Evaluation Of A Formal Methodology For Developing Aircraft Vertical Flight Guidance Training Material

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ABSTRACT

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 use of a formal methodology in the design of interface, procedures and training material for an aircraft vertical guidance system, and two experiments to evaluate the interface and training packages respectively. The formal method, referred to as the Operational Procedures Method, integrates the design of the system with the design of the training, procedure and display information requirements for that system [6]. 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 with experienced pilots showed that the training, coupled with the new display, provided significantly less errors on a simulated flight.

Keywords

Automation, Flight Guidance, Flight Mode Annunciator, Formal Methods, Part-Task Training

INTRODUCTION

Pilot Training in Avionics

Increasing complexity is an unfortunate consequence of the increase in functionality of modern avionics. The complexity of current aircraft autopilots is a combination of 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. windshear recovery, Traffic Collision Avoidance). Therefore, reduction in operational complexity would be possible only with a reduction in functionality, although a reduction in "perceived complexity" may be possible with the introduction of a coherent model.

Aircraft manufacturers, aircraft avionics vendors and airlines have traditionally avoided training the complexity of modern avionics systems by only providing training for basic operating techniques[4]. 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. Safety Recommendations based on incident and accident reports have shown that these "self-developed" models can be erroneous and lead to incidents and accidents[2].

Hutchins[7] 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.

Currently. most training programs provide information about avionics systems through the flight manual, classroom time, individual instruction with a simulator or mock-up and/or in a full mission flight simulator. Generally, students without modern avionics system experience are required to read about the system in the airplane flight manual, then are given a question and answer session with an instructor, sometimes in front of a mock-up of the interfaces of the relevant systems. After, the sit-down ground session, students may be introduced to the systems in a Fixed Based Simulation before moving on to the full flight simulator.

While this training approach has evolved over the years to address many of the issues associated with learning the autopilot and Flight Management Systems, there is a need for a more principled approach to training these complex, dynamic and time-critical systems. In particular there is a need for a single source of information that can be used by the design team, engineers, training, procedure, and flight deck design teams and regulatory personnel. These groups should work from this single reference and use the reference as the completion standards for the training, procedure and interface development. Added to this reference, a set of guidelines from the appropriate communities could allow the development of a principled approach to the design of training, interfaces and procedures.

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 system interface, procedures and training material. This formal methodology is referred to as the Operational Procedure Method [10]. The method uses a table to integrate the requirements of the users with the requirements of the design engineers. The resulting combinations can be formally checked for situations that 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 table is seen in Figure 1. The gray shaded portions of the table are completed by the end users of the system. The Users of the system use the Operational Procedure cells of the table to define what they would like the aircraft system (autopilot, Flight Management System, etc.) to do (e.g. Climb, Cruise, Descend, etc). Inside each Operational procedure the users describe a number of scenarios. These descriptions are used to define the different situations an aircraft may need to cope with. For example, when climbing an aircraft may have an engine fail, and the system may need a behavior to deal with it. The Behaviors, and Behavior Descriptions describe how the user would like the aircraft system to handle the defined situation. For example, if there is a failed engine during climb, the user may want the autopilot to pitch the airplane for a particular speed.

The white portions of the table are completed by the design engineers and define the parameters that will satisfy the needs of the users. Examples of scenario inputs are altitude, airspeed, weight, etc., and examples of behavior outputs are pitch – thrust commands, targets, etc.

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

Figure 1. Operational Procedure Table Template

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 [6]. More than 75% of the pilots surveyed felt that pieces of the Vertical Flight Guidance system were trained inadequately, including: the FMS Speed Logic, PROF (Vertical Navigation Mode), and the interpretation of the Flight Mode Annunciator (FMA).

Following these results, the Operational Procedure Methodology was used to design a new interface, procedures and training material for the Vertical Flight Guidance system. We will now discuss 2 experiments that were designed to evaluate the use of the Operational Procedure Methodology for this design.

