

Simulator Evaluations of Increasing Automation in an eVTOL Vehicle on Pilot Performance of Secondary Tasks

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The Automation-Enabled Pilot (AEP) studies began with a goal to develop an alternative means of compliance for novel powered lift aircraft. The first AEP study focused on developing a set of flight test maneuvers (FTM) for evaluating advanced automation functions in aircraft as an alternative means of compliance. This paper describes the second study in the series (AEP-2), particularly the development and findings associated with pilot performance of a secondary task. The AEP-2 study evaluates the effect of varying levels of automation on pilot workload during the transition from forward flight to hover for a lift-plus-cruise (LPC) aircraft during approach. A secondary task, traffic detection and avoidance, was designed to evaluate how the pilot-automation interaction can change pilot behavior including their scan of the cockpit displays and the out-the-window view.

I. Introduction

This paper is focused on the effect of increasing automation on a pilot's performance of a secondary task, traffic detection and avoidance, during the transition from forward flight to hover in an LPC aircraft. One proposed solution to the control challenges presented by electric vertical takeoff and landing (eVTOL) aircraft is increasing automation to assist the pilot. The use of indirect flight controls allows for a greater diversity of proposed aircraft designs that must be evaluated [1]. In this study, three different levels of assistive hover automation (AHA) concepts were compared for their effect on performance throughout approach. The Simplified Vehicle Control Concepts that were developed for this conceptual Lift Plus Cruise eVTOL vehicle, including the Assistive Hover Automation (AHA) strategies evaluated in this study, are discussed in greater detail in [2].

II. Lift Plus Cruise Vehicle

The Lift Plus Cruise (LPC) aircraft model flown in this simulation, shown in fig. 1, was developed by NASA's Revolutionary Vertical Lift Technology (RVLT) project [3]. The aircraft uses its lifting rotors to takeoff and at low speeds, while at higher speeds the aircraft is able to conserve energy by staying on the wing. Further details on the control concepts and lift modes can be found in [2].

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Fig. 1 NASA RVLTL Lift-Plus-Cruise conceptual model.

III. Assistive Hover Automation (AHA) Concepts

This simulation evaluated three levels of Assistive Hover Automation (AHA) on an approach to landing maneuver to assess the effect on performance, pilot workload and safety. The AHA levels are briefly described below; further information can be found in [2].

- AHA-0 serves as a baseline “hover” mode, which engages only when the groundspeed decreases below 10 knots and does not assist with the deceleration.
- AHA-1 activates a deceleration to reach zero velocity at a target location indicated on the map display. The predicted hover location does not account for disturbances and will shift in certain environmental conditions like high gusts.
- AHA-2 drives a deceleration rate to achieve zero velocity at a position chosen on the map display. It locks onto the coordinates and will adjust the deceleration rate to account for disturbances.

IV. Cockpit Displays

The pilots were provided with three informational displays: a Navigational display, a Primary Flight display (PFD), and a Health Status display. The navigational display contains the flight plan with waypoint altitude and velocity constraints, trajectory lines to aid the pilot in turns, as well as TCAS-like indicators (Traffic Alert and Collision Avoidance System) for nearby aircraft with color codes based on separation distance. In addition, this display contains the hover circle which indicates where the aircraft will reach zero velocity if hover is armed at that moment (for AHA-1 and AHA-2) (see fig. 2). To maintain view of the landing pad during approach, there is a downward facing belly camera that the pilot can activate that replaces the navigation display.

The PFD contains the flight director, pitch ladder, horizontal situation indicator, glide path marker, along with the altitude and speed tapes that contains MCP (mode control panel) targets when active (see fig. 3). There are also flight mode annunciators (FMA) at the top of the PFD that the pilot can reference to determine if hover mode is engaged. The health and status display contains information about the lift mode and AHA level as well as information about the power to each rotor and control inputs (see fig. 4). In addition to the out-the-window view, there are two chin windows to the left and right of the pilot seat seen in fig. 5. Further details on the displays and informational elements can be found in [4].

V. Arrival Procedure

The scenario under study was an arrival procedure into a heliport at Edwards Air Force base. The arrival consisted of a STAR (Standard Terminal Arrival Procedure), STAR transition, approach and approach transition to helipad H1 shown in fig. 6. The arrival procedures were developed from current RNP-AR (Required Navigation Performance Authorization Required) procedures with consideration for the envisioned high-capacity operations of UAM. The flight path was built of radius-to-fix (RF) legs to allow for curved legs with RNP 0.1 constraints which permit up to 0.1 nm in lateral deviation and 75 feet of vertical deviation [5]. Pilots were instructed to fly at 100 kts and slow to 70 kts by the initial approach fix (IAF) just prior to the turn onto final, and to maintain 70 kts until arming the AHA in order to stay

