THE EVALUATION OF TWO CDU CONCEPTS AND THEIR EFFECTS ON FMS TRAINING

Terence S. Abbott
NASA - Langley Research Center
Hampton, VA 23681-0001

ABSTRACT

One of the biggest challenges for a pilot in the transition to a "glass" cockpit is understanding the Flight Management System (FMS). This is due to both the complex nature of the FMS and to the pilot-FMS interface. For these reasons, a large portion of transition training is devoted to the FMS. The intent of the current study was to examine the impact of the primary pilot-FMS interface, the Control Display Unit (CDU), on FMS training. The hypothesis of this study was that the interface design could have a significant impact on training. An FMS simulation was developed with two separate interfaces. One interface was similar to a current-generation design and the other was a multi-windows CDU based on graphical user interface techniques. For both application and evaluation reasons, constraints were applied to the graphical CDU design to maintain as much similarity as possible with the conventional CDU.

This preliminary experiment was conducted to evaluate the interface effects on training. Sixteen pilots with no FMS experience were used in a between-subjects test. A time-compressed, airline-type FMS training environment was simulated. The subjects were trained to a fixed-time criterion and performance was measured in a final, full-mission simulation context. This paper describes the technical approach, simulation implementation, and experimental results of this effort.

INTRODUCTION

One of the biggest challenges for a pilot in the transition to a "glass" cockpit is understanding the Flight Management System (FMS). Part of this challenge is brought about by the complex nature of this system and part of this may be attributed to the pilot-FMS interface (Eldredge, Mangold, & Dodd, 1992; Mann & Morrison, 1986; Sarter & Woods 1992; Sarter & Woods 1994). For these reasons, a large portion of transition training is devoted to the FMS. The intent of the current study was to examine the impact of the primary pilot-FMS interface, the Control Display Unit (CDU), on FMS training. The hypothesis of this study was that the interface design could have a significant impact on training. For this initial design, the interfaces were of the same physical size and were as functionally equivalent as possible, with the graphical interface “layered” over the conventional system. Further constraints were also applied so that the evaluation could focus primarily on the effects of the multiple-windows and direct-manipulation aspects of GUI designs. FMS-pilot training was based on a traditional airline training syllabus, but the training time was severely abbreviated. At the end of the training, an evaluation was conducted in a final, full-mission simulation context. This paper briefly describes the results of this effort.

ABBREVIATIONS

ATC	Air Traffic Control
CBT	Computer-Based Training
CDU	Control Display Unit
CRT	Cathode Ray Tube (display screen)
FMC	Flight Management Computer
FMS	Flight Management System
GUI	Graphical User Interface
ILS	Instrument Landing System
ND	Navigation Display
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
VOR	Very-high frequency Omni-directional Range

EXPERIMENTAL FMS AND THE CDU CONCEPTS

An experimental FMS was developed to provided a highly flexible tool for the further development and evaluation of both advanced FMS guidance algorithms and interface concepts. The FMS databases included U.S.-wide information on VORs, low- and high-altitude airway structures, airports, and geometry of airport ILS and runway configurations. Databases were also included for specific SIDs, STARs, and approaches for a limited number of selected airports. Performance optimization was based on a Boeing 757-class of airplane which was also the performance model for the airplane simulator used in the evaluation. This optimization provided climb, cruise, and descent schedules; fuel flow estimation; estimated waypoint crossing speeds and altitudes; and waypoint arrival-

time estimation. The algorithms also accommodated pilot-entered climb, cruise, or descent speeds; cruise altitudes; and waypoint speed and altitude crossing constraints. The FMS could simultaneously handle four paths or profiles: a primary or active path, a modified active path, a secondary path, and a data-link path. The navigation display (ND) on the simulator instrument panel could display a primary or active path and either a modified active path or a secondary path. In the latter case, the modified active path had priority for display.