Experiment 1 - The Flight Mode Annunciator (FMA) Interface

The first experiment involved a change in the organization and wording of the Flight Mode Annunciator in a modern, transport category aircraft to make the display more understandable.

The baseline condition, referred to as the "Control-FMA" is what is currently displayed in the MD-11. It is referred to as the Control-FMA because the current FMA displays information about aircraft "controls", or <u>how</u> an aircraft is achieving its goals. This is contrasted with the experimental FMA, referred to as the Guidance-FMA . The Guidance-FMA was organized around the design of the logic of the vertical guidance system as specified in the OPM and displays <u>what</u> the aircraft goals are. The hypothesis is that if the goals of the automation were displayed, pilots could quickly match their expectations of aircraft behavior with the goal of the aircraft automation. Additionally, the modification to the existing display was intended to improve training, with the thought that, if the system is easier to learn, it will be better retained in memory.

The Speed Control mode window of the current MD-11 FMA (Figure 2) 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:

- **CLIMB THRUST**
- **HOLD**
- **VERTICAL SPEED**
- **IDLE**

These annunciations are presented in combinations. For example, possible annunciations for descent are either "PITCH" and "IDLE," or "THRUST" and "V/S." The combination "THRUST" and "IDLE", for example, 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 (Figure 2) takes advantage of the same groupings of situations that were used by the team of pilots and engineers who designed the system through the OPM model of the vertical guidance 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 Guidance-FMA (G-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 G-FMA uses one annunciation that describes the overall behavior of the aircraft.

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

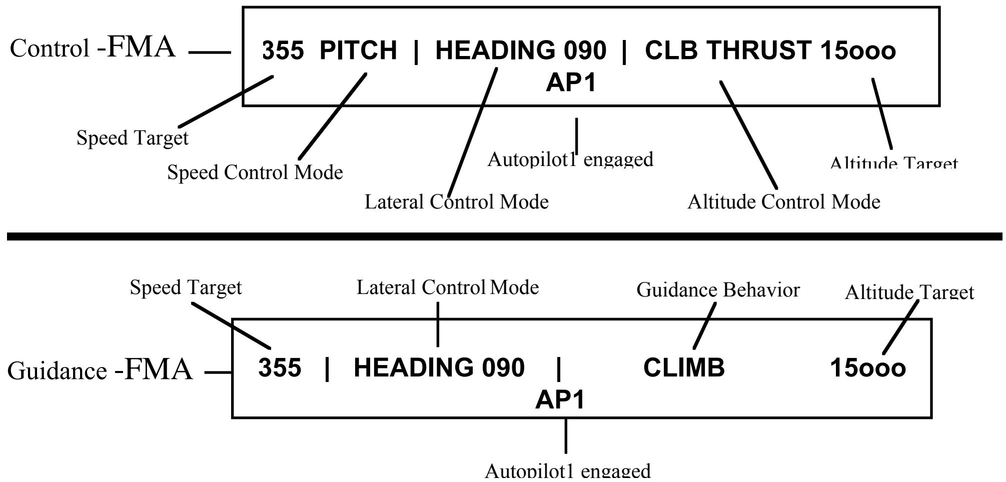

Figure 2 - Diagrams showing the existing MD-11 FMA and the guidance model.

Note: Presentation on the Primary Flight Display is white or magenta text on black background.

METHOD – Experiment 1

27 current MD-11 pilots with at least one year of experience on the airplane participated in the study. Three conditions(control, training and training + G-FMA) were used to compare effects of training versus display effects. 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 work 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 and pilots were questioned 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 [6].

RESULTS – Experiment 1

The “display” (training + G-FMA) condition showed significantly better performance for situation awareness type questions in this study. An F-Test, indicated 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 ”display” 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 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.

Experiment 2 - The Autopilot Tutor Training Package

Currently pilots are presented with the technical details of operating much of the autoflight systems, but not an accurate, coherent representation of the system. The lack of an accurate model may not only result in erroneous pilot actions, but may also be more difficult to train, and in the long term may require more training time.