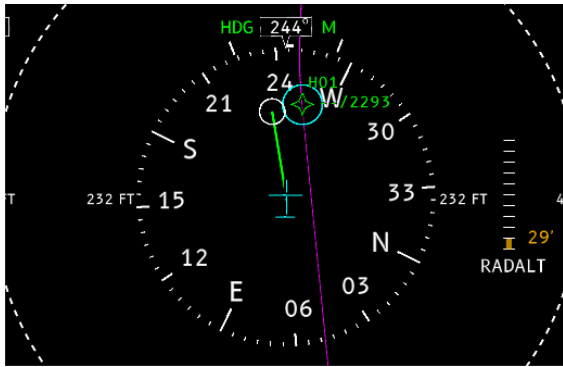


Fig. 2 Navigation Display



Fig. 3 Primary Flight Display (PFD)

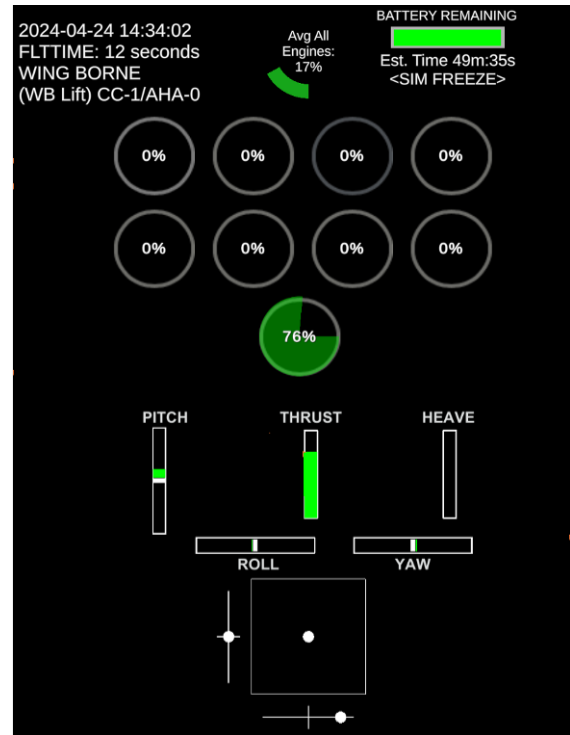


Fig. 4 Health Status Display



Fig. 5 VMS Cockpit

on the wing and conserve energy. After the turn onto final, the pilot captures a 6- or 12- degree glide path (see fig. 7 and 8). For the 12-degree glide path, there was an additional deceleration to 45 kts at the GORDO waypoint midway down the final approach (see fig. 8). The pilots were held to RNP 0.1 precision until the decision altitude defined as 200 feet AGL (above ground level). An approach and final approach procedure were derived from this arrival and are discussed further in the Experimental Methods section.

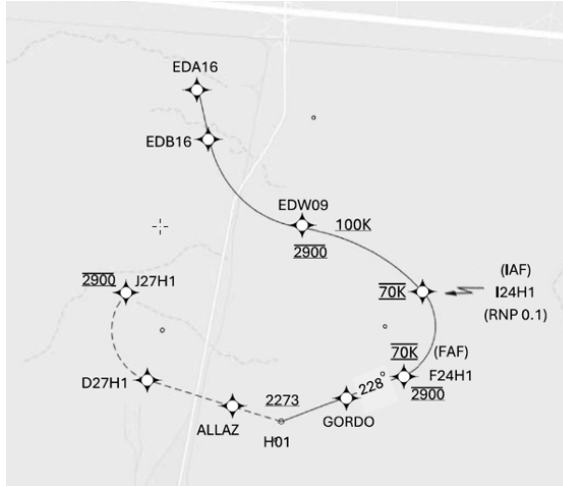


Fig. 6 AEP-2 Arrival Procedure Flight Path

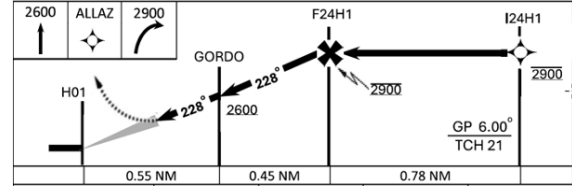


Fig. 7 Final Approach Profile for 6 degree glide path

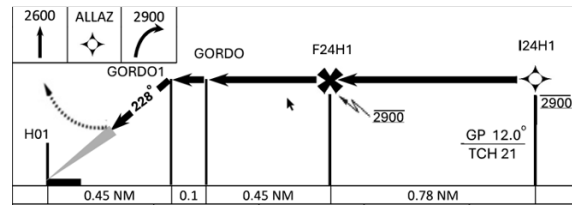


Fig. 8 Final Approach Profile for 12 degree glide path

VI. Experimental Methods

A. Description of Participant Pilots

Eleven pilots were recruited for this simulation study including test pilots and operational pilots from industry. The sample size of pilots is not sufficient for a full statistical analysis but satisfactory for observing certain trends between the independent conditions. The various sources of participants are listed below:

- Airworthiness (3 test pilots)
- Aircraft Evaluation (3 pilots)
- Flight Standards (2 pilots)
- Industry (eVTOL manufacturer) (3 test pilots)

B. Participant Training

Prior to the study, each pilot received an Aircraft Training Manual for the LPC aircraft and procedures flown. Their first day was spent in the fixed-base ACEL-RATE (Aerospace Cognitive Engineering Lab Rapid Automation Test Environment) simulator. The training began with a discussion of the pilot's background in powered-lift aircraft and aircraft evaluation as well as an overview of the study including a breakdown of the study schedule of activities. The pilots were trained on the aircraft controls, automation concepts, informational displays, procedures flown as well as the rating scales used to evaluate each run. Further details on the pilot training, ACEL-RATE lab environment and Vertical Motion Simulator (VMS) can be found in [4].

