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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 a component of this complexity may be the pilot-FMS interface (refs. 1–4). 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 initial FMS pilot training. The hypothesis of this study was that the interface could significantly impact training. For this experiment, two CDU interfaces were developed. One of the CDU's was similar to a current-generation design, and the other was a multi-windows concept based on graphical-user-interface (GUI) techniques. For this initial design, both CDU's were of the same physical size and were as functionally equivalent as possible, with the graphical interface functionally superimposed over the conventional system. Further constraints were applied so that the evaluation could focus primarily on the effects of the multiple-windows and direct-manipulation aspects of GUI designs. The FMS pilot training was based on a traditional airline training syllabus, but with the training time 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 study.

Acronyms and 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 omnidirectional range

Experimental Flight Management System (FMS) and Control Display Unit (CDU) Concepts

An experimental FMS was developed as 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 very-high-frequency omindirectional ranges (VOR's), low- and high-altitude airway structures, airports, and the geometry of airport instrument landing system (ILS) and runway configurations. Databases also were included for specific standard instrument departures (SID's), standard terminal-arrival routes (STAR's), and approaches for a limited number of selected airports. Performance optimization was based on a Boeing 757 class of airplane that 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.

Two CDU concepts were developed for this study: a generic, baseline concept and a graphical-user-interface (GUI) CDU concept. Both CDUs used the same underlying experimental FMS software that included the databases, path-definition routines, and path-optimization techniques. Because of the requirement for a flexible interface, the CDU's were physically implemented on a 10-in. diagonal, 16-color liquid-crystal, flat-panel display, which allowed both concepts to be implemented on the same physical device. Operator input was provided via a touch panel that overlaid the flat-panel display.

Baseline CDU

The generic, baseline CDU, based on the Boeing FMS concept, generally was modeled after the Boeing 747-400 CDU (ref. 5). The actual aircraft CDUs are approximately 10 in. diagonally with a 5.5-in. diagonal CRT. As noted previously, 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 (fig. 1) had several significant differences from the system on which it was based. Probably the most obvious difference was the "soft" interface, which used the liquid-crystal display (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

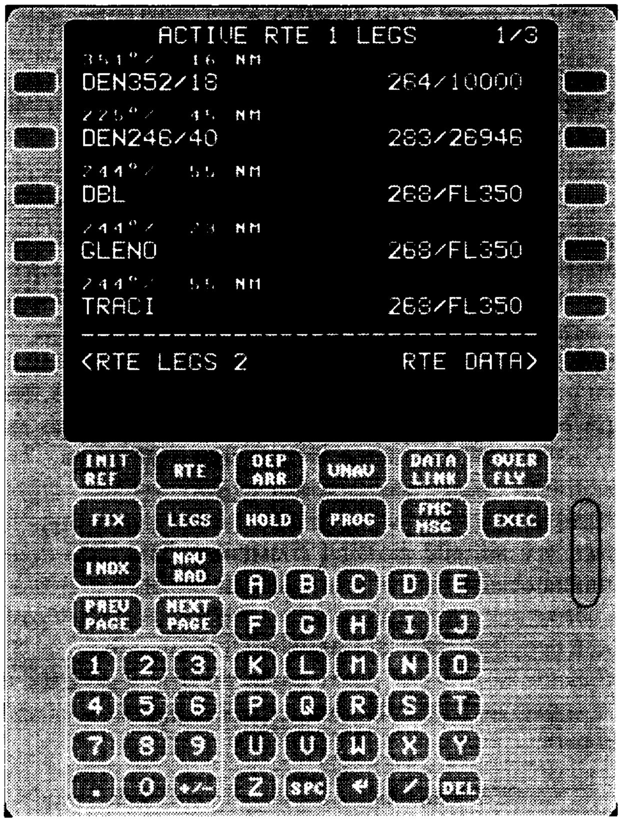

Figure 1. Baseline CDU with representative page.

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 cathode ray tube (CRT) display screen. 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 wherein the place was DEN, the bearing was 123°, and the distance was 50 mi. 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 according to the following scheme: magenta was used for FMS initialization data (e.g., zero fuel weight or the departure airport), green was used for performance enhancement data, and white was used for all other entries. Magenta was used on the title line of each route-specific page to identify the active route, as well as 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 monochromatic device.