A more productive first step in training 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.

The next step in the process would be the introduction of guided “drill and practice” exercises. Pilots may have thousands of hours of experience in flying different aircraft before they may get to an automated airplane for which they may have no background or experience. The “drill and practice” exercises are a way of giving the pilot “hands-on” experience, but in a “part-task” environment so that the autoflight system is isolated and can be concentrated on. The exercises would translate the conceptual details just learned into situation-response pairs and begin to develop automatic responses to situations. After some practice and interaction with the behavior of the real system, students should be able to make predictions about which actions will be required and what the result of a particular action will be.

Recently, PC-based computer simulations of the automated systems have become commercially available. Currently however, many of these devices suffer from the lack a complete and accurate model of the autopilot/Flight Management System behavior. As this hurdle is overcome, these devices will need modification to present a curriculum and training tools designed to train an accurate model of the system.

Computer Based Training – The Autopilot Tutor

As a proof of concept, Sherry, Feary, Polson, and Palmer [11] developed a web-based Autopilot Tutor based on the OPM model of the autopilot (Figure 3). It is available on the internet and can be viewed by contacting authors 1 & 2 through the e-mail addresses at the end of this document. The autopilot tutor Since the OPM model is created from the actual autopilot software it reflects the exact operation of the actual autopilot.

The Autopilot Tutor was based on the OPM created from the actual autopilot software, and therefore reflects the actual behavior of the autopilot. It consists of three pieces: the Tutor Controls and Displays, the Aircraft Controls and Displays, and the Simulator Controls.

The Tutor controls and displays differentiate the Tutor from a freeplay device. The only tutor control is a button with a variable label that turns the "scaffolding" on or off. "Scaffolding" refers to the additional information that is presented on the PFD and FCP to provide information missing from the displays of current aircraft. There are many different types of missing information, including information for making predictions, and information explaining current modes. Examples of the type of prediction information added to the aircraft displays in the tutor are the display of the capture region on the altitude tape, and the pop-up labels which give the next mode based on a pilot action. The scaffolding was created after looking through the OPM model to determine where there was insufficient information to distinguish and predict automation behaviors. The obvious implication for design is that this information should be provided on the aircraft displays, however, for this study the training scaffolding can be thought of as "training wheels" which will be removed as the training progresses.

The aircraft controls and displays represented on the Autopilot Tutor are similar to MD-11 Primary Flight Display and Flight Control Panel (FCP). The difference on the Autopilot Tutor is that the FCP does not have any lateral controls. The simulator portion of the Autopilot Tutor consists of 2 controls, the INIT button which initializes the tutor at 5000 feet and the STEP AIRPLANE FORWARD button which moves the