Two CDU concepts were developed for this study: a generic, baseline concept; and a GUI-based, graphical CDU concept. Both CDUs used the same underlying experimental FMS software that included databases, path definition routines, and path optimization techniques. Because of the requirement for a flexible interface, the CDUs were physically implemented on a 10-inch diagonal, 16-color liquid crystal, flat-panel display. Operator input was provided via a touch-panel that overlaid the flat-panel display.

Baseline CDU

The generic, baseline CDU was based on the Boeing FMS concept and was generally modeled after the Boeing 747-400 CDU (Honeywell, Inc., 1989). The actual aircraft CDUs are approximately 10-inches diagonally with a 5 1/2-inch diagonal CRT. As noted above, color flat-panel displays were used to emulate these devices. These CDUs employed left and right line-select keys, dedicated function keys, and alphanumeric keys for data entry.

For this study, the baseline CDU (shown in figure 1) had several significant differences from the modeled system. Probably the most obvious difference was the "soft" interface using the LCD and touch-panel combination instead of an actual keyboard. This "soft" interface did not provide the tactile feedback associated with real button interaction. However, because key-press, data-entry errors were not an experimental issue for this study, this lack of tactile feedback was not considered to be a significant factor. The second difference between this baseline CDU and its real-world counterpart was in the line-length on the emulated CRT. The emulated CRT for the baseline CDU was a 14-line by 30-character display while the actual CDU uses a 14-line by 24-character display. This 30-character capability allowed for the display of long waypoint names without the need for name sequence-coding. For example, a place-bearing-distance waypoint (where the place was DEN, the bearing was 123 degrees, and the distance was 50 miles) would be displayed as "DEN123/50" on the baseline CDU while an actual CDU would display "DEN01" (where 01-49 are unique sequence numbers for special waypoints associated with DEN). The last major difference was the use of color coding on the emulated CRT of the baseline CDU. Data entry box-prompts were color-coded using the following scheme: magenta was used to color-code data required for FMS initialization (e.g., zero fuel weight or the departure airport), green was used to color-code data for performance enhancement, and white was used for all other entries. Magenta was also used on the title line of each route-specific page to identify the active route. In addition, magenta was used to color-code the active waypoint data on the page displaying the individual legs of the flight plan (the route legs page, "RTE LEGS"). It should be noted that the CRT on an actual 747-400 CDU is a monochrome device.

Figure 1. Baseline CDU with representative page.

Graphical CDU

This experimental CDU was founded on graphical user interface (GUI) concepts that can be seen in the early Xerox PARC designs (Norman, 1986) and are probably best exemplified in the Apple Macintosh interface (Apple Computer, 1992). For both application and evaluation reasons, constraints were applied to this implementation to maintain as much similarity as possible with the conventional CDU. The interfaces were of the same physical size and were as

functionally equivalent as possible, with the graphical interface “layered” over the conventional FMS. This constrained approach was taken for several reasons. From an application standpoint, size was maintained to support the potential for hardware retrofit of this type of technology into the current commercial aircraft fleet. From an experimental perspective, this initial design was aimed primarily at evaluating the effects of the multiple-windows and direct-manipulation aspects of GUI designs. To support this focus, the following design constraints were used (relative to the baseline CDU): maintain the same physical size, use an equivalent number of “pages,” use a similar or equivalent hierarchy of page structures, maintain the same terminology, and use the same underlying functionality. Given these constraints, three major features that are familiar to GUI users were not used: pull-down menus, resizable windows, and scroll-window scroll-bars. The graphical equivalent of the baseline CDU is shown in figure 2. In this example, the waypoint “DBL” could be edited by touching the line on the CDU containing the data for DBL. A waypoint entry window would then be displayed over the existing LEGS window (figure 3). This edit window would then display all of the available edit options for DBL and also display, in a partially masked fashion, options that are not currently valid for this waypoint.

