Towards an Improved Pilot-Vehicle Interface for Highly Automated Aircraft: Evaluation of the Haptic Flight Control System

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ABSTRACT

The control automation and interaction paradigm (e.g., manual, autopilot, flight management system) used on virtually all large highly automated aircraft has long been an exemplar of breakdowns in human factors and human-centered design. An alternative paradigm is the Haptic Flight Control System (HFCS) that is part of NASA Langley Research Center's Naturalistic Flight Deck Concept. The HFCS uses only stick and throttle for easily and intuitively controlling the actual flight of the aircraft without losing any of the efficiency and operational benefits of the current paradigm. Initial prototypes of the HFCS are being evaluated and this paper describes one such evaluation. In this evaluation we examined claims regarding improved situation awareness, appropriate workload, graceful degradation, and improved pilot acceptance.

Twenty-four instrument-rated pilots were instructed to plan and fly four different flights in a fictitious airspace using a moderate fidelity desktop simulation. Three different flight control paradigms were tested: Manual control, Full Automation control, and a simplified version of the HFCS. Dependent variables included both subjective (questionnaire) and objective (SAGAT) measures of situation awareness, workload (NASA-TLX), secondary task performance, time to recognize automation failures, and pilot preference (questionnaire).

The results showed a statistically significant advantage for the HFCS in a number of measures. Results that were not statistically significant still favored the HFCS. The results suggest that the HFCS does offer an attractive and viable alternative to the tactical components of today's FMS/autopilot control system. The paper describes further studies that are planned to continue to evaluate the HFCS.

1 INTRODUCTION

There have been many criticisms of the current flight management/autoflight system in modern aircraft (Weiner, 1998). In 1996, the FAA determined that a major problem with the modern flight deck was the disconnect between the pilot and the autoflight systems in the aircraft (Abbott, et. al, 1996). This disconnect led to instances where pilots would remark, "Why is the aircraft doing that?" or "What's it doing now?" There are many ways to frame and consider these problems in terms of human factors. The perspective considered in this paper is one of languages and interfaces. After framing the problem in this way, the paper briefly describes the Haptic Flight Control System (HFCS) and the potential benefits of the HFCS. Next, it describes a simulation study that evaluated some of these benefits.

1.1 Languages and interfaces

There are three 'languages' that the pilot uses to command the modern highly automated aircraft. The first is manipulating the control surfaces and propulsion systems via the control inceptors, that is, stick, rudder and throttles. Examples of the commands are pitch up, bank left, and increase thrust. The mapping of the commands onto the actions on the control inceptors is intuitive. Pull back to pitch up, turn right to bank right, push the throttles forward for more thrust.

The second language is based on direction and speed. The commands in this language are heading commands, airspeed commands, altitude and altitude rate commands. These commands are usually made through the knobs and dials on the autoflight system.

The third language is one of earth-referenced locations and clock time. It is by far the richest language. The pilot can specify an approach into Reagan National Airport, a departure from Heathrow, a specific jetway in the airspace system, or a waypoint by its latitude and longitude. The commands are given to the FMS cockpit display unit through an alphanumeric keypad with single purpose and multi-use buttons. The language has an elaborate and rigid syntax.

The pilot of a modern aircraft is faced with three different languages, using three different input devices and all three different systems can be controlling the aircraft in some combination at the same time. Given the limitations of the human pilot, this design is a recipe for confusion, high memory workload, high display requirements, and miscommunication. This error-proneness is further exacerbated by the ability to preprogram route changes and arm modes – allowing for the passage of time between error commission (e.g., when the pilot sets a command) and the manifestation of that error (e.g., when the aircraft actually performs that command).

We have developed a single flight control system that speaks all three languages and uses a single intuitive interface – it's called the Haptic-Multimodal Flight Control System.