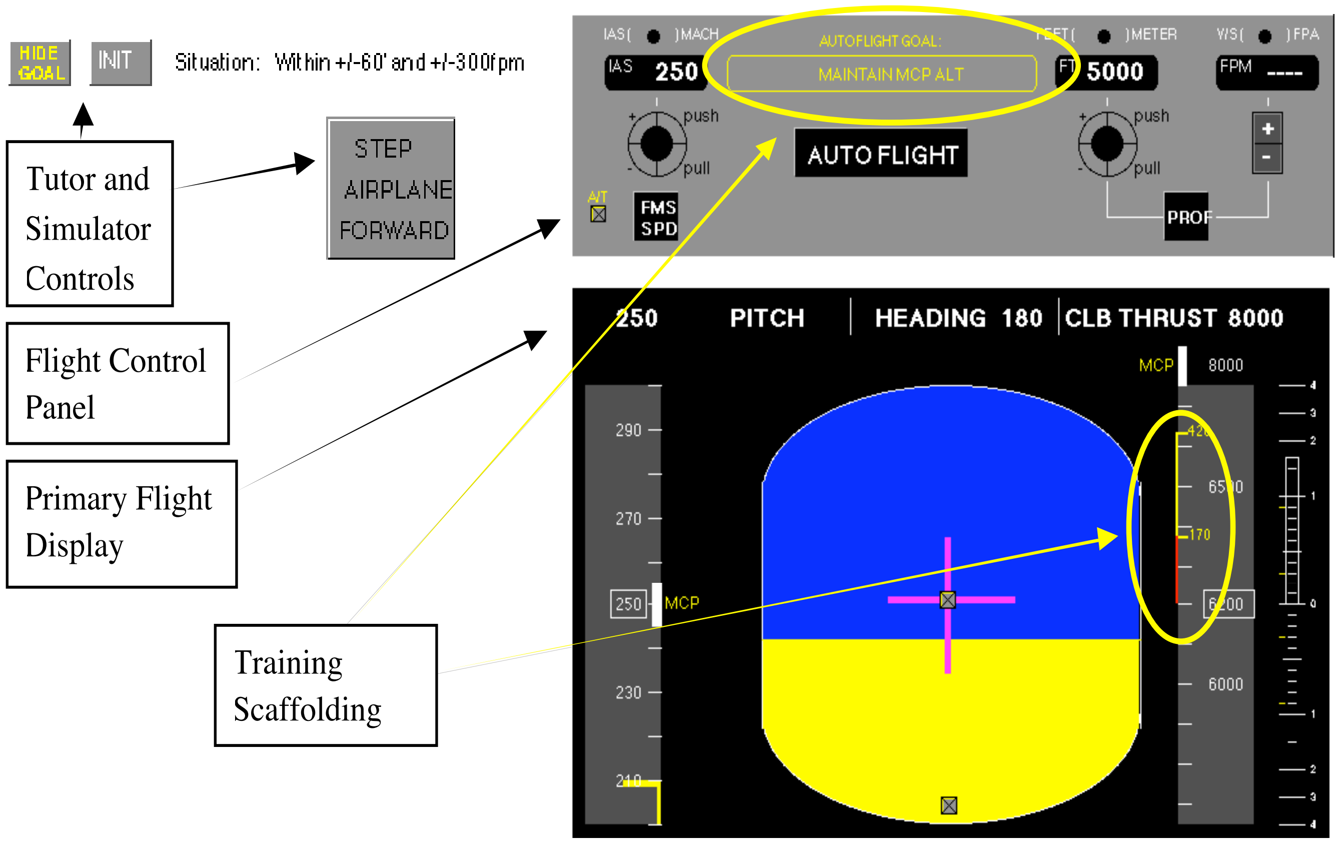

Figure 3. The Autopilot Tutor Website

simulator forward in time, but is represented as 100 foot changes in altitude each time the button is pressed. If there is no change in altitude commanded, the PFD will not change.

The addition of the STEP AIRPLANE FORWARD button allows students to take time to examine what has changed on the displays for each input, action and automatic mode transition. This is important because some of the most critical mode transitions appear to happen instantaneously, making it more difficult for the pilot to learn. Prototype versions of the tutor also include an ability to reverse in steps, so that the student can examine all of the differences for a particular mode transition.

Accompanying the tutor is a workbook with the definition of the autopilot goals, situations and behaviors. The workbook also includes questions and realistic flight scenarios that require the student to interact with the tutor to answer the questions.

METHOD – Experiment 2

A usability test of the Autopilot Tutor is being conducted. This testing has so far comprised of three general aviation pilots of varying backgrounds, but holding a minimum of an instrument rating, to validate the training material. The training material has three parts. First, a workbook, which introduces the Autopilot Tutor web interface, and 14 preliminary knowledge questions. Second, a set of exercises to allow the pilot "drill and practice" the knowledge introduced by the workbook. Embedded in these exercises are 55 questions intended to develop the student's rote knowledge into procedural knowledge and to start automate the student's autopilot interactions. The third set of materials is an exam consisting of 25 questions which test the student's knowledge. The exam also requires the use of the autopilot tutor interface to answer some of the questions correctly.