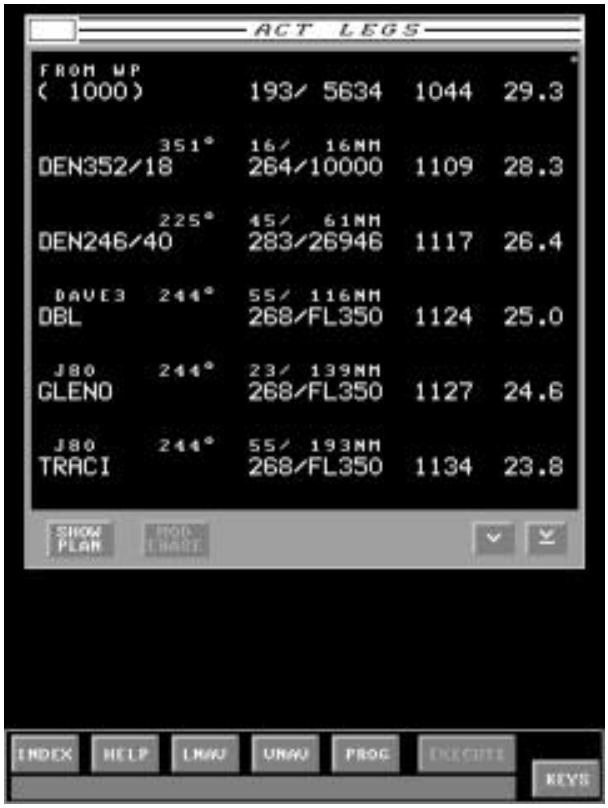

Figure 2. Graphical CDU with representative page.

EVALUATION DESIGN AND CONDITIONS

This study was conducted to evaluate the interface effects on pilot training. Because of this, the evaluation approach was to develop and use a minified, airline-type training environment that focused on the pilot-training aspects of the FMS. The target subject pools for this evaluation were those pilots who would be potential candidates for a transition from an older generation flight deck into a "glass" cockpit. The minimum pilot selection criteria were: a commercial pilots license with instrument rating, no prior FMS training, and recent experience in a paid piloting position. Flight instructor positions did not qualify for the paid position requirement. Sixteen pilots were used with the pilots split equally between the two CDUs. The entire training and evaluation session for each pilot was conducted in a single day using a highly structured training syllabus. The training included sessions in an aircraft simulator and a computer-based training system. The evaluation was conducted in the aircraft simulator.

Figure 3. Graphical CDU with edit window.

Aircraft Simulator

The fixed-base flight simulator used in this study was a generic two-engine transport with performance characteristics equivalent to a Boeing 757. This simulator provided a full-mission capability and

included models of most major aircraft systems. Flight deck features included a fly-by-wire side-stick control system and electronic flight displays. The noteworthy features relative to this experiment were the NDs and the physical placement of the CDU flat-panel displays. The NDs were used in a map-mode where the lateral paths generated by the FMS were then displayed. The flat-panel CDUs were placed in front of and slightly to the right of each pilot. They were mounted at an angle of approximately 15° from the horizontal on a surface that allowed the pilots to rest the palms of their hands while interacting with the CDU. The control characteristics and knowledge of the aircraft systems were not considered a factor in this experiment since that subjects were not required to fly the aircraft nor were they responsible for aircraft systems management.

ATC Simulation

An ATC simulation was used during the latter part of the simulator training sessions and the evaluation session. This simulation included a remote ATC controller's station and an audio communication link with the aircraft simulator. In addition to the geographical information normally shown at the controller's station, this simulation could also display the flight plan routes generated by the aircraft simulator's FMS.

Computer-Based Training

A computer-based training system was developed to support this test. This system was modeled after airline training systems for FMS training and consisted of two personal computers that were connected over a communication network. One of the computers represented the FMS that was used in the flight simulator. This computer used a color CRT with a touch-panel interface to mimic the flight simulator's CDU. The second computer modeled the simulated aircraft and provided the training subject with an ND that displayed information in a fashion similar to the ND in the flight simulator. This training system also included an operator's manual for the appropriate CDU, a short "how-to" document, and a 50-task training syllabus. This syllabus was a super-set of the tasks that were used in the evaluation.

