22	Landing	2	1693	80	
23	Landing	3	1752	59	
24	Landing	10	1786	34	Closed-pattern after go-around
25	Takeoff	9	1845	59	Takeoff delay for go-around by #4
26	Takeoff	1	1890	45	
27	Landing	5	1957	67	
28	Landing	6	2032	75	
29	Takeoff	2	2063	31	
30	Landing	4	2113	50	Closed-pattern after go-around
31	Landing	7	2168	55	
32	Takeoff	3	2204	36	
33	Landing	8	2254	50	
34	Takeoff	10	2301	47	
35	Takeoff	5	2354	53	
36	Takeoff	6	2382	28	
37	Landing	9	2439	57	
Average time per operation (secs.)				50	
Average tempo, operations per hour				72	

time pressure in Table 3[‡]. In a related modification, most of the pilots would commit to slowing at the DDP if the vertipad was occupied but the prior operation was perceived as likely to be completed before they reached the land boundary of Bader. As shown in Table 3, on average at the DDP, an in-bound aircraft was typically still one minute away from landing at the vertipad, while taxi and takeoff for an expedited departure required an average of 30 seconds (Table 2). Note that while the attempted departure of #9 triggered the go around and was clearly time-pressured, the resulting time to actually leave the pad was an outlying 57 seconds as they waited for #4 to travel some distance down range from the vertipad before they departed. For this reason, this time was not included in the average for time-pressured takeoffs shown in Table 2. The average time required for non-time pressured departures was 40 seconds.

Two other factors also likely contributed to the go-around. First, due to another CTAF announcement, the pilot of #9 delayed announcing the initiation of their taxi for 9 seconds after they had actually started taxiing for departure (nearly 30% of the time required to complete an expedited takeoff and vacate the vertipad). This late announcement likely caused #4 to assess that #9's departure would be insufficiently expedited. Further, #9's announcement was made right as #4 was arriving at the DDP, elevating the perception of a conflict as defined in Step 10. Finally, as one of the less experienced pilots, #4 may have been more conservative in following the recommended decision process at the DDP.

In the post-scenario interview, the pilots reported that on average, the flight operations involved relatively low workload, but with two flight tasks involving elevated workload. First, the pilots highlighted that assessing whether there was sufficient time to takeoff could be mentally challenging in time-pressured situations, particularly if the spacing and/or speed of the inbound aircraft differed from expected targets, as was experienced following the go-arounds. If the negative consequences of a go-around merit it, the pilots recommended some sort of clear, conservative go/no-go criteria be available to reduce the temptation to push against operational margins. The pilots also suggested that the time between the prior vertipad operation and a takeoff could be significantly shortened by eliminating the ground-taxi segment beyond the hold-short line. This could be done by allowing the aircraft to hover-taxi from the hold-short line and initiate takeoff as the vertipad was approached (a common practice for helicopter takeoffs from busy heliports). While the hover endurance of eVTOLs is expected to be limited, this technique would likely involve

Table 2 Takeoff event times

Operation Number	Aircraft Tail		Time pressure		Takeoff time	Elapsed Time	Notes
	Number	Previous Pad Usage	to depart	Taxi Time (secs.)	(secs.)	(secs.)	
2	8	Landing #1	High	645	673	28	
4	9	Landing #2	High	740	765	25	
6	10	Landing #3	High	818	857	39	
8	1	Landing #4	High	922	957	35	
10	2	Landing #5	-	989	1037	48	
12	3	Landing #6	-	1091	1123	32	Waited for two landing aircraft
14	4	Landing #7	-	1198	1233	35	
16	5	Landing #8	-	1273	1327	54	
18	6	Landing #9	-	1386	1423	37	
19	7	Go Around #10	-	1467	1502	35	
21	8	Landing #1	High	1587	1613	26	
25	9	Landing #10	High	1788	1845	57	Waited for two aircraft, but triggered go-around by #4
26	1	Takeoff #9	-	1845	1890	45	
29	2	Landing #6	-	2037	2063	26	Waited for two landing aircraft
32	3	Landing #7	-	2171	2204	33	
34	10	Landing #8	-	2254	2301	47	
35	5	Takeoff #10	-	2304	2354	50	
36	6	Takeoff #5	High	2355	2382	27	
Average time for expedited takeoff						30	

[‡] During these time-pressured departures, pilots typically shortened the taxi time by initiating taxi as soon as the preceding aircraft began to taxi off the pad (a likely benign modification to Step 2); taxiing at slightly faster speeds; and shortening the taxi distance by tracking closer to a straight line from the departure queue to vertipad rather than staying centered on the taxi lines.

minimal additional time in powered-lift mode and may be a useful means of improving vertiport productivity if it is a significant limiting factor in UAM system throughput.

Second, the pilots noted that conducting the approach and landing task, from the DDP to touchdown, could be challenging to judge, which resulted in variable timing (apparent in Table 3) and precision. This was the only phase of flight where pilots spent significant time in powered-lift flight (60 seconds on average and a maximum of 87 seconds) and also required precise deceleration and path control. While not explicitly evaluated, handling of the simulated aircraft during this task would probably be considered “adequate”, with control of longitudinal and lateral translation being sluggish and requiring significant pilot attention. The pilots suspected the presence of winds and turbulence would further increase workload and task variability. In addition to improving the controllability of the basic aircraft, they suggested that display guidance or control automation aiding the longitudinal deceleration to hover over the vertipad could reduce workload while reducing landing times and variability.