Graphical CDU

The experimental graphical CDU was founded on GUI concepts that can be seen in the early Xerox PARC (Xerox Palo Alto Research Center) designs (ref. 6) and are probably best exemplified in the Apple Macintosh computer interface (ref. 7). 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 functionally superimposed over the conventional FMS. This constrained approach was taken for several reasons. From an application standpoint, physical 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 compared to conventional 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 window scroll bars. The graphical equivalent of the baseline CDU is shown in figure 2. In this example, the waypoint "DEN352/18" could be edited by touching the line on the CDU containing the data for DEN352/18. A waypoint entry window would then be displayed over the existing LEGS window (fig. 3). This edit window would display all of the available edit options for DEN352/18 and, in a partially masked fashion, options that are not currently valid for this waypoint.

Evaluation Design and Conditions

This study was conducted to evaluate interface effects on pilot training. 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 to a "glass" cockpit. The minimum pilot selection criteria were a commercial pilot's 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

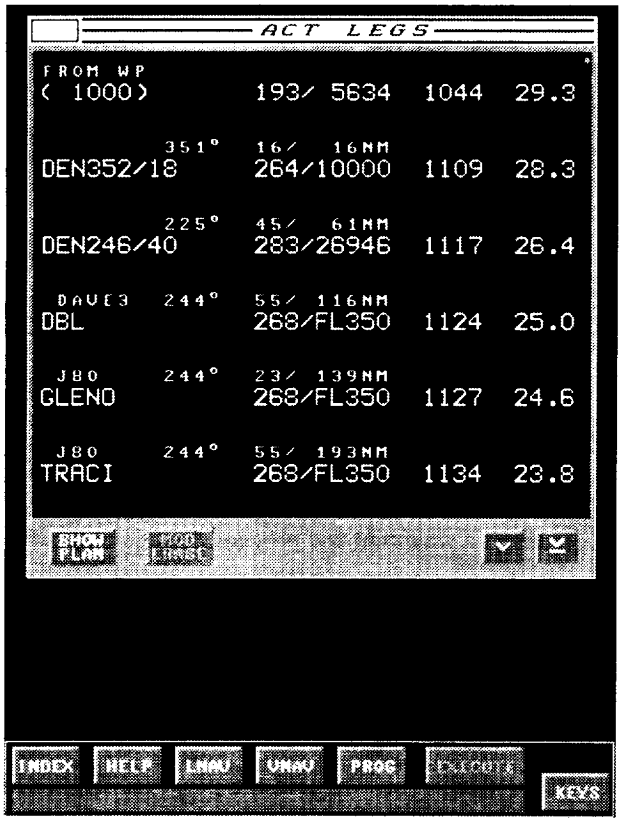

Figure 2. Graphical CDU with representative page.

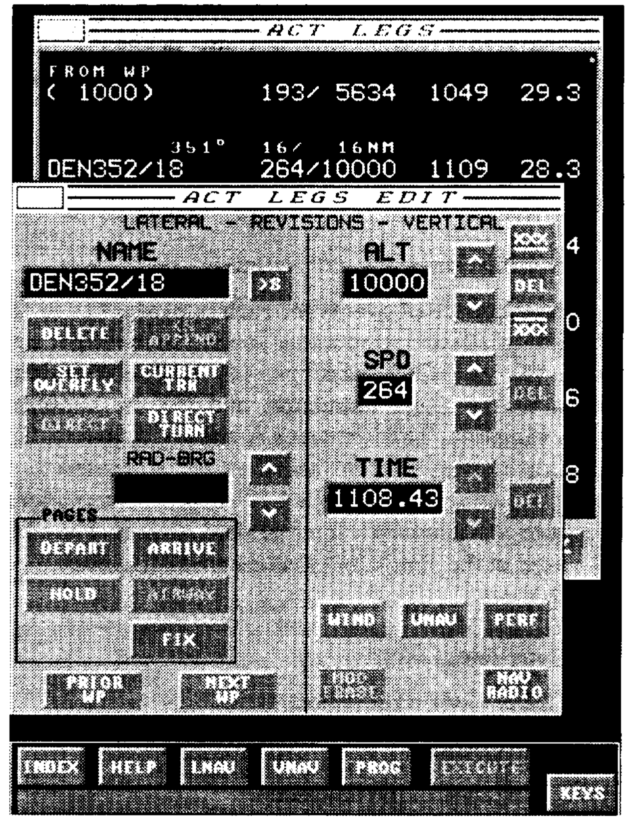

Figure 3. Graphical CDU with edit window.