Training Sequence and Syllabus

The sequence of events for each pilot was: an initial briefing, an introductory period in the flight simulator, two computer-based training sessions, a second training period in the flight simulator, and the simulator flight evaluation. This sequence is shown in table 1. The simulator training sessions and the CBT were structured around a flight planned from Los Angeles International Airport to San Francisco International Airport. A list of the FMS tasks that were used in the simulator sessions is shown in table 2.

Two pilot-confederates acted as training instructors for the initial briefing and the two simulator training periods. They also assisted in the development of the evaluation tasks, criteria, and scenarios. During the evaluation portion of the test, one or the other of these pilot-confederates functioned as the copilot and performed duties as the pilot-flying.

Session	Time (minutes)	Description
• Initial briefing	30	- overview - description of the simulator - introduction to FMS concepts
• FMS training session 1	110	- simulator familiarization - FMS/CDU introduction - ND introduction - initial FMS training
• CBT session 1	50	- begin CBT tasks
• CBT session 2	80	- complete CBT tasks
• FMS training session 2	60	- reinforce CBT skills
• FMS evaluation	60	

Table 1. Training sequence.

- Initialize the FMC
- Initial route entry.
- Check the navigation radios.
- Proceed direct to a waypoint.
- Change the climb airspeed.
- Retrieve route information.
- Proceed direct to a waypoint not on the route.
- Divert to the origin airport.
- Build an approach path.
- Insert and delete a holding pattern at a fix.
- Change a speed constraint at a waypoint.
- Change of runway on final (session 2 only).

Table 2. Pilot tasks for the simulator training sessions.

Evaluation Conditions and Tasks

The evaluation scenario and tasks (table 3) were similar to the prior simulator training and CBT sessions. The major distinction was that the proposed flight plan was now from Denver Stapleton International Airport to San Francisco International Airport. For the evaluation, the subjects' duties were

limited to FMS interaction. All other duties were the responsibility of the pilot-confederate. During the test, the subjects were requested to briefly verbalize their actions using a verbal protocol technique. In addition, the simulation was stopped temporarily after an evaluation sequence was performed. At that time, the subjects were required to complete a short questionnaire. A pilot debriefing with an associated questionnaire was completed after the evaluation session.

- 1 - Initialize the FMS (to include the initial route entry)
- 2 - Taxi out with a runway change
- 3 - Intercept a departure radial to a VOR
- 4 - Insert a waypoint and proceed direct
- 5 - Build an approach path
- 6 - Display an abeam waypoint
- 7 - Insert a holding pattern at a fix
- 8 - Change the landing runway

Table 3. Evaluation tasks.

EVALUATION RESULTS

Qualitative Results

At the completion of each evaluation sequence, the subjects were required to complete a short questionnaire. This questionnaire included five items: two yes-or-no questions and three rating questions. The two yes-or-no questions were: (1) could you perform the task in the time allotted and (2) could you perform the task with the FMS. If either of these questions was answered "no," the questionnaire was considered to be completed for that task. The remaining three questions, questionnaire items 3 to 5, were rated on a five-part scale and dealt with the following: (3) the translation or understanding of a requirement (e.g., an ATC clearance) into FMS actions, (4) the ease of the actual task on the FMS, and (5) the speed to complete the task. The subjects were briefed that correct task performance was significantly more important than speed. For the first two questions, the differences in the responses to these questions were not significant. From the last three questions, only differences in the responses to question 3, concerning the translation or understanding of a requirement into FMS actions, were found to be significant. From the responses to question 3, the graphical CDU received a more favorable rating than the conventional CDU. A possible explanation of this result is given in a subsequent section.