C. Segments of the Arrival

In addition to the full arrival procedure, shorter approach and final approach segments were assessed:

- The full arrival begins just prior to the STAR transition waypoint (EDA16) and continues through the STAR, approach transition and then final approach to touchdown. The full arrival procedure has a glide path of six degrees.

- The full approach procedure begins on the turn to final prior to the F24H1 waypoint and continues through the final approach and touchdown. The full approach may be flown with a 6- or 12- degree glidepath.
- The final approach begins midway down the final approach path just past the GORDO waypoint and continues to touchdown. The final approach may be flown at a 6- or 12- glidepath.

While each block focused on a particular segment of the arrival procedure, there were variations in winds, visibility, and glide path angle across runs within a given block (see Table 1). Additionally, the AHA level was randomized across sub-blocks to mitigate learning effects. Further details on these variations will be discussed in following sections.

Table 1 Block descriptions

Blocks	Total Runs	Visi- bility	Winds	AHA	Glide- path	Conflicting Traffic	Conflicting Runs
Arrival	6	DVE, GVE	RQH, NW	0	6°	slow preceding quadcopter	3
Full Approach	24	GVE	QH, QT, NW	0 – 2	6°,12°	late arrival and late departure from H1	6
Final Approach	15	IMC	CW, QT	0 – 2	6°,12°	taxiing aircraft to H1 taxiing aircraft to H1	3

D. Description of a Secondary Task

A secondary task was designed to ensure the pilot maintains an out-the-window scan and work towards a more operational environment. Each VMS run included traffic, either nominal or conflicting traffic. The conflicting traffic conditions required the pilot to either slow down on approach or declare a go-around to maintain safe spacing; while nominal traffic conditions consisted of distant aircraft and did not require pilot intervention. Nominal spacing was considered about 20-30 seconds separation to represent the expected high-density operations of UAM. Traffic scenarios were designed for each of the three procedure segments with each having unique conflicting traffic designs. The conflicting and nominal traffic conditions were randomized across the runs for each segment. Pilots were told that decision height was 200 feet AGL and allowed to execute a go-around or slow on approach.

- For the full arrival, the conflicting traffic involved a preceding, slower quad-copter on the same approach path to H01.
- For the full approach, two different conflicting traffic scenarios were designed. The first scenario consisted of a late arriving aircraft on a different approach pad to the same destination helipad, while the second involved a late departing aircraft from the destination helipad. Additionally, a static queue of aircraft was placed on the adjacent taxiway to set up the conflicting traffic scenario for the final approach.
- For the final approach, the conflict scenario involved an aircraft slowly taxiing towards the destination helipad from the taxiway queue as the pilot makes their approach. To effectively set up this scenario, a static queue of aircraft was placed on the taxiway adjacent to the helipad throughout the full approach and final approach runs. For all traffic conditions, the queued vehicles were visible to TCAS and indicated on the pilot's navigation display.

E. Data Collection

In addition to video recording of each run performed in the VMS, multiple data points were collected including:

- A set of performance criteria for the flight trajectory and touchdown defining the maximum allowable deviation allowed for desired or adequate performance for a given metric such as cross track error or vertical speed at touchdown. A discussion of these performance metrics can be found in a companion paper [6].
- Following each run, the pilot was provided with their performance metrics and asked to give a Cooper-Harper handling qualities rating (see fig. 9) and Bedford workload rating (see fig. 10). Further description of the Cooper-Harper and Bedford rating scales can be found in [7] and [8] respectively.
- Throughout the test runs, the pilots wore Tobii 3 eye-tracking glasses to collect information about their scan patterns and focus on various areas of interest including the displays and out-the-window view [9].

At the end of the day, the pilot was given a debriefing survey to provide feedback on the automation, display utility, and feedback about the simulation study. Pilots were also given the chance to discuss concerns or provide feedback verbally.