1.2 The Haptic-Multimodal Flight Control System

In the Haptic-Multimodal Flight Control System (HFCS), the pilot issues commands to the aircraft solely through the stick and throttle (Schutte, et al, 2007, Goodrich, et al, 2011). The HFCS can best be described as a point and shoot interface. All of the route information currently in the FMS (e.g., waypoints and airway structure) is presented on the Primary Flight Display (PFD) and the Map Display (MD). The pilot points the aircraft at one of these features, selects it, pulls the trigger on the stick and the automation then flies the aircraft according to the procedure in the database. To fly to a heading, the pilot simply turns the aircraft to that heading and pulls the trigger. Since no published procedure is selected, the automation holds that heading. If the aircraft is pointing at multiple features, the pilot can cycle through them and pull the trigger when the feature he wants is selected. If the pilot wants to arrive at the next waypoint at a certain time, he points the aircraft at that waypoint, pulls the trigger, then moves the throttle while watching the predicted arrival time to that waypoint (displayed on the PFD and MD). He adjusts the speed until it is at the desired arrival time, and pulls the trigger on the throttle. Even non-published commands such as fly parallel to a jetway can be easily performed. Nearly every tactical command that can be given to the current stick/autoflight/FMS combination can be accomplished through the two inceptors.

The common elements between the pilot and the automation with regard to the control of the aircraft are the back-driven stick and throttle. When the automation moves the aircraft, the pilot can see and feel what the automation is doing by watching the controls and/or having a hand on the inceptor. When the pilot moves the aircraft using the inceptors, the automation is aware of what the pilot is doing.

One feature that current automation has but is missing from HFCS is the ability to preprogram an entire route and then 'set it and forget it'. While the pilot can plan the route on a separate planning device and display this plan on the PFD and MD, the automation will not fly the entire route – rather the pilot has to make all coarse turns and altitude changes. The automation will accomplish the individual features with all the efficiency of current automation, but the pilot must be in the loop whenever major changes in the aircraft's trajectory are made. This lack of preprogramming provides a benefit from a human factors perspective. Humans become complacent with reasonably reliable pre-programmed automation. But one of their primary roles is to monitor the mission progress and the automation. In order to effectively monitor over long durations they need to be engaged in the task at regular intervals. Having the pilot perform the simple task of pointing the aircraft to the next goal can provide just such engagement. In the HFCS, the pilot will never ask what the aircraft is doing, because the pilot is the one that just commanded it to do it.

One potential Achilles Heel for the HFCS is that the pilot must remember to reengage and make the next move. Humans in general have a very difficult time with this prospective memory – easily forgetting or becoming distracted. Automation, however does not suffer from this problem. So the automation is used to prompt the pilot (at various levels of interruption) that a move will soon need to be made, is pending, or has been missed. Thus if the HFCS is coupled to a jetway and is approaching a 'fork in the road' or decision point, the pilot will be given alerting cues. If the pilot has entered a plan (using a separate planning device), these cues can be more specific to the plan.

At first glance, the single-point-of-control concept can appear to be a technological step backwards. In a modern flight deck, the pilot rarely has to touch the control inceptor. In fact, the use of the control inceptor to fly the aircraft is virtually the hallmark of the unautomated aircraft. The HFCS appears to be increasing pilot workload back to the levels of manual flight before automation. The purpose of this study is to explore how pilots feel about this new control concept and to see how it affects their workload and their situation awareness.

2 METHOD

2.1 Participants

Twenty-four general aviation pilots were used as subjects. The subjects were all right-handed males with no color blindness. They were VFR-certified but not IFR-certified. Each had more than 50 hours and fewer that 300 hours total flying time and they had logged between 12 and 48 hours in the 12 months prior to the experiment.

2.2 Apparatus

The experiment used a PC-based flight simulation environment (Figure 1). The aircraft model used was a simplified version of a deHaviland Dash-8. The control inceptor was an active, force feedback side arm controller made by Stirling Dynamics, Ltd. There were no throttles (speed was automatically controlled in all conditions) or rudder pedals. There were two main displays, a Primary Flight Display (PFD) and a Map Display (MD). In addition to the MD, there was a planning interface that was implemented on a tablet PC to the subject's right. Three large out-the-window displays and a laptop computer were used to provide secondary tasking.