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 through the use of 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.

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 full-mission capability with models of most major aircraft systems. Flight deck features included a fly-by-wire side-stick control system and electronic flight displays (captain and first officer). The features relative to this experiment were the ND's and the physical placement of the CDU flat-panel displays. The ND's were used in a map mode where the lateral paths generated by the FMS were displayed. The flat-panel CDU's, placed in front of and slightly to the right of each pilot, were mounted at an angle of approximately 15° from the horizontal on a surface that allowed the pilots to rest the heels of their hands while interacting with the CDU. Knowledge of the control characteristics and the aircraft systems was not considered a factor in this experiment because the subjects were not required to fly the aircraft nor were they responsible for aircraft systems management.

Air Traffic Control (ATC) Simulation

To add operational realism, an ATC simulation was used during the latter part of the simulator training sessions and during 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 FMS.

Computer-Based Training (CBT)

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

Training Sequence and Syllabus

The sequence of events for each pilot was (1) an initial briefing, (2) an introductory session in the flight simulator, (3) two CBT sessions, (4) a second training session in the flight simulator, and (5) the simulator flight evaluation. This sequence is shown in table 1. The simulator training sessions and the CBT were structured around a planned flight from Los Angeles International Airport to San Francisco International Airport. The FMS tasks used in the simulator sessions are as follows:

1. Initialize FMS.
2. Enter initial route.
3. Check navigation radios.
4. Proceed directly to a waypoint.
5. Change the climb airspeed.
6. Retrieve route information.
7. Proceed directly to a waypoint not on route.
8. Divert to origin airport.
9. Build an approach path.
10. Insert and delete holding pattern at fix.
11. Change a speed constraint at a waypoint.
12. Change a runway on final approach (session 2 only).

Table 1. Training Sequence

Session	Time, min	Topics
Initial briefing	30	Overview Description of simulator Introduction to FMS concepts
Flight simulator introductory session	110	Simulator familiarization Introduction to FMS/CDU Introduction to ND Initial FMS training
CBT session 1	50	Begin CBT tasks
CBT session 2	80	Complete CBT tasks
Second flight simulator	60	Reinforce CBT skills
Simulator flight evaluation	60	

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 of these pilot confederates functioned as the copilot and performed duties as the "pilot flying."

Evaluation Conditions and Tasks

The evaluation scenario and tasks, similar to the prior simulator training and CBT sessions, were

1. Initialize 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 landing runway.

The major distinction was that the proposed flight plan was now from Denver Stapleton International Airport to San Francisco International Airport. For the evaluation, duties of the subjects 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 by using a verbal protocol technique. In addition, the simulation was stopped temporarily after an evaluation task 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.

Results

Qualitative Results

After finishing each evaluation task, the subjects completed a short questionnaire that 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 three through five, dealt with the translation into FMS actions or understanding of a requirement (e.g., an ATC clearance), the ease of performing the actual task on the FMS, and the speed with which the subject completed the task. The subjects were briefed that correct task performance was significantly more important than speed. For the first two questions, the resulting differences in the responses were not significant. For the last three questions, only differences in the responses to question 3, concerning the translation into FMS actions or understanding of a requirement, 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 the "Additional Observations" section.

Quantitative Results

After completion of the data collections, the two pilot confederates rated each task for each subject on both a pass-fail basis and on a scale of 1 to 5. (See appendix.) These ratings were done with a combination of video data, written notes, and FMS-recorded keystroke data. Ratings were then analyzed by tasks.

For the pass-fail analysis (table 2), only the ratings for task 3 (intercept a radial to a VOR) were significantly different. For this task, the graphical CDU provided better performance than did the conventional CDU. A possible explanation of this result is given in the "Discussion of Results" section.