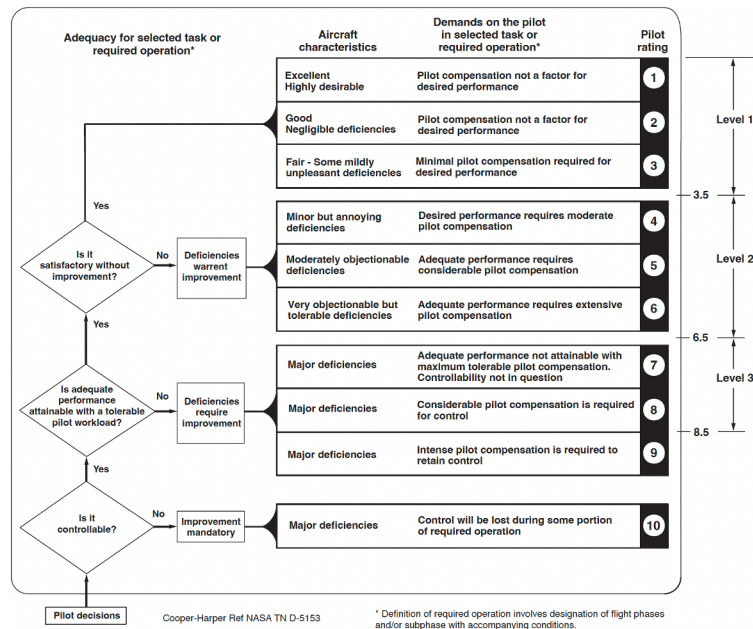


Fig. 9 Cooper-Harper Scale

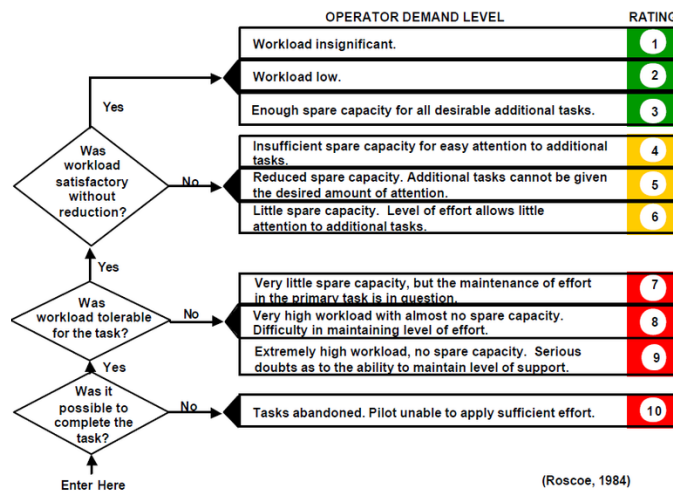


Fig. 10 Bedford Scale

VII. Simulation Environment

At the start of their second day, pilots were provided a safety briefing and up to 30 minutes of run time to acclimate to the inceptors, motion cues, and field-of-view in the VMS cab. The day consisted of 45 measurement runs split across three 90-minute sessions with a 30-minute break between each. Throughout each session, a researcher was present in the jump-seat to assist with collecting handling quality and workload ratings. Each procedure block is described in more detail in the next sub-sections.

A. Block One: Full Arrival

The first block consisted of six runs of the full arrival procedure. For the full arrival, all runs were completed with AHA-0 and a 6-degree glide path; however, there were random variations in the wind conditions (no winds (NW) and quartering headwinds (QH) of 17 knots with 5 knot gusts), visibility (good visibility (GVE) or misty conditions (DVE)) and traffic scenarios for each run such that there were 3 nominal scenarios and 3 conflicting traffic scenarios. Given the length of the full arrival, two Cooper-Harper and two Bedford ratings were collected for each run. One rating was given for the initial segment (up to the final approach fix) and the second for the final approach to touchdown segment.

B. Block Two: Full Approach

The second block consisted of 24 runs organized into three groups of eight runs such that the AHA level was held constant within any group of 8 and all AHA levels were utilized for the total set of 24 runs in random order. Within each group there was random variation of glide path of 6- and 12- degrees, as well as wind variations between 17 knot quartering headwinds (QH) and quartering tailwinds (QT) from the left or right with 5 knot gusts, as well as a no wind condition (NW). All 24 full approach runs were performed in a good visual environment (GVE). The traffic scenarios were varied such that each subgroup consisted of six nominal traffic runs and two conflict conditions (late arriving or late departing aircraft) in random order.

C. Block Three: Final Approach

The last block consisted of 15 final approach runs split across three subgroups of five runs. Like the full approach runs, the AHA level was held constant for each subgroup such that all three AHA levels were utilized in random order in the session. Additionally, the visibility was IMC (instrument meteorological conditions) and held constant across all runs with a breakout altitude of about 250 feet AGL. Within each subgroup the winds were varied between left and right crosswinds (CW) and quartering tailwinds (QT) of 17 knots with 5 knot gusts. The traffic conditions were randomized such that each subgroup consisted of four nominal runs and one conflict run with an aircraft taxiing to the destination helipad.

VIII. Results

The primary focus of this section is the Cooper-Harper and Bedford ratings and pilot questionnaire responses; a detailed analysis of the performance data can be found in a companion paper [6]. However, it should be noted that generally, performance and repeatability increased with the automation level.

A. Cooper-Harper & Bedford Ratings

For the full arrival procedure performed with AHA-0, the initial segment had handling quality and workload ratings in the satisfactory range (ratings of three or less). However, the final segment had median ratings in the ‘deficiencies warrant improvement’ region (see figs. 11 and 12). This is consistent with the pilot questionnaire responses indicating that the handling and workload of the scenarios was manageable, but that the time available to stabilize the aircraft on final was insufficient for many pilots (see fig. 13).