Quantitative Results

After the completion of the data collections, the two pilot-confederates rated each task for each subject on a pass-fail basis (see table 4). This rating was done using a combination of video data, written notes, and FMS-recorded keystroke data. These pass-fail ratings were then analyzed by tasks. From this analysis, only the ratings for task 3, intercept a radial to a VOR, were found to be significantly different. For this task, the graphical CDU provided better performance than the conventional CDU. A possible explanation of this result is given in the following section.

Discussion of the Results

Considering that only one of the eight tasks showed a significant performance difference, which favored the graphical design, an assumption could be made that a graphical interface approach to CDU design may not be a worthwhile endeavor. However, what was noted in analyzing the results from task 3, intercept a radial to a VOR, was that there appeared to be a better task-mapping between the task requirements and the interface for the graphical CDU. That is, the graphical CDU waypoint-edit window, by segregating the waypoint options into functional groups, probably contributed to the subjects' ability to identify and select the appropriate option. In addition, to perform this task with the conventional CDU, the subjects had to initially make the VOR-waypoint the first waypoint on the route legs before the intercept course could be entered. With the graphical CDU, the subjects only needed to select or "edit" the VOR-waypoint and then enter the radial-course. While this result was not unexpected (Polson, Irving, & Irving, 1994; Abbott, 1990), it was surprising that some of the other graphical features did not have a larger positive effect.

	Task number							
	1	2	3	4	5	6	7	8
Convention CDU	3	6	1	7	3	4	7	8
Graphical CDU	2	8	7	7	3	5	8	7

Table 4. Number of passing scores by task.

Additional Observations

In addition to the formal data, an examination of the pilot-confederates' and the experimenter's notes lead to several observations on the results. One of the most striking observations was the similarity in the pilots' confusion with both CDUs caused by the use of abbreviations and acronyms for function key labeling. Coupled with this use of abbreviations and acronyms is the fact that even when these phrases are understandable, they may not be meaningful. That is,

the phrase "VNAV," for vertical navigation, may not intuitively bring to mind the association "climb, cruise, and descent data." Furthermore, this function labeling scheme probably lead to one of the more fundamental problems observed in the training: the CDU functions did not always match the tasks the pilots were trying to perform. This was especially true for ATC clearances that required FMS interaction where the "language" of the FMS usually did not match the "language" of the clearance. The last observation noted was in regard to the page or window hierarchy. For the initialization of the FMS and the initial route entry, both CDUs provided a mechanism that allowed for a logical progression through the various windows with one exception. To add a departure runway or SID, the pilots were required to deviate from the normal sequencing. This lead to some confusion during the entry of the initial route data. In addition, for the conventional CDU, there was not an explicit function hierarchy (there was no hierarchical index). While one was provided for the graphical CDU, it was not necessarily used. Also as noted by Polson, et al (1994), "one of the major sources of difficulties for new and experienced users uncovered in our studies was the mismatch in many cases between the task defined by an Air Traffic Control (ATC) clearance and the organization of the operations required to program the FMC to quickly carry out these directives." Overall, the combination of the less than optimum function hierarchy and the mismatch between ATC clearances and the pilots' task to implement those clearances was the largest deficiency observed during this study.

CONCLUSIONS AND RECOMMENDATIONS

This was an initial study to examine the impact of using a graphical CDU on pilot training. Design constraints were applied to this preliminary concept to emphasize the effects of the multiple-windows and direct-manipulation aspects of the GUI design. The results of this study showed marginally better pilot performance and subjective ratings for the graphical CDU over the conventional design. However, while some advantages were noted with this design, the constraints imposed on this initial implementation potentially minimized major, operationally significant benefits. From an informal analysis of the performance data and experimenter observations, it appears that greater benefits could be obtained by a design that focuses on two aspects of the pilot-system interaction. First, functions need to be provided that more directly support the pilots' operational tasks, especially in the area of ATC clearance requirements. Second, a window or page hierarchy must be provided that offers a natural linking and tractability mechanism between these functions. Future designs that support these goals should exhibit reduced pilot training requirements and improved pilot-FMS performance.

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