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Human-Machine System Simulation for Evaluating Flight Deck Display Based on Knowledge Representations of Expert Pilots

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HUMAN-MACHINE SYSTEM SIMULATION FOR EVALUATING FLIGHT DECK DISPLAY BASED ON KNOWLEDGE REPRESENTATIONS OF EXPERT PILOTS

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For evaluations higher level safety in aviation, it is required to reduce accidents involving human errors. Actualizing appropriate Human-Machine Interface (HMI) design is recognized as a key issue for preventing significant hazards resulted from human errors. The present study has proposed a human-machine system simulation called Pilot Cognitive Simulator (PCS) as an evaluation method for HMI. The PCS aims at qualitative evaluations of HMI design from the aspect of information contents thorough analysis of the interaction between pilots' cognitive process and HMI in a simulation environment. In an experimental simulation-based evaluation of a prototype supporting display, the PCS could successfully reveal the effectiveness and the possible adverse effect of the display. These results are considered to demonstrate the basic effectiveness of PCS as a supporting tool for achieving more reliable HMI design.

Introduction

For achieving higher level safety in aviation, it is strongly required to reduce accidents involving human errors [1]. Human machine interface (HMI) supporting pilots in maintaining proper situation awareness(SA) is recognized as a key issue for preventing significant hazards resulted from human errors in many previous researches [2, 3].

Although various improvements of flight deck displays have ever been suggested and installed, further studies are required in terms of evaluation methods for HMI. To make HMI more effective and reliable, analysis of interactions between HMI and cognitive process of the operator is quite important in finding out potential flaws of HMI design. However, it is difficult to perform such analysis by experimental method using experts as subjects because of difficulty in interpreting subjects' cognitive behavior and also because of the unavailability of the subjects.

To solve the above mentioned problem, the human-machine system simulation which enables visualization of interaction between simulated human operators and systems on a computer is expected to serve as an effective tool for the evaluation of the human system interactions in the initial phase of HMI design process. The Air Man-machine Design and Analysis System (Air MIDAS) in a flight deck or the Simulation-based Evaluation and Analysis support system for MAn-machine Interfaces Design (SEAMAID) in the central control room of a nuclear power plant are typical examples of human-machine system simulations aiming at supporting HMI design [4, 5]. These previous studies on human-machine system simulations have emphasized the quantitative evaluation of HMI design focusing on the cognitive load of operators. Although the quantitative evaluation is undoubtedly important for better HMI design, our research group has also focused on the process-based HMI evaluation based on qualitative analysis of HMI design focusing on sequential interaction between pilots' cognitive process and HMI. The process-based HMI evaluation method is expected to uncover positive and negative effects in the human-machine system when any modification of HMI design is introduced.

In the present study, as a core tool for process-based HMI evaluation for aircrafts' flight decks, the human-machine system simulation called the Pilot Cognitive Simulation (PCS) has been developed aiming to analyze pilots' cognitive process and pilots-system interaction. The effectiveness of the proposed PCS for HMI evaluation has been assessed through experimental evaluation of a prototype information display.

Analysis

In the present study, the authors have focused on pilots' perception and attention allocation to information presented on the flight deck displays because about 80% of SA errors is considered to originate from errors of level 1 SA (perception of elements in current situation) defined by Endsley [2]. As mentioned in previous researches, human cognitive process should be considered as proactive process driven by a prediction rather than passive process driven by cognitive stimuli from surroundings. It means that a human operator proactively selects necessary information exists around him/her and pays her/his attention to the information based on the result of mental simulation using mental model (Fig. 1).

Pilots learn to use the basic scan patterns to gauges through their education and training process. Some of them are explicitly described in the pilot's training manuals. However, in addition to the skills and knowledge obtained through training process, various external resources in a field such as operating procedures, related documents or implicit resources such as operators' know-how for safe and efficient operation, custom or culture in a field are also important pilots' knowledge representations for guiding pilot's attention allocation derived from their experiences and practical knowledge. Therefore, the authors performed the analysis of such resources in order to reveal cognitive factors controlling their attention allocation. The belief summary of the process and results of the analysis is described in this chapter.

Procedure and Result of Analysis

The analysis was performed based on the following steps.

(1) Analysis of resources in a field of line operation
(2) Interview with an expert pilot
(3) Open-ended questionnaire to three airline pilots

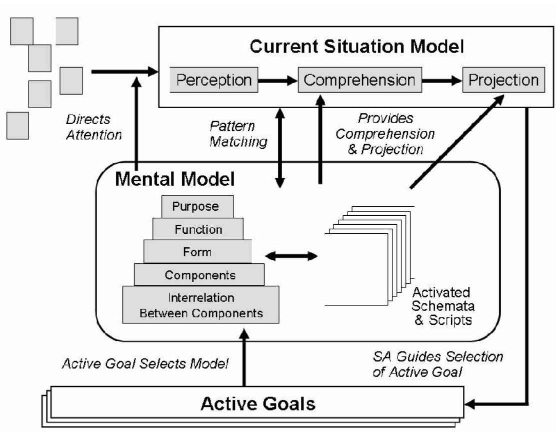


Figure 1. Role of Mental Model [2]

In the step (1), the analyses of following materials were performed, which are routinely utilized in a line operation.

- Company clearance
- Navigation log
- Standard Instrument Departure (SID) chart
- Approach chart

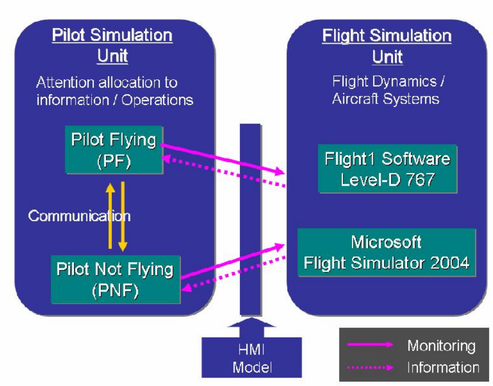
In addition to the above mentioned written materials, standardized contents of cockpit crew's briefings which are required to perform at the specific points during the operation were analyzed.

- Take off briefing
- Landing briefing

In the step (2) and (3), an interview with an expert pilot and open-ended questionnaires to three airline pilots were performed. For example, the standardized contents of takeoff and landing briefing has items for confirming flight procedure in normal and off-normal situations following flight sequence such as passing waypoints, altitude and speed restrictions, and relating procedural operations. Additionally, in the interview and questioners, pilots mentioned his practice to have made a mental image of the flight operations before flying new routes to memorize the flight procedure in advance. These results of the analysis have strongly implied that pilots construct mental image which represents in-flight situations and operations in advance, and utilizes it as a reference for detection of a possible risky situation in its early stage. The details of the analysis are described in [6].

Table 1. Implementation Environment of PCS

OS	Windows XP
Flight Simulator	Flight Simulator 2004 (Microsoft)
Aircraft Simulator	Level-D 767 (Flight 1 Software)
Flight Simulator 2004 I/F	FSUIPC (Peter Dowson)
Development Environment	Visual C++.NET 2003 (Microsoft)



Pilot Cognitive Simulation

The Pilot Cognitive Simulation (PCS) has developed with focusing on the simulation of pilot's attention allocation to information in a flight deck and the cognitive mechanisms which control attention allocation. In the PCS, a simulated pilot has mental image of a flight operation which can be utilized for detection of a possible risky situation based on the result of the analysis describe in the previous chapter. Some additional knowledge of pilots which were obtained through interviews with pilots and analysis of some materials have also been installed into the PCS. The details concerning configurations and functions of PCS are described in the following sections.

Basic Configurations of PCS

Pilot Simulation Unit Pilot simulation unit simulates behaviors of two pilots (Pilot Flying (PF) and Pilot Not Flying (PNF)). They are internal cognitive activities, operations and communications. Based on a cognitive model which describes cognitive process relating to SA by Endsley (Fig. 1), each simulated pilot in the PCS has an internal situation model (ISM) which is separated from actual situation model (ASM). Pilot's cognitive functions are implemented as assembly of various agents. Each agent has a specific cognitive function such as information acquisition from a gauge, execution of an operation, storing a procedural knowledge and so on. Those agents activate each other, and the activation levels of agents determine the overall behavior of the simulated pilot. The details of PCS's architecture and functions are described in the following.

- *Internal Situation Model* The internal situation model (ISM) is pilot's mental representation concerning task environment involving temporal and spatial description of the objective system and the surroundings. Most of the agents decide their behavior in reference to the state of ISM. It means that the simulated pilot's behaviors such as attention allocation, execution of specified procedures, operations of instruments are determined based on the ISM. The ISM is updated in response to the following events.

1) Information acquisition from external world (i.e. from actual situation model)
2) Predictions based on obtained external information and pilot's knowledge
3) Manual operations by a simulated pilot (e.g. manual mode change of autopilot system)
4) Cognitive stimuli from surroundings (e.g. kinds of advisory or warning messages from aircraft's systems and communications with another pilot like callout and callback procedure concerning autopilot's mode change)

The separation of ISM from ASM enables PCS to simulate not only passive monitoring process but also active monitoring process based on mental simulation. It also enables PCS to simulate the situation in which chain of errors occurs resulting from the discrepancy between ISM and ASM caused by erroneous recognition of a parameter and inappropriate attention allocation.

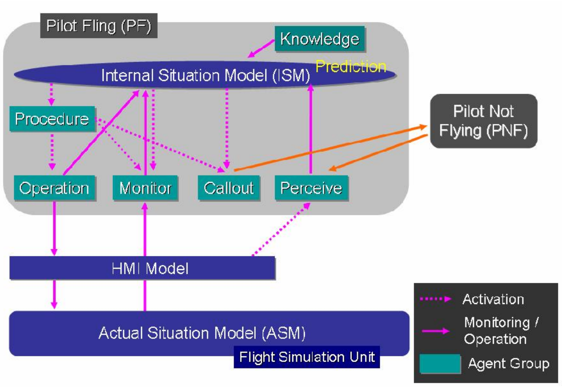


Figure 3. Structure of PCS

- *Agent Groups.* The PCS have six types of agent groups. The general functions of each agent group are shown in table 2.

Table 2. Agent Groups and Functions

Type of Agent Group	General Functions
Knowledge Agents	Storing various kinds of knowledge such as knowledge of autopilot's modes, knowledge of limitations of each parameters and practical knowledge which actual pilots have
Procedure Agents	Storing procedural knowledge such as basic scan pattern for gauges, prescribed callout of parameters
Monitor Agents	Acquiring Information from an indication and its surrounding indications. Enhanced monitoring provides highly-detailed information and a narrow view
Callout Agents	Utterance of simulated pilots such as callouts of acquired information or advices to another pilot
Perceive Agents	Perceive visual and aural stimuli such as utterance of another pilot or warning indications. After perceiving information, Perceive agents activate other agents to execute necessary processing
Operation Agents	Operation of aircraft's system such as an autopilot system, speed brakes and so on

- *HMI Model.* The HMI model is a functional model of gauges and warning systems. The target HMI of simulation-based evaluation by PCS is implemented as a part of HMI model.

Control Mechanism

The simulated pilot's behaviors in PCS are determined by two factors: the activation levels of agents and the available cognitive resources. Under a situation in which simulated pilots have no particular tasks to perform, they perform periodical monitoring of cockpit's instruments (i.e. information acquisition from ASM) following the established basic scan pattern of gauges as same as actual pilots do. Agents representing the pilot model monitor the ISM and activate other relating agents based on the state of the ISM. The simulated pilot's behavior is constrained by four types of cognitive resources. They are visual, aural, cognitive and motor resources. Each behavior of simulated pilot requires and blocks at least one cognitive resource. Therefore, tasks which require same kind of cognitive resource can not be executed at the same time. Only a task driven by the agent with higher activation level is executed in the time step. The standing-by task can be executed in the next time step or later. As the activation level of an agent decreases in every time step unless the agent is re-activated, the standing-by task is not always executed. It depends on its own activation level and ones of other agents. By incorporating this mechanism of agent activation, the simulation of quasi-parallel and flexible task execution is realized.

Human Errors

In PCS, human error rates of information acquisition from monitoring gauges or from communication with another pilot are incorporated in the simulation. Information acquisition errors make it impossible to correct ISM by the accurate information from ASM. In that case, ISM is updated only by pilot's prediction regardless of the appropriateness of the prediction. It represents the possible situation when a pilot erroneously recognizes the situation.

Output Data

As a result of simulation, PCS provides a simulation log, numerical time-series data of ISM and of ASM and data of activation levels of agents. A simulation log shows cognitive and physical behavior of simulated pilots in each time step (e.g. activated knowledge and system operations by pilots). It also records various factors which affect pilots' cognitive behavior such as communications between PF and PNF or activation of warning systems.

Validation of PCS

For the validation of primary function of the PCS, a numerical simulation simulating the descent phase of a line operation was performed. The PCS was validated thorough the analysis of the obtained results based on the following performance indexes.

1) Adequate knowledge is activated under the ongoing situation.
2) Operating procedures are appropriately executed reflecting the role sharing between PF and PNF.
3) Consistency of ISM and ASM is maintained in error-free condition based on pilot's prediction and monitoring.
4) Behavior concerning the attention allocation of a simulated pilot has enough consistency with that of an actual expert pilot.

Simulation for HMI Evaluation

In this chapter, the effectiveness of PCS as tool for HMI evaluation is validated through simulation-based experimental evaluation of a prototype information display called the Enhanced Primary Flight Display (EPFD), which is developed by our research group.

Enhanced Primary Flight Display (EPFD)

The EPFD has been designed to support pilot's SA in the early stage of potential dangerous situation in order to prevent accidents caused by SA errors such as Controlled Flight Into Terrain (CFIT) accidents. In order to decide information contents to be displayed on the supporting display, we made a detailed survey on explicit and implicit resources utilized in the filed of flight operations. The operating procedures, navigation charts for departure and approach phases are the resources used in the analysis. In addition, the interview with four airline pilots has been made to reveal their practices which are not explicitly described in the written procedure. The results of the analysis has showed that a pilot constructs mental image which represents in-flight situations and operations in advance, and utilizes it as a reference for detection of a possible risky situation in its early stage. Based on the result, in EPFD, the additional cues supporting to relate pilot's mental image concerning a flight operation to actual situation are presented with minimum information load (Fig. 4). EPFD is expected to support early detection of a non-normal situation with possible danger leading to a CFIT accident.

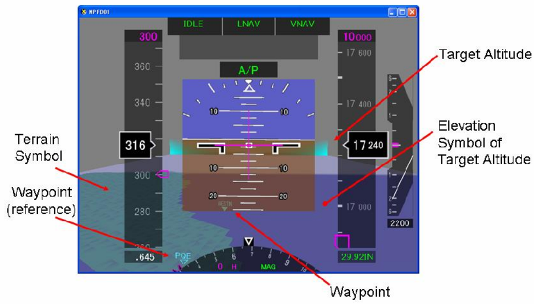


Figure 4. Examples of Enhanced PFD

Table 3. Supporting Information by Enhanced PFD

	Supporting Information / Available Conditions	Error Rate (in the enhanced monitoring)
	Traditional gauges	5% (2.5%)
1	Indication shows altitude restriction by FMS or by MCP	5% 2.5%
2	Indication shows kinds of altitude restriction Above, At, Below	10%
3	Indication shows erroneous target altitude setting below the ground elevation in viewing field of EPFD	5%
4	Indication shows Aircraft within 2000 feet of Target Altitude	5%
5	Indication shows 7000 feet or more difference between Pilot's Intended Altitude and Target Altitude set to Autopilot	20%
6	Indication shows crash into the ground within 20NM	50% 25%

EPFD's Implementation to PCS

For simulation-based HMI evaluation by PCS, the supporting functions of EPFD, the information which can be obtained from the supporting display and its available condition have been modeled based on the design specification of EPFD. In addition, error rates of information acquisition from EPFD were presumed as described in Table 3. The purpose of this simulation-based evaluation by PCS is to assess the effectiveness of EPFD as a supporting display in a crucial situation with multiple human errors. The human error rates in information acquisition from EPFD have been assumed to be apparently higher than realistic error rates to emphasize the erroneous situations in which the EPFD may contribute to prevent accident to happen.

Overview of Simulation-based Evaluation

Simulation Scenario. For evaluating possible positive and negative effects provided by EPFD, simulation-based experiments have been performed utilizing three kinds of simulation scenarios. Each scenario consists of 12 cases of simulation with EPFD and 12 cases without EPFD (same as traditional displays in an existing flight deck). As simulations by PCS are not deterministic, it is basically required to perform multiple cases of simulation runs and to take the average of those numerical results. The total numbers of cases in this simulation experiment is 72 cases.

Evaluation Index. The results of this simulation experiment are evaluated based on the following evaluation indexes.

1) Error detection time
2) Information or knowledge which provides cues of error detection to a simulated pilot
3) Adverse effects leading additional pilot's load caused by EPFD

Results of Simulation-based Evaluation

The typical examples of the results of the simulation-based evaluation, a result of error detection time and an adverse effect caused by EPFD, are described in the following sections because of space limitations.

Scenario 1 (Fig. 5). The result of error detection time in the scenario 1 is shown in Table 4. The average detection time of erroneous setting of target altitude is 18 sec. with EPFD, which is approximately half the time without EPFD. Through analysis of simulation logs, in 9 out of 12 cases of simulation with EPFD, the pilots detected the error from supporting information by EPFD. These results clearly demonstrate the effectiveness of EPFD as a support of SA in the early stage of potential risky situation.

Scenario 3 (Fig. 6). Scenario 3 has been prepared to check the adverse effects caused by EPFD in a normal operation. Therefore, any initial errors like erroneous settings are not incorporated in this scenario. The result of a specific case of simulation with EPFD indicated that EPFD can cause adverse effect, resulting from the possible mismatch of pilot's mental image concerning a flight operation and actual situation. In this case, unnecessary activities of information acquisition from Navigation Display (ND) have been observed in transitions on a way point with altitude restriction.

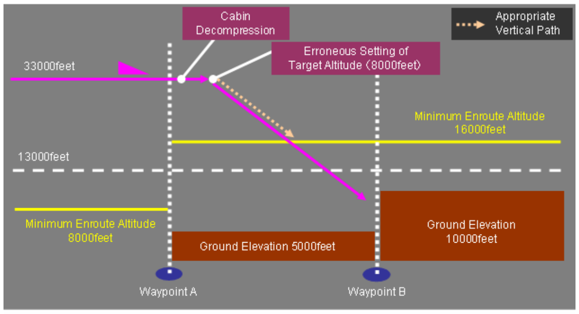


Figure 5. Description of Simulation Scenario 1

Erroneous Setting of Target Altitude in Emergency Descent Procedure: In the early stage of emergency descent procedure, pilots unconsciously set lower target altitude which is minimum enroute altitude of previous position. The pilots started emergency descent without detecting the erroneous setting of target altitude.

Table 4. Results of Simulation (Scenario 1)

	Error Detection Time	Cues of Error Detection
EPFD	18 sec. SD 4.0	Terrain Informnatiuon of EPFD 9/12 Traditinal Indication of Target Altitude 3/12
Traditional PFD	36 sec. (SD 10.6)	Traditinal Indication of Target Altitude 12/12

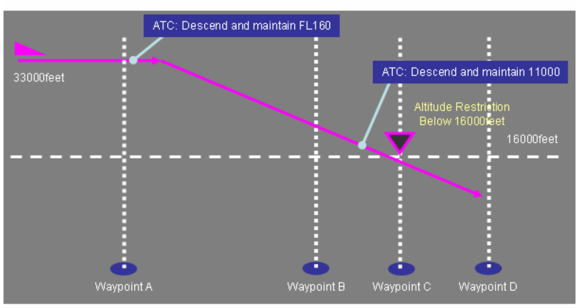


Figure 6. Description of Simulation Scenario 3

Normal Descent: In descending to 16000 feet, pilots perceived the next ATC clearance which requires continuous descent to 11000 feet.

Discussion

The discussion with an expert pilot has been performed to further consider the possibility of the adverse effect described in the previous section. The expert pilot has pointed out that the similar problem can happen in transitions on a way point with altitude or speed restriction in an actual existing flight deck without EPFD. The transition of altitude or speed restriction can cause automatic changes of the aircraft states during flight operations by autopilot system, which might be recognized as unexpected aircraft's behavior for the pilots. Therefore, in the actual flight decks, operation manuals require pilots to monitor and to call out the pass of waypoints for maintaining appropriate SA.

Through simulation-based evaluation, PCS has shown to be capable of detecting a possible problem caused by EPFD which is considered reasonable as compared to the pilot's opinion and the flight decks' operations. This result implies the basic effectiveness of PCS as a supporting tool for describing complex human machine interaction, which may contribute to realizing more reliable HMI design.

Conclusion

In the present study, as a core tool for process-based HMI evaluation, the human-machine system simulation called the Pilot Cognitive Simulation (PCS) has been developed aiming to analyze pilots' cognitive process and pilots-system interaction. The effectiveness of PCS in HMI evaluation has been validated through experimental evaluation of a prototype information display called EPFD.

PCS could detect the possible adverse effect caused by EPFD which was unexpected problem for designers of EPFD. Although further analyses covering extensive situations should be performed to ensure the generality of the proposed PCS as a supporting tool for interaction evaluation, authors believe that the obtained results imply the advantage of the PCS over conventional evaluation methods requiring a number of experts as subjects.

The human-machine system simulation introducing air traffic controller as another actor to ensure the safety of aviation is now under development. Authors believe that the human-machine simulation of the aviation system can contribute to enhance the aviation safety by providing the methodology for systematic evaluation method for complex system including human as a fallible component.

Acknowledgement

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