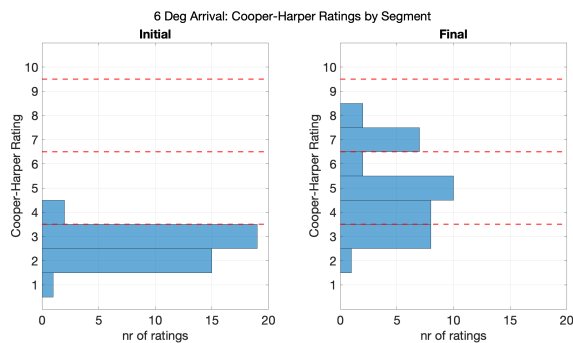


Fig. 11 Cooper-Harper Ratings for Arrival

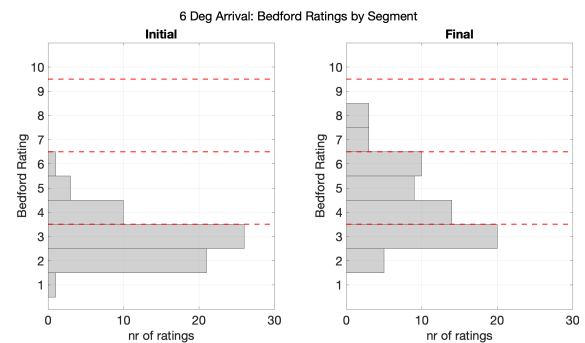


Fig. 12 Bedford Ratings for Arrival

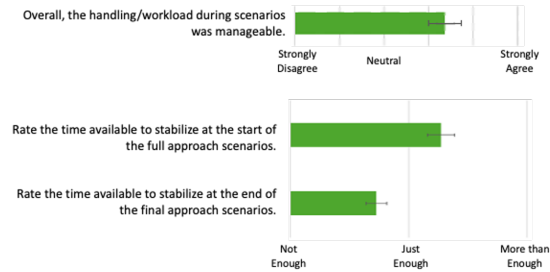


Fig. 13 Pilot Responses

For the full approach and final approach procedures, pilot ratings generally improved with increased automation with the 6-degree glide path runs showing improvement more consistently than the 12-degree glide path. For the 6-degree full approach, there was slight improvement across the AHA levels with only the AHA-2 runs showing median Cooper-Harper ratings in the satisfactory without improvement region (see fig. 14). This trend holds for the 12-degree full approach runs; however, less improvement is shown in the Cooper-Harper ratings between AHA-0 and AHA-1 (see fig. 16). In contrast, the median Bedford rating decreased 1 unit per AHA level increase, potentially due to the increased time compression of the 12-degree approach compared to the 6-degree (see figs. 15 and 17).

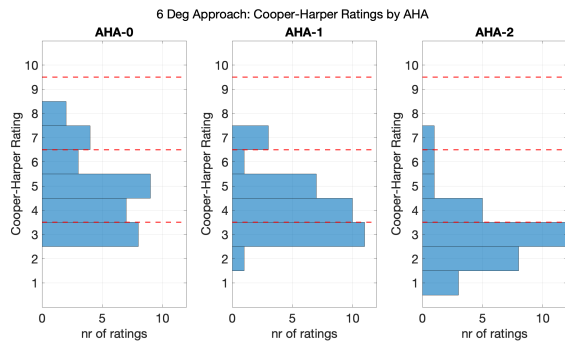


Fig. 14 Cooper-Harper Ratings for 6-deg Approach

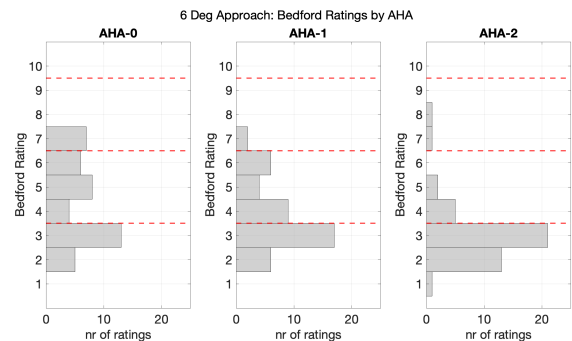


Fig. 15 Bedford Ratings for 6-deg Approach

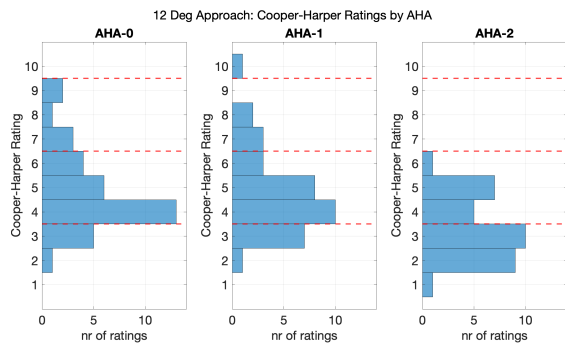


Fig. 16 Cooper-Harper Ratings for 12-deg Approach

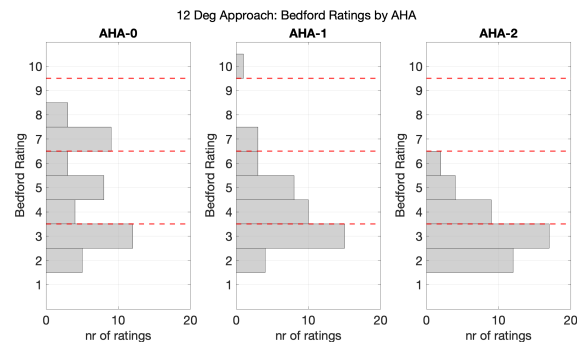


Fig. 17 Bedford Ratings for 12-deg Approach

The final approach runs demonstrates similar trends with the 6-degree glide path showing more consistent improvement across AHA levels compared to the 12-degree glide path. However, in contrast with the full approach larger improvements are seen between AHA-0 and AHA-1 with the handling quality rating dropping from the upper region of 'warrants improvement' to the upper region of 'satisfactory without improvement' for the 6-degree glide