RESULTS – Experiment 2

The preliminary results show that the tutor interface can be learned rapidly, in approximately 10 minutes. Additionally the initial autopilot training, consisting of reading the training material and running through 55 "drill and practice" questions as well as a 25 question test, can be completed in less than 2.5 hours. The 25 question test is divided into 4 types of questions: select pilot action, predict the FMA after a pilot action, predict the FMA after an automatic mode transition, and predict when the capture will occur.

The first type of questions, "select pilot action", the required the students to select the actions on the FCP that would be needed to comply with a clearance. The students tested to this point have answered 100% of these questions correctly. They were also very successful with the second type of questions, "predict an FMA after a pilot action", with 93% of the questions answered correctly to date.

The performance for the third and fourth types of questions is much different. For the third type of questions, "predict the FMA after an automatic mode transition," 67% of the questions were answered correctly. The fourth type of questions has even lower performance, with only 61% of the questions answered correctly at this point.

The performance (or lack thereof) of the students on the third and fourth sets of questions is not a surprise, and appears to be easily explained. The performance decrease of these 2 types of questions really results from 2 questions, which none of the students have answered correctly thus far.

These 2 questions are very similar. The first question asks the student to make a prediction about an "armed" mode in the sense that the altitude capture is armed during the 2 seconds after the Vertical Speed wheel has been rotated. Students need to project into the future where the aircraft will be in relation to the capture region. The second question, although it was located at a different place in the exam, builds on the first by asking the student what behavior the automation will transition to after the 2 second period has elapsed. The result of misunderstandings about the behavior being tested in these 2 questions has been seen in aircraft incidents and accidents. In fact and has been cited by the U.S. National Transportation Safety Board as a deficiency and recommended change by the manufacturer. [9] Armed modes will continue cause problems for pilots because tasks which require monitoring do cause problems for humans. Additional training is also not likely to solve these problems. This leads to design solutions, such as those introduced as training scaffolding in the Autopilot Tutor.

CONCLUSIONS

Overall, the results from these 2 studies are very encouraging. These experiments have shown that it is possible to use a formal methodology as a basis for a design of interface and training design requirements. The experiments have also shown that the use of a particular methodology, the Operational Procedures Method, can improve pilot training and interface design. Using the formal method has resulted in training that is more complete, functionality that is better understood, and annunciations that are direct representations of the intentions of the designers. These improvements also come with a relatively small investment in time, but the training package is portable, so students can spend as much time as they wish before they come to formal training.

The most powerful means pilots have of learning the behavior of the autopilot is through observation. The Autopilot Tutor provides interaction time with the real behavior of the system, with enough time to comprehend what the system is doing. The workbook and exercise portion of the tutor allows the student to see the complete set of behaviors for the autopilot and focuses the students on learning the skills needed to successfully use the autopilot. These skills include, but are not limited to: the correct sequence of actions, the correct cognitive activities and the correct instrument scan. At the present time is difficult to compare the results from the Autopilot Tutor with existing materials, because there are no equivalent guided learning materials available.

Scaffolding, exemplified by the capture region predictor on the altitude tape is a good example of where a training solution has implication for the interface, system and procedure design communities. The training scaffolding was added by looking through the OPM model to determine where the information needed to distinguish and predict behaviors was located in the aircraft. If a piece of information could not be found, it was added in the form of "training scaffolding" but the obvious implication of this for the design process is to base the design of the interfaces on a complete model of the system in the beginning, and avoid the deficiencies in the current systems.

The two experiments discussed have also shown that reducing or eliminating differences between pilots' operational models and the operational models encoded in the autopilot may achieve a reduction in perceived complexity. More specifically, 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. [5] have demonstrated the value of providing more complete annunciations of autopilot behavior. 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. An additional benefit may be a reduction in perceived complexity as the correct, complete operational model is organized to be more coherent and allow students to reason through the model. This is a line of research that is being examined for the future.

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