The pilots also suggested additional information be available to help manage relative spacing and speed from the preceding aircraft during in-trail operations. While the moving-map provided a visual depiction of spacing, they suggested it be augmented with quantitative information regarding the current in-trail time interval and relative speed. Alternatively, graphic elements like a spacing noodle projected ahead of ownship on the map display was suggested.

The pilots noted that the way the procedures were defined and displayed in the cockpit from takeoff to touchdown made the operation feel something like a hybrid of visual and instrument flight operations. This was not intended as a criticism, but a recognition that the additional structure could support implementing some of the additional,

Table 3 Approach and landing event times

Operation Number	Aircraft Tail Number	Final Deceleration		Deceleration Decision Time (sec.)	Landing Time (sec.)	Time from final fix to landing (sec.)	Time from Deceleration to Landing (sec.)	Time from prior landing (sec.)	Notes
		Approach Fix Time (sec.)	Decision Altitude (feet)						
1	1	549	320	566	642	93	76	NA	
3	2	641	330	661	739	98	78	97	
5	3	738	300	757	817	79	60	78	
7	4	830	260	852	923	93	71	106	
9	5	920	320	941	981	61	40	58	2-stage deceleration at DDA, hard touchdown
11	6	1018	240	1042	1087	69	45	106	
13	7	1126	290	1148	1196	70	48	109	
15	8	1197	230	1222	1271	74	49	75	
17	9	1301	290	1323	1384	83	61	113	
NA	10	1394	400	1416	Go around after DAA	NA	NA	NA	Go around due to unstable approach
20	1	1482	360	1499	1586	104	87		
22	2	1590	370	1610	1693	103	83	107	
23	3	1667	340	1684	1752	85	68	59	
24	10 re-sequenced	1707	240	1739	1786	79	47	34	Approach flown slow for spacing (74kts). Pad occupied at DDA, but no 2nd go-around
NA	4	1778	Go around @ 220'	1807	NA	NA	NA	NA	Go around; pad occupied at DDA by tail #9
27	5	1865	NA	NA	1957	92			Slow final (~67 kts) and long-slow deceleration rather than distinct slow-down
28	6	1948	320	1970	2032	84	62	75	Landed slightly short of
30	4 re-sequenced	2044	375	2056	2113	69	57	81	Rushed touchdown short of vertipad; likely felt time pressure from following
31	7	2083	240	2114	2168	85	54	55	Final flown at 77 kts for spacing, 4 still on pad after
33	8	2188	160	2218	2254	66	36	86	Slow deceleration prior to DDA for spacing (initiated at
37	9	2353	330	2372	2439	86	67	185	Relative slow deceleration at DDA, drawn out landing
Aggregate Performance				Average time		83	61	89	
				Standard deviation		12	14	32	
				Minimum time		61	40	34	
				Maximum time		104	87	185	

suggested automation. The observation also raises the need to more closely assess the division of attention between being eyes-out looking for traffic versus being heads-down in the cockpit, if UAM operations conducted under VFR also incorporate cockpit displays designed to aid in increasing the tempo of flight operations.

An observation by the author was that the circular vertiport traffic pattern may have made late adjustments to spacing, such as needed to accommodate resequencing following a go-around, more difficult as compared to conventional airport traffic patterns. The circular pattern tends to encourage speed management as the primary or only factor for spacing adjustments, whereas the variable timing of the downwind to base turn of a conventional pattern makes path-stretching and its effects on spacing easy to predict and apply. Using only speed adjustment also has a limited range of affect when the applicable time of flight is short.

Overall, the pilots, many of whom who have flown high-fidelity motion-based eVTOL simulations at NASA and high-fidelity engineering simulators at the leading eVTOL developers, reported the multi-pilot environment afforded by the Flyers provided a useful tool for assessing and refining candidate technologies and procedures of UAM flight operations. While noting differences between the Flyer environment and real-world, flight operations, the consensus was that the Flyers provided a representative and valid tool for screening and refining concepts intended for use in visual flight operations. The Flyers, and similar simulation environments, should primarily be used to help design and inform future, higher-fidelity simulation and flight tests.

VII. Summary and Future Work

This report summarizes the results and observations from an exploratory simulation study of early, commercial UAM flight operations under VFR and pilot performed sequencing and spacing in the context of flight operations at a non-towered vertiport. The simulation involved ten evaluation pilots performing closed-circuit flights, taking off and landing at vertiport with a single vertipad. The pilots self-managed the sequencing and spacing of takeoffs and landings using current-day, FAA recommended procedures for operations at non-towered airports. For the relatively simple operations assessed in this study, the evaluation pilots found these procedures effective for eVTOL aircraft. The operational tempo achieved during the study was 72 vertiport operations per hour, although this tempo was accompanied by two go-arounds. The average time the vertipad was dedicated to aircraft conducting “expedited” departures was 30 seconds while the average for landings was 61 seconds. Pilot comments suggest procedural modifications and technology enhancements intended to improve the operations in terms of reducing pilot workload, occurrences of go-arounds, and vertipad occupancy times. The pilots also provided feedback on the medium-fidelity, multi-pilot simulation environment (i.e., the UAM Flyers”) itself as a tool for assessing and refining procedural and technologies for UAM. Their comments were supportive of the Flyers complimenting more traditional, single-aircraft simulation tools.

The Flyers are currently being used in conjunction with the FAA to assess initial UAM integration at a major international airport, as well as supporting NASA research into concepts and technologies intended to facilitate UAM operations consistent with the Midterm operations stage as described in the FAA’s UAM ConOps.

VIII. References

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