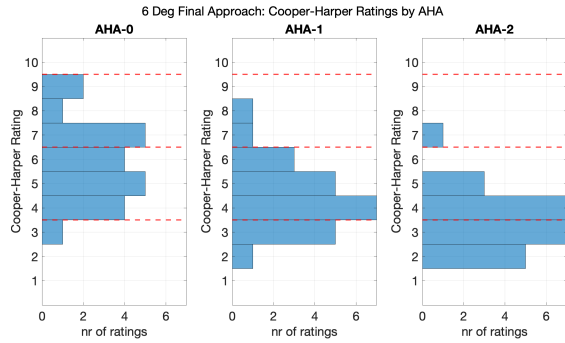


Fig. 18 Cooper-Harper Ratings for 6-deg Final

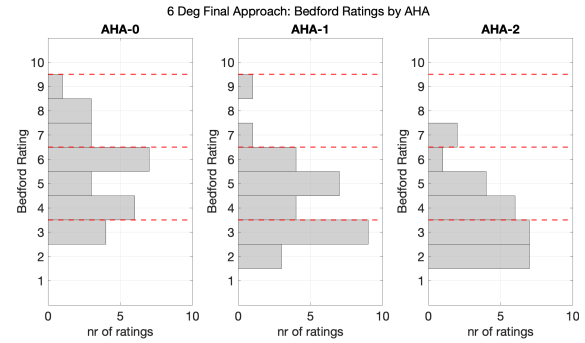


Fig. 19 Bedford Ratings for 6-deg Final

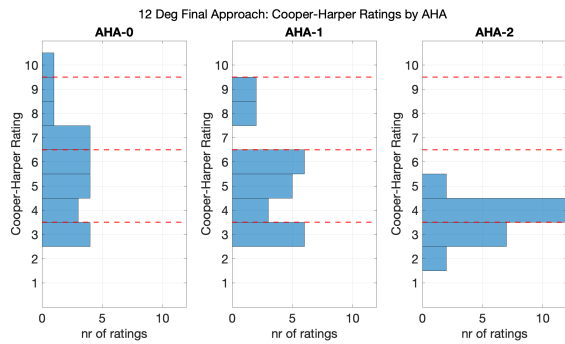


Fig. 20 Cooper-Harper Ratings for 12-deg Final

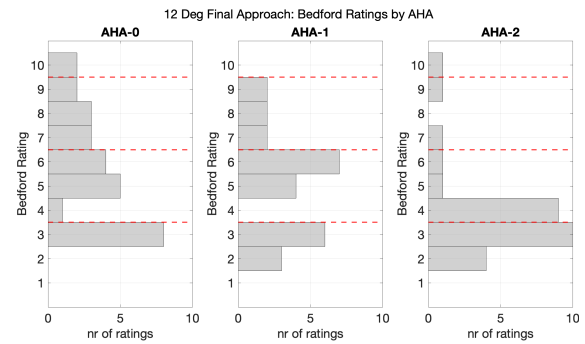


Fig. 21 Bedford Ratings for 12-deg Final

path (see fig. 18). The Bedford ratings show a similar but reduced improvement with the median rating only reaching the satisfactory without improvement region for AHA-2 (see fig. 19). The ratings for the 12-degree final approach show minimal improvement between AHA-0 and AHA-1 and in contrast with the 6-degree final, the median ratings do not reach the satisfactory without improvement region for the Cooper-Harper or Bedford ratings (see figs. 20 and 21). Given that the final approach is the most time-compressed procedure and further compressed with the shorter duration 12-degree glide path compared to the 6-degree, these results confirm the pilots' reporting of insufficient time to stabilize the aircraft prior to touchdown.

B. Eye-Tracking & Display Ranking Findings

Areas of interest were defined for each display and out-the-window view and grouped as either information displays or out-the-window displays to assess the heads down time compared to the heads up or time spent looking out-the-window for each run (see fig. 22).

