EVALUATION OF A FORMAL METHODOLOGY FOR DEVELOPING AIRCRAFT VERTICAL FLIGHT GUIDANCE TRAINING MATERIAL

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Aircraft automation, particularly the automation surrounding vertical navigation, has been cited as an area of training difficulty and a source of confusion during operation. A number of incidents have been attributed to a lack of crew understanding of what the automation is doing. This paper describes the translation of information from a formal methodology used in design of an automated vertical guidance system to a training package, and an experiment that tested the new training. This study is part of a larger project to improve the recognition and understanding of the "objectives and behaviors" of automated systems through a formal methodology. The formal method, referred to as the operational procedures methodology, integrates the design of the system with the design of the training and display information requirements for that system (Sherry, 1995). The study utilized a training package designed to teach the vertical guidance portion of the Flight Mode Annunciator (FMA), as seen in normal operations of the Boeing MD-11. The results of the study showed that this type of training can be successfully delivered via a computer based training device. Additionally, a study in a full cockpit simulator showed that the training, coupled with the new display, provided significantly less errors on a simulated flight, although the training alone did not provide significantly better performance.

SUMMARY

Aircraft automation, for the purposes of this paper, will be defined as the autopilot and autothrottle subsystems, and the Flight Management System. The autopilot controls the heading and pitch of the aircraft, and the autothrottle, as the name implies, controls the different power settings required for the automated tasks in flight. The Flight Management System (FMS) contains information used to calculate the most optimal trajectory of the aircraft. Early autopilot systems could only handle one or two functions, but with the addition of the FMS, the new "autoflight systems" have gained considerable complexity. This complexity requires pilot knowledge of the different "modes", or configurations, of the system.

Pilot Training in Avionics

Airframers and airline operators have traditionally avoided the complexity of modern avionics systems by only providing training for the basic operating techniques. Pilots are given the knowledge to perform certain "critical" tasks with the avionics and then required to develop their own mental model through operational "line" flying and the operator manuals provided by the manufacturer and/or airline.

When viewing the situations for which the automation is designed to handle, it is evident that the operational complexity in the behavior of the automation is necessary given the tasks of modern aviation. The behavior of the autopilot is determined by parameters that represent the environment (terrain and weather), aircraft dynamics, pilot delegation of authority to the automation, operational procedures, and technologies that enhance capacity and safety (e.g. glideslope). Therefore, reduction in operational complexity would be possible only with a reduction in functionality.

Hutchins (1996) suggests that training pilots in the conceptual framework of the airplane and its behavior should decrease training time. He points out that retention is much better when what is learned can be integrated into a conceptual framework. This is a basic tenet of training system design and should find its way into pilot training programs. When students without modern avionics system experience are brought into classes, they are immediately exposed to procedures and task-response pairs. A more productive first step may be to acquaint students with an overall conceptual understanding of the advanced flight deck, how it uses computer technology to optimize the flight path, and an understanding of the different flight modes.

A New Approach to the Problem

In 1997, a research team comprised of avionics designers, pilots, and human-automation researchers began investigation of the use of a formal methodology for integrating the design of a system interface, procedures and training material of a complex system. This formal methodology is referred to as the Operational Procedure Model (Sherry, 1995). The model uses a matrix to integrate the ideas of the operators and the inputs and outputs required by the design engineers. The resulting combinations can than be formally checked for situations which do not have appropriate input, or output behaviors. This formal representation of the system contains the information required for a pilot to build an accurate conceptual model of the system. An example of the matrix is seen in Figure 1. The tables are hierarchical in nature, where the

		Operational Procedure	
Scenario		Scenario Description 1	Scenario Description 2
Input	State		
Behavior		Behavior Description	
Output	Function		

Figure 1. Operational Procedure Table Template

top-level name of one table is a component behavior output of another. The Operational Procedure Name is an operator defined aircraft task, such as CLIMB. The scenario descriptions differentiate between the different situations when the Climb task may be invoked. An example of this is passing the acceleration altitude following takeoff. The acceleration altitude is the altitude above which the rate of climb can be reduced and the aircraft can accelerate. This is done for safety and noise abatement.

Design engineers use the Scenario Input States and the Behavior Output Functions (the vertical portion of the table) to differentiate between the different Operational Procedures and scenarios. An example of this is an altimeter input, which allows an altitude check, to determine when the acceleration altitude has been crossed.

Each Operational Procedure has a corresponding Behavior Output and Description. These descriptions are also developed by the operators to reflect how the aircraft should handle the different situations. An example Behavior is an aircraft climbing with a speed restriction until passing the acceleration altitude.

We propose that the Operational Procedures, Scenario Descriptions and Behavior Outputs be used as the basis for the Interface and the training material.

The Domain – Vertical Flight Guidance

To determine where the methodology should be focused, a survey was distributed to MD-11 line pilots to assess where pilots thought they were having difficulty, and where they would like the most help with the automation (Feary et al., 1998). Less than one quarter of the pilots surveyed felt that the FMS Speed Logic, PROF (Vertical Navigation Mode), and the interpretation of the Flight Mode Annunciator (FMA) were adequately trained, all of which are pieces of the Vertical Flight Guidance system.

Following these results, the Operational Procedure Methodology was used to design a new interface, procedures and training material for the Vertical Flight Guidance system.

The Interface – The Flight Mode Annunciator (FMA)

The novel approach to the design of the experimental interface, the Guidance - Flight Mode Annunciator (G-FMA) is that it was organized around the design of the logic of the vertical guidance system, and the training for the system. The modification to the existing display came about as an improvement to training, with the thought that if the system is easier to learn, it will be better retained in memory.

The Guidance-FMA (Figure 2) takes advantage of the same groupings of situations that were used by the team of pilots and engineers who designed the system. These groupings replaced the combination of speed and altitude control mode information, and gave a higher level view of the "behavior" of the airplane automation.

The Speed Control mode window of the current MD-11 FMA has two primary annunciations for normal operations: speed controlled by PITCH, and speed controlled by THRUST. The Altitude Control mode window can display several values or modes:

- **TAKE-OFF THRUST**
- **TAKE-OFF CLAMP**
- **CLIMB THRUST**
- **HOLD**
- **MCT THRUST**
- **VERTICAL SPEED**
- **FLIGHT-PATH ANGLE**
- **PROF (OR VERTICAL NAVIGATION MODE)**
- **IDLE**
- **IDLE CLAMP**

These annunciations are presented in combinations. For example, possible annunciations for descent are either "PITCH" and "IDLE," or "THRUST" and "V/S." The combinations "PITCH" and "PROF," or THRUST" and "IDLE" will never be seen. These combinations of annunciations may not be exclusive either. For example, "PITCH" and "IDLE" are used as the annunciation for 3 different aircraft behaviors.

The Guidance-FMA presents the mode information differently. Instead of having two annunciations that give information about how the aircraft is being *controlled*, which require a translation to interpret the behavior of the aircraft, the Guidance FMA uses one annunciation that describes the overall behavior of the aircraft. The behavior names simplify the vertical guidance logic by eliminating the mental transformation from the control mode information to the aircraft behavior. This behavior name consists of one of the following (under normal operations):

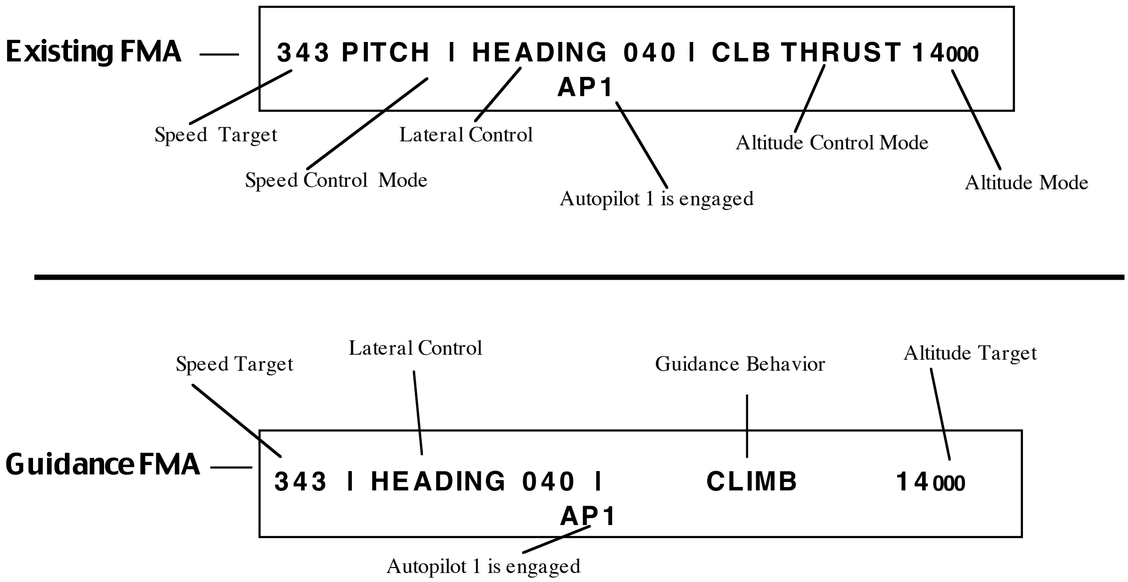

Figure 2 - Diagrams showing the existing MD-11 FMA and the guidance model.
Note: Presentation on the Primary Flight Display is white or magenta text on black background.

- **CLIMB**
- **CLIMB INTERMEDIATE LEVEL**
- **CRUISE**
- **DESCENT**
- **EARLY DESCENT**
- **LATE DESCENT**
- **DESCENT INTERMEDIATE LEVEL**
- **DESCENT OVERSPEED**

Paper Based Training – The Flight Crew Operations Manual (FCOM)

Content and Form of Training Material. The official source of information on the operation of the avionics is the Flight Crew Operators Manual (FCOM). The FCOM is written and published by the airframe manufacturer. Airlines typically republish adapted versions of the airframers FCOM with additional airline specific information, policies and procedures.

The FCOM is required to include a wide range of information:

- description of the cockpit panels and displays
- procedures (normal operation) for each phase of flight
- procedures (abnormal and emergency operation) for each phase of flight
- checklists
- description of the modes and the behavior of the modes of the aircraft systems
- description of the architecture of the aircraft systems

An FCOM is typically developed during flight-test and certification of an aircraft or new equipment. The developers of the FCOM, with training and publishing backgrounds, work with specifications of the system furnished by the engineers and with expert pilots. Frequently sections of the FCOM can be derived from earlier generations or manuals from other airplanes (Novick & Tazi, 1998). Following iteration and the review and certification processes, the final version of the manuals is made available for publication and distribution. Updates to the manuals are provided to pilots with additional information about new avionics loads and improved sections.

The authors of the FCOM are faced with a number of human-factors issues in capturing and presenting the information in readable, understandable formats. In addition, the FCOM is required to serve as both a means for educating the beginner as well as a reference source for the expert operator.

Approximate descriptions. Using the Vertical Speed Mode as an example, the current FCOM description of the behavior is an approximate and incomplete description. The FCOM includes 12 of the 16 situations (scenario descriptions) in the actual software for engagement of the mode, and 4 of the 12 situations in the actual software in which the selection of the mode is inhibited or in which the mode is automatically disengaged.

The FCOM description of behavior is based on 9 parameters. The description of behavior of the avionics software is based on 12 parameters (scenario inputs). It is easy to see that it is difficult for a pilot to develop an accurate mental model of the avionics without a complete and accurate description of the behavior of the avionics.

It is also important to note that although an example was given for the Vertical Speed/Flight Path Angle Mode, this same phenomena is found in the descriptions of the other modes.

Some of these modes are more conceptually difficult to understand than others, and for these modes enhanced training may be required. This is exemplified in the most automated Vertical Guidance modes, referred to as the Vertical Navigation (VNAV) or Profile (PROF) modes. These modes include 289 situations (scenario descriptions) based on 55 parameters (scenario inputs). This group chose to enhance training by developing a computer based training package to illustrate the different modes, and the situations for which the modes were developed.

Computer Based Training - The Vertical Guidance Tutor

The Vertical Guidance Training Package was developed in conjunction with an MD-11 Flight Standards check pilot. The level of abstraction to be covered was determined by the Operational Procedure Model of the Vertical Guidance system, which was based on the research team's organization of the information into Normal Operations, Abnormal Operations (i.e. emergencies), and Special Operations (which are not trained). The organization of the material in the training package consisted of five training modules, and a test module. The test questions were identical except for the FMA display. The training material was almost identical, with the only exception being items that were unique to each display. The reduction in the number of display items in the "Behavior-Based" FMA resulted in slightly less training material (about 5% less) for that condition. The information covered in each training module included the lower-level automated modes, referred to as the basic modes, and the fully automated (Flight Management System) modes, referred to as the PROF modes.

1. FMAs for GCP Operations (Flight Mode Annunciator, Glareshield Control Panel (GCP) operation)
2. FMAs for PROF Operations (Phases of Flight, Optimum Altitude Selection)
3. Climb Intermediate Level, Descent Intermediate Level and Cruise Step Climb
4. PROF Early and Late Descent (Vertical Profile Performance)
5. PROF Descent Overspeed
6. Evaluation

The final section was composed of an evaluation section with 20 test questions. These questions were developed so as not to favor the "Behavior-Based" FMA. There were 4 categories of questions. The first category presented one FMA configuration and asked the participant to select the appropriate description. The second category presented an FMA and asked about the future behavior of the aircraft. The third category presented a situation and asked the participant to select the correct FMA from among a set of FMAs. The last category presented the participant with a situation and asked which FMA would be correct for the future behavior.

The Guidance-FMA showed significant benefits for questions for which pilots were given an FMA and asked to choose a situation description. This result prompted the team to go forward with the next study, which used the training material to create equivalent groups for comparison across the two display groups in a full flight simulation experiment.

METHOD

27 current MD-11 pilots with at least one year of experience on the airplane participated in the study. Three conditions to establish adequate control groups for comparison. The control condition consisted of pilots who flew the simulation without training and with the existing FMA on the MD-11. This condition provided a baseline of how pilots fly with the current training and experiences. The second condition, "training", had subjects go through a training program on vertical guidance techniques. In the third condition, "display", the subjects went through the training program and then flew the scenario with the new Guidance FMA display. The control and training groups used the existing MD-11 displays for their flight scenarios.

A Line-Oriented Flight Scenario was developed to test the understanding of the participants. The flight was from Portland to Seattle and took advantage of the Seattle FMS transition into runway 16R. For each flight, the pilot participant was designated as the Pilot Flying, while the experimenter was the Pilot Not Flying and Air Traffic Control Information Source. The pilot was instructed at the beginning of the flight that they were to keep the system in full automatic mode (PROF) for as long as possible enroute. The experimenter set up the airplane configuration and readied the FMS for departure.

At eight points during the flight, the simulator was stopped so that we could ask pilots questions about their understanding of the avionics. The questions consisted of a description of the current flight situation, a description of the future flight situation, and a prediction of the next FMA display. More information about this study is available in Feary et al. (1997).

RESULTS

The Guidance-FMA with training condition emerged as the superior condition in this study. We found that the pilots in this condition could more accurately describe the current behavior and predict the next mode of operation than the pilots in the control group ($p>.03$). Pilots in the Guidance-FMA group were also better at constructing the next FMA when compared to the control group ($p>.01$). The combination of training the pilot on the vertical navigation system and then displaying that information on the FMA resulted in the best demonstration of pilot knowledge of the three groups. This may be a reflection of better understanding the avionics, more descriptive annunciation, or both, given the types of questions that were asked.

The training condition gave more correct responses (when comparing means) than the control condition for all data collection metrics, but these were not significant differences at the 0.05 level. Under these conditions, we can only say that there was a *trend* for the training condition to be better than the control condition. In the subjective evaluation, pilots reported that they liked the tutor and that it presented the topics adequately, had an acceptable interaction, and had an acceptable speed of training delivery. A few negative comments were obtained, from a minority of pilots in each case. These comments had to do with the elimination of the speed mode information and the perception that this was a reduction in information. Part of this response can be attributed to familiarity with the current FMA, but this needs to be investigated further.

To the overall question that asked for a rating of the tutor, responses were largely positive and pilots found the training program beneficial. For each of the measures of understanding, the display group was significantly better, with the training group having a higher, non-significantly different mean from that of the control group. This indicates that both are necessary to really make an impact on the pilot. It may not be sufficient to train pilots in the operation of the airplane, but in combination with a matching interface the understanding of a complex system can be significantly improved.

CONCLUSIONS

Reducing or eliminating differences between pilots' operational models and the operational models encoded in the autopilot may achieve a reduction in perceived complexity. Complete rule-based descriptions of the behavior of the autopilot provide the basis for understanding the perceived complexity of the autopilots, the differences between pilot conceptual models and autopilot behavior, and the limitations in training materials and cockpit displays.

The most powerful means pilots have of learning the behavior of the autopilot is through observation. When the cockpit displays do not annunciate the complete behavior of the autopilot, the pilot is left to create approximate models of the autopilot's behavior. Feary et. al. (1997) have demonstrated the value of this approach.

To support pilots learning complete canonical descriptions of the behavior, Sherry & Polson (1998) propose using interactive, computer-based training to incrementally increase the pilots' mental model. Modern theories of complex skill acquisition (Anderson, 1993) suggest that it is reasonable to assume that pilots can learn to anticipate and monitor the behavior of large rule-based systems.

This research team is developing an operationally-centered model-based method for designing the: behavior of the automation, the information required for the interfaces, and the training material. This approach has shown at least partial success in each of these areas.

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REFERENCES

Anderson, J. (1993) *Rules of the Mind.* Lawrence Erlbaum & Associates. Hillsdale, NJ.

Ellis, S. R., & Hitchcock, R. J. (1986). The emergence of Zipf's law: Spontaneous encoding optimization by users of a command language. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-16* (3), 423-427.

Engelbeck, G. E. (1986). Exceptions to generalizations: Implications for formal models of human-computer interaction. Masters thesis, Department of Psychology, University of Colorado, Boulder, CO.

FAA (1996). Federal Aviation Administration human factors team report on: The interfaces between flight crews and modern flight deck systems. Washington, D. C.

Feary, M. (1997). Control-Based vs. Guidance-Based Annunciations for Automated Vertical Flight Guidance. Masters Thesis, San Jose State University, San Jose, CA.

Feary, M., McCrobie, D., Alkin, M., Sherry, L., Polson, P., Palmer, E., & McQuinn, N. (1998). Aiding Vertical Guidance Understanding. (NASA Technical Memorandum 112217). Moffett Field, CA:NASA Ames Research Center.

Hutchins, E. L. (1996). The Integrated mode management interface. (NASA Contractor Report), Moffett Field, CA: NASA Ames Research Center. Manuscript in preparation.

Novick, D. G., and Tazi, S. (1998) Flight Crew Operating Manuals as Dialogue: The Act-Function-Phase Model. *International Conference on Human-Computer Interaction in Aeronautics.* 179-184

Sherry, L. (1995). A formalism for the specification of operationally embedded reactive systems. In *Proceedings International Council of System Engineering*, St. Louis, MO.

Sherry, L., & Polson, P. "Implications of Situation-Action Rule Descriptions of Avionics Behavior," International *Conference on Human-Computer Interaction in Aeronautics,* May 1998, pp. 213-219.

Sherry, L., Kelley, J., McCrobie, D., Polson, P. G., Feary, M., Hynes, C. S., & Palmer, E. A. (1997). A framework for the design of intentional systems in support of cooperative human-machine systems. In R. S. Jensen (Chair), *Proceedings of the Ninth International Aviation Psychology Symposium Conference*, Columbus, OH: The Ohio State University.