Table 2. Number of Passing Scores By Task

Control display unit	Passing scores for task number—							
	1	2	3	4	5	6	7	8
Conventional	3	6	1	7	3	4	7	8
Graphical	2	8	7	7	3	5	8	7

Table 3. Composite 1-to-5 Scores By Task

Control display unit	Composite scores for task number—							
	1	2	3	4	5	6	7	8
Conventional	25	14	31	10	25	15	15	8
Graphical	27	11	10	11	27	19	10	12

The results for the 1-to-5 ratings (table 3) were similar to the pass-fail results. Again, only the ratings for task 3 (intercept a radial to a VOR) were significantly different. For this task, the graphical CDU provided better performance than did the conventional CDU.

Discussion of Results

Considering that only one of the eight tasks showed a significant performance difference in favor of the graphical design, an assumption could be made that a graphical interface approach to CDU design may not be a worthwhile endeavor. However, researchers noted in analyzing the results from task 3 (intercept a radial to a VOR) that there appeared to be 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 initially had to 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 (refs. 8 and 9), it was surprising that the other graphical features did not have a larger positive effect.

Additional Observations

In addition to the formal data, an examination of notes made by the pilot confederates and the experimenters led to several observations on the results. One of the most striking observations was the similarity in the confusion experienced by the pilots with both CDU's, 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 led 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 mismatch 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 CDU's 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 need to deviate led to some confusion during entry of the initial route data. In addition, for the conventional CDU, there was not an explicit function hierarchy (no hierarchical index). While one was provided for the graphical CDU, it was not necessarily used. Also, as noted in reference 8, "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.

Concluding Remarks

This initial study examined the impact on pilot training of the use of a graphical control display unit (CDU). Design constraints applied to this preliminary concept emphasized the effects of the multiple-windows and direct-manipulation aspects of the graphical user interface (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 pilot operational tasks, especially in the area of air traffic control (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 flight management system (FMS) performance.

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Appendix

Scoring Method

Each task was rated with both a pass-fail rating and a numeric scale. Table A1 details the score, criteria, and criteria definitions for each level.

Table A1. Scoring System

Score	Criteria	Criteria definition
1	Subject makes no errors	• Time to complete the task is not a factor as long as it is within the allocated time. • Repeating clearances, spelling of words, and explanation of the situation does not constitute help. • Input errors and software failures are not considered as errors. • Suggestions about how to operate the interface (e.g., finger position) are not considered as help. • Circuitous methods are not considered as errors. • A single, unsolicited confirmation of a modified route from the pilot confederate does not constitute help.
2	Subject makes an error but corrects it without help	• All elements for a score of 1 apply. • Errors include any cognitive error or wrong procedure, among others.
3	Subject makes an error and corrects it with minor help	• All elements for a score of 1 apply. • Minor help includes confirming past actions or drawing attention in a general way, but does not include drawing attention in a pointed way, providing the subject with choices, or telling the subject what to do. • Minor help is generally characterized by open-ended questions. • Minor help includes: - Confirming past actions, such as, "O.K." or "Looks good." - Drawing attention in a general way, such as, "On what page do you find abeam information?" - A single oblique clue such as, "What are you trying to do?" or "How do you open the option window?" - A single peripheral clue, such as, "You might want to clean up the screen."
4	Subject makes an error and corrects it with major help	• All elements for a score of 1 apply. • Major help includes drawing attention in a pointed way, providing the subject with choices, and telling the subject what to do. • Major help includes: - Drawing attention in a pointed way, such as, "Are you trying to construct a waypoint or go to a waypoint?" - Providing the subject with choices, such as, "You can enter the runway information while you are on this page or do it later." - Telling the subject what to do, such as, "Press the DELETE key." - A core clue involving a key concept of the task, such as, "You need to put DBL in 1L." or "No, not that." - Multiple minor clues. - Any direct instruction regardless of whether it is a core or peripheral issue.
5	Subject is unable to complete the task	• Time to complete the task is not a factor as long as it is within the allocated time.

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One of the biggest challenges for a pilot in the transition to a "glass" cockpit is understanding the flight management system (FMS). Because of both the complex nature of the FMS and the pilot-FMS interface, a large portion of transition training is devoted to the FMS. The current study examined the impact of the primary pilot-FMS interface, the control display unit (CDU), on FMS training. Based on the hypothesis that the interface design could have a significant impact on training, an FMS simulation with two separate interfaces was developed. One interface was similar to a current-generation design, and the other was a multiwindows 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.

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