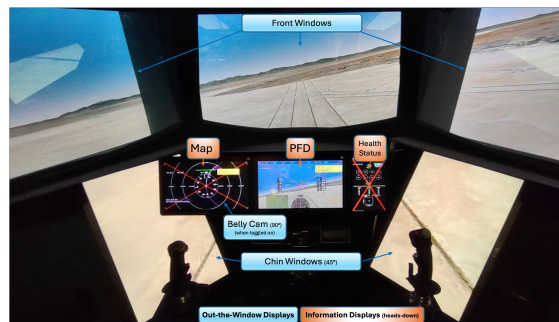


Fig. 22 VMS Cockpit - Areas of Interest

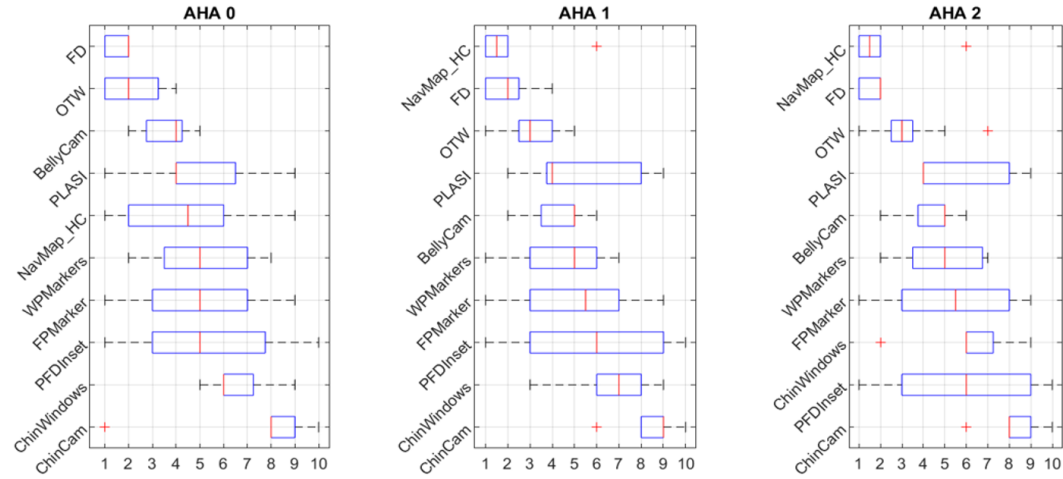


Fig. 23 Pilot Rankings of Utility of Display Elements

Eye-tracking data confirms the pilots' utility ranking of the different displays available for each AHA. Overall, 87% of pilots' focus was on the PFD or front window views, while less than 1% of their focus was on the Health Status display or chin windows. It is worth noting that the conditions were generally nominal for these flight segments. The introduction of an off-nominal event might increase the pilots' focus on the Health Status display. For all AHA levels, the flight director (on the PFD) was ranked in the top two most utilized display elements while the chin windows consistently ranked as the least utilized display (see fig. 23). Pilots stated that the flight director was most useful for precisely following the flight path up until the final approach segment whereas the belly camera was most useful late in the final approach for maintaining sight of the landing area and centering the aircraft on helipad at touchdown. For the higher AHA levels, the hover circle on the navigation display overtook the flight director as the most utilized display element as the hover predictor needed to be precisely placed over the helipad when engaged for best touchdown performance (see fig. 23).

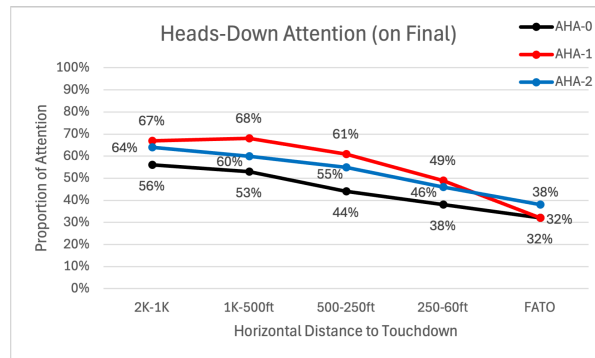


Fig. 24 Heads-Down Attention on Final

On the final approach, heads-down attention decreased as the pilots' progressed towards the landing site [10]. Over half of their attention was heads-down at 1,000 – 2,000 feet from the helipad but decreased by 20% – 30% depending on the AHA level (see fig. 24). However, it was observed that the heads-down attention increased by 9% - 14% for the higher automation levels with AHA-1 showing the largest increase until the FATO (Final Approach and Takeoff) boundary is reached. By time the FATO boundary was reached, this increase in heads-down attention weakens for AHA-1 and no difference is seen compared to AHA-0, while AHA-2 still shows a 6% increase in heads-down time. The higher proportion of heads-down time seen in AHA-1 compared to AHA-2 can be explained by the fact that the hover prediction in AHA-1 does not correct for disturbances forcing pilots to continually look down at the navigation display to adjust the prediction position over the helipad.

Further analysis of the eye-tracking data can be found in a related NASA technical publication [10].

C. Effects of Traffic

Most pilots maintained desirable performance throughout the initial arrival procedure and provided satisfactory without improvement ratings for the handling qualities and workload. Merging eye-tracking and performance data highlights how traffic conditions can negatively impact the route conformance task. When analyzing the vertical and lateral deviations throughout the initial arrival up to the final approach fix (FAF), deviations are seen in moments when the pilot is scanning for traffic out the window. This may indicate that the pilots' workload is higher than self-reported with the Bedford ratings as a few-second distraction resulted in performance deviations near the margins (see figs. 25 and 26).

