AUTOPILOT TUTOR:
BUILDING AND MAINTAINING AUTOPILOT SKILLS

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ABSTRACT:

This paper describes a web-based tutor used to build and maintain pilot skills in operating a modern autopilot. The tutor, based on a goal-based model derived from the actual autopilot code, explicitly defines: (1) knowledge to recognize all unique autopilot behaviors from information on the flight mode annunciation (FMA) and other primary flight display (PFD) cues, (2) knowledge to convert pilot goals into pilot actions on the mode control panel (MCP). The tutor builds and maintains pilot skills by requiring the pilot to "solve problems" by executing Air Traffic Control instructions. The tutor provides immediate feedback to reinforce correct pilot behavior and rectify incorrect pilot behavior.

Keywords:
Automation surprise, cognitive tutor, flight mode annunciation, goal-based model, human factors

INTRODUCTION

The mismatch between expectations of the pilot and the behavior of the automation is a widespread well documented phenomenon that has been labeled "automation surprise" (BASI, 1999; Sarter, Woods, & Billings, 1997; Vakil & Hansmann, 1999; Degani & Heymann, in press; Javaux, 1998). The phenomenon is characterized by pilots asking questions of the automation; "what's it doing now ?" "what's it going to do next ?" and "why is it doing that ?" (Wiener, 1988). The FAA report, *Interfaces Between Flightcrews and Modern Flightdeck Systems* (FAA, 1996) describes automation surprises in the context of pilot situational awareness (pages 43 to 66) and issues with pilot's management of the automation (pages 33 to 41). The report catalogues the "gaps in pilot's understandings of the capabilities, the limitations, the modes, and the operating principles and techniques of the modern cockpit automation."

Although automation surprises have not been cited as the contributing factor in any incidents or accidents, there is a consensus among researchers that the gap between pilot's understanding of the avionics behavior, and the actual behavior of the avionics, leads to increased workload in the cockpit. Many, airlines, rather than face the task of training the pilots on the operation of functions perceived to be too complex, have explicitly decided to placard the function or provide training on only limited use of the function (Hutchins, 1994). Furthermore, pilots simply choose not to use parts of the automation (Sarter, Woods, & Billings, 1997).

At the root of the increase in pilot workload is the "hidden behavior of the cockpit automation" (Sherry & Polson, 1999). Unique autopilot behaviors (modes) are hidden by the annunciation of the same FMA (Sherry, Feary, Polson, & Palmer, in press - a). Also the effect of pilot actions on the MCP are hidden by unlabeled MCP control devices that can invoke different autopilot behaviors depending on the autopilot situation (Sherry, Feary, Polson, & Palmer, in press – b).

To eliminate these ambiguities, decrease pilot workload, and improve cockpit safety, there are two research questions that must be addressed: (1) can all of the knowledge required to operate modern cockpit automation be explicitly defined in a meaningful operational manner, and (2) can pilots be trained to use this knowledge within the time and cost constraints of a typical airline training program.

This paper describes how knowledge to infer the autopilot behavior from the FMA and PFD, and knowledge to map pilot goals to pilot MCP actions, is embedded in a web-based tutor used to build and maintain pilot competence in operation of a modern autopilot. The tutor, based on the cognitive tutors for complex skill acquisition demonstrated by Anderson & Lebiere (1998), holds an explicit model of the knowledge required by the pilot to operate the autopilot. This knowledge is derived from a model of the actual autopilot software.

APPROXIMATE MENTAL MODELS & PILOT TUTORS