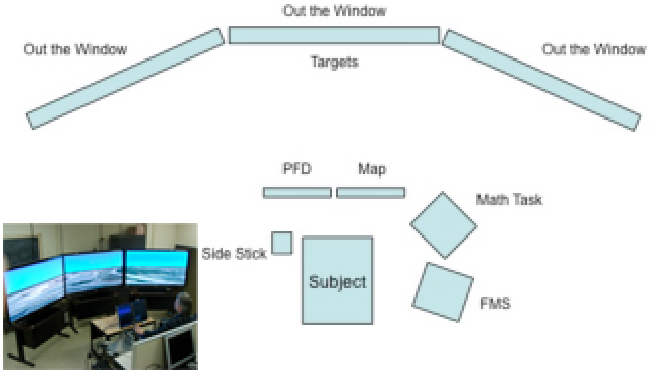

Figure -1: PC-based simulator

2.3 Subject Task

A test run for this experiment occurred in three phases. (1) Planning the route on paper, (2) entering the route into the electronic planner, and (3) flying that route using the simulator.

Planning the route on paper - For this experiment, we created an airspace over a fictitious island consisting of seven airports. Each airport had one or two runways. The terminal area was defined by pathways that were used for departures and approaches. Aircraft could fly from airport to airport using 18 airways connected by eight waypoints. The prescribed flight altitude for all airways was 2500 ft. Each subject an origin and a destination along with necessary charts and airway instructions. The subject then highlighted the route on the paper charts.

Entering the route into the electronic planner - The subject would take his paper map over to the electronic planner. He entered the route by 'connecting the dots' on the map. The route was then reviewed by both the subject and the experimenter. Then it was transmitted to the flight control and display system to be presented on the display (for all conditions) and used by the HFCS and Full Automation conditions to provide automated control.

Flying that route using the simulator - The simulator was initialized to a fixed point along the route and was paused. The subject was responsible for flying the aircraft to its destination along the route that he had planned and entered. At different points in the simulation, the subject was requested to make one of three changes: a strategic change in the route, which consisted of him making a change to the flight plan but required no change in his flight trajectory at that time; a tactical change that required him to fly a route parallel to the planned route (supposedly to fly by traffic); and a parallel runway change on approach. The run was always terminated before touch down.

2.4 Experimental Protocol

Over a two-day period, each subject spent 12 hours in the study. The first half day consisted of training on all tasks. The subject flew the simulation in the Manual mode (i.e., no automation assistance) in order to become acquainted with the simulator handling and performance. In the second half, the subject was trained on the first automation condition (Manual, HFCS, Full Automation). He was given one of four routes to plan/fly. The conditions and routes (see below) were counterbalanced. The subject then filled out a post run questionnaire. After a break, he was trained on another condition, given another route to plan and fly. Again, he was given the post run questionnaire. The subject left for the day.

The subject returned the next morning and was allowed to fly the simulator in the Manual mode to refresh his familiarity. Then the subject received training on the last condition and flew another run with this condition and route. After completing the post run questionnaire, the subject was given a break. The subject was then given one last route to plan and fly. One of the three automation conditions was assigned (counterbalanced). After the post run questionnaire, the subject was given a post experiment questionnaire and released. Thus each subject saw all three conditions at least once and saw one condition twice.

2.5 Experimental Conditions

There were three experimental conditions: Full Automation (FA), HFCS, and Manual. In all conditions, the subject received visual flight guidance on the PFD and MD as well as aural and tactile warnings of impending turns. PFD guidance used a tunnel in the sky with rings that the aircraft had to fly through.

Full Automation: The subject had only to monitor the flight. The automation was always coupled to the flight plan. Any tactical changes (i.e., runway changes, side-step maneuvers) were made in the electronic planner. This condition represents the most automated functionality of modern aircraft.

Haptic Flight Control System: The subject could lock on or couple to any straight line route segment (planned or published) and the automation would hold the aircraft on that segment. At the end of a segment, the automation would release control of the aircraft and the pilot would have to steer the aircraft onto the next segment. Once in the proximity of the next segment, the subject pulled the trigger on the side stick and the automation coupled to the path. When uncoupled to a path, the flight control system was essentially that of the Manual condition.

Manual: In the Manual condition, the subject would hand fly the aircraft using the stick. They were instructed to follow the centerline of the route as displayed on the PFD and fly through tunnel rings. Random winds were introduced to move the aircraft off course if its attitude was not attended to by the subject.

2.6 Run Definitions

Four runs were used in the experiment. In each run the subject was given tactical and strategic changes such as might be given from Air Traffic Control. The tactical changes were introduced by having the subject either fly an offset parallel to the planned course or make a runway change while on approach. The strategic change involved a change in the flight plan that required no immediate movement of the aircraft. In addition, one run contained an automation failure where the automation was turned off with no alert. This meant that in the FA condition, the aircraft would remain in a turn (flying in circles) and in the HFCS condition, the automation could not be recoupled after the turn.

2.7 Secondary Tasks

Workload was increased for each subject by giving them two secondary tasks – a visual task and a cognitive task. The visual task required the subject to monitor the center out-the-window display and look for dots that randomly appeared and then disappeared. The dots had no operational significance. The cognitive secondary task was a simple addition of two double-digit numbers. Thus the subject could set his own pace regarding answering the math questions. The subject was told that flying the aircraft was always to be his highest priority.

2.8 Dependent Variables

The following dependent variables were recorded: Situation Awareness was recorded using SAGAT (Endsley, 1988) and subjective ratings. Workload was measured using the NASA-TLX (Hart and Staveland, 1998) and subjective ratings. Pilot Involvement was measured using subjective ratings. Secondary task performance was objectively measured. The time to recognize the automation failure was measured from the onset of the failure until the subject either verbalized the problem or corrected for the problem – whichever came first. Remaining subjective data was collected using questionnaires.

2.9 Hypotheses

Hypothesis 1: Flight Situation Awareness for the HFCS condition will be higher than that of the FA condition.

Hypothesis 2: Secondary Task Situation Awareness for the HFCS condition will be higher than that of the Manual Condition.

Hypothesis 3: Secondary Task Performance for the HFCS condition will be higher than that of the Manual condition.

Hypothesis 4: Subjective Workload for the HFCS condition will be less than that of the Manual condition.

Hypothesis 5: Automation failure will be detected sooner in the HFCS condition when compared to the FA condition.

Hypothesis 6: Subjects will prefer the HFCS condition over the Manual and the FA conditions.

3 EXPERIMENT RESULTS

While all results favored the HFCS condition and the hypotheses, only a few of those turned out to be statistically significant. All statistical tests were performed using IBM$^©$ SPSS$^©$ Statistics Version 19.0.

Hypothesis 1: Situation awareness was measured objectively using the SAGAT score. While the results favored the hypothesis (FA: Correct = 138, Incorrect = 86; HFCS: Correct = 149, Incorrect = 75), a Pearson Chi-Square test of the differences between the HFCS condition and the FA conditions was not significant $\chi^2(1, N=448) = 1.73, p=.29$.

The post-run questionnaire asked the subject to rate their awareness regarding aircraft position, aircraft heading, and the progress of the aircraft with regard to the flight plan. Table 1 shows the data. While the raw data favors the hypothesis for all three, independent t-tests demonstrated that only the difference for the progress awareness question was significant, $t(62) = 2.00, p < .05$.

Table 1: Results of Subjective Awareness Assessment

	FA		**HFCS**	
	M	***SD***	***M***	***SD***
Aircraft Position	13.9	4.0	15.1	3.3
Aircraft Heading	13.6	4.6	13.9	4.5
Aircraft Progress to Plan	15.3	3.8	16.9	2.4

Hypothesis 2: Comparisons between Manual and HFCS of SAGAT measurements for the secondary tasks yielded results that favored the hypothesis (HFCS: Correct = 113, Incorrect = 111; Manual: Correct = 101, Incorrect = 123). However, these results were not statistically significant $\chi^2(1, N=448) = 1.29, p=.26$.

Hypothesis 3: Again, for this hypothesis, the results all favored HFCS but not statistically, although the Math Speed scores approached significance ($t(62) = -1.85, p = .07$). Table 2 shows the raw data.

Table 2: Results of Secondary Task Performance

	HFCS		**Manual**	
	M	***SD***	***M***	***SD***
Target Accuracy (% Correct)	81.4	12.5	75.5	18.1
Math Accuracy (% Correct)	96.6	2.2	96.0	2.9
Math Speed (Question/min)	4.3	2.0	3.4	2.0

Hypothesis 4: Subjective workload was measured using the NASA-TLX workload instrument. The TLX asks the subject to rate six different workload categories (Mental, Physical, Temporal, Performance, Effort, and Frustration) using a Likert scale with 20 divisions. Table 3 shows the data. Independent t-tests were used in comparing the HFCS condition to the Manual condition. Only the Mental ($t(62) = 4.98$, $p < .01$) and Effort ($\underline{t}(62) = 4.31$, $p < .01$) measures were found to be statistically significant.

Table 3: Results of NASA-TLX

	HFCS		**Manual**	
	M	***SD***	***M***	***SD***
Mental *(lower = better)*	12.5	4.0	16.6	2.3
Physical *(lower = better)*	8.5	3.9	8.9	4.2
Temporal *(lower = better)*	9.0	4.6	9.9	4.5
Performance *(higher = better)*	14.1	3.3	13.5	3.5
Effort *(lower = better)*	12.5	3.5	15.6	1.9
Frustration *(lower = better)*	7.5	4.0	9.3	3.9

Hypothesis 5: All subjects detected the automation failure. An independent t-test comparing the two conditions showed that the failures in the HFCS condition were detected sooner than the FA condition. This difference was statistically significant $t(14) = -2.19$, $p < .05$, (HFCS M=26.4 seconds, $SD = 7.44$; AUTO M=117.0, $SD = 116.78$).

Hypothesis 6: After experiencing all conditions, subjects were asked to choose one condition from among the three as their most preferred. They were asked this with regard to just the flying task (i.e., if there was no secondary task) and with regard to the combined task (i.e., flying and all secondary tasks). Pearson Chi-square test was used to test for significance. For both flying and combined, the subjects preferred the HFCS condition over both the Manual and the FA conditions at the .01 significance level.

Comparing the HFCS condition with the FA condition yielded $\chi^2(2, N = 24) = 6.86$, $p < .01$ (HFCS = 15, FA = 6) for just the flying task and $\chi^2(2, N = 24) = 6.76$, $p < .01$ (HFCS = 16, FA = 7) for the combined tasks.

Similarly, comparing the HFCS condition with the Manual condition yielded $\chi^2(2, N = 24) = 10.54$, $p < .01$ (HFCS = 15, Manual = 3) for just the flying task and $\chi^2(2, N = 24) = 20.49$, $p < .01$ (HFCS = 16, Manual = 1) for the combined tasks.

4 DISCUSSION OF EXPERIMENTAL RESULTS

To summarize the statistically significant findings: The HFCS condition improved flight progress situation awareness over that of FA. The HFCS condition caused less Mental workload and Effort when compared to the Manual condition. Subjects detected a failure of the automation in the HFCS condition sooner than they detected it in the FA condition. Subjects preferred the HFCS condition over both the FA and the Manual conditions when considering just flying the aircraft and when considering flying the aircraft along with secondary tasks.

It is also important to note that none of the actual data refuted the hypotheses – that is, they just did not pass the test of statistical significance. The number of SAGAT probes that could be reasonably used was relatively small (usually only three or four per run) and the distribution of answers in the different categories was not normal. Since all of the data supported the hypotheses, it may be that the sample size was not large enough for sufficient power or that the measurements were not sensitive enough.

Nonetheless, the statistically significant results themselves are impressive and they reinforce the claims of increased situation awareness, reduced workload, and high pilot preference when using the HFCS. The HFCS holds promise for ameliorating many of the human factors problems found in current automation in modern flight decks.

5 FUTURE RESEARCH

In the future, the power and sensitivity components of the dependent measures will be improved to further examine the hypotheses. Also, more mature versions of the HFCS including a more robust alerting system will be tested. Other types of failures including failures of the alerting system (that is, the subjects will not be cued to make a transition) will be tested. Usability studies will be conducted to improve the HFCS interface.

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