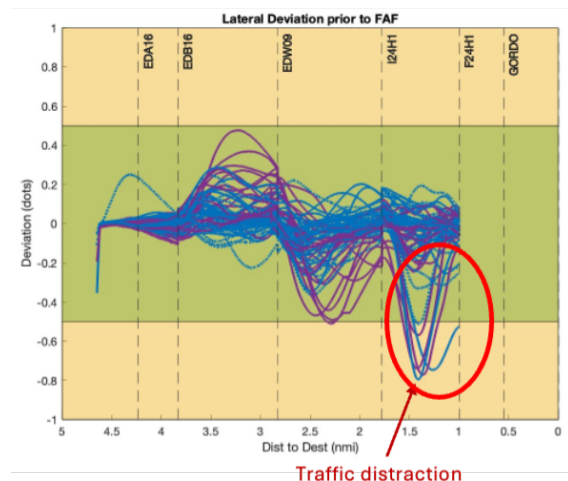


Fig. 25 Lateral Deviation prior to FAF

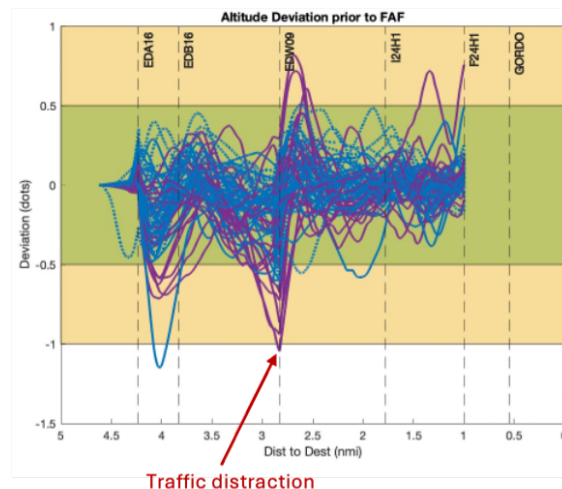


Fig. 26 Altitude Deviation prior to FAF

The most apparent effect of traffic was observed in the final approach procedure. All but one pilot had a close-call, defined as less than 40 feet of separation, with the intruder aircraft taxiing towards the helipad. Moreover, almost half of the pilots had a likely collision with the intruder aircraft defined as less than 14 feet of separation. While this segment presents the most difficult conditions given the time compression of starting mid-way down the final approach, it occurred at the end of the day when pilots were primed for traffic conflicts. In addition, the benefit of an uncluttered environment at Edwards AFRC was countered by the degraded visibility as well as crosswinds that resulted in an aircraft attitude with a sub-optimal field-of-view of the helipad. However, when AHA level is considered, it's clear that most of the close-calls and collisions occurred in the AHA-2 condition, accounting for seven of the 12 instances (see fig. 27). While eye-tracking data showed the proportion of heads-down attention was similar by time the aircraft reached the FATO boundary, pilots missed opportunities to spot the intruder aircraft earlier in the approach path while they were arming the hover automation. A hammer plot of the out-the-window view in the right crosswind condition (fig. 28) shows the intruder aircraft was visible out the left window for about 20 seconds after breakout and was largely hidden behind the window partitions afterward illustrating the importance of maintaining an out-the-window scan throughout the final approach.

IX. Major findings

Overall, the results indicate that Assistive Hover Automation (AHA) reduces pilot workload on final and improves performance. However, automation can affect pilot scanning behavior and their ability to detect hazards in the landing environment including intruder traffic. Moreover, the effect of automation on a pilot's behavior may not be immediately apparent and is dependent on other factors such as traffic density, winds and visibility. The results emphasize the importance of the environment and activities envisioned for simulation evaluations of novel aircraft and operations including realistic visuals and motion cues. Without the addition of traffic and eye-tracking data, only the benefits of increasing automation would be observed. Furthermore, it is valuable to obtain multiple measures of performance and workload to supplement the subjective pilot ratings collected.

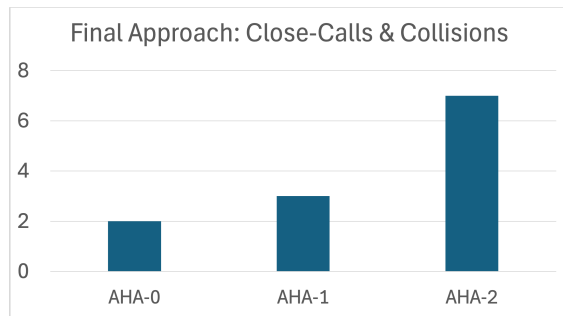


Fig. 27 Close-calls and Collisions by AHA

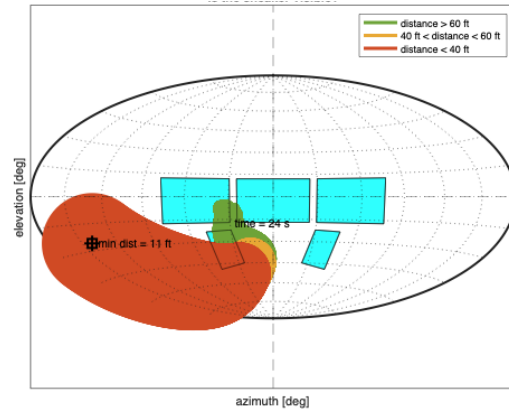


Fig. 28 Hammer Plot of Out-the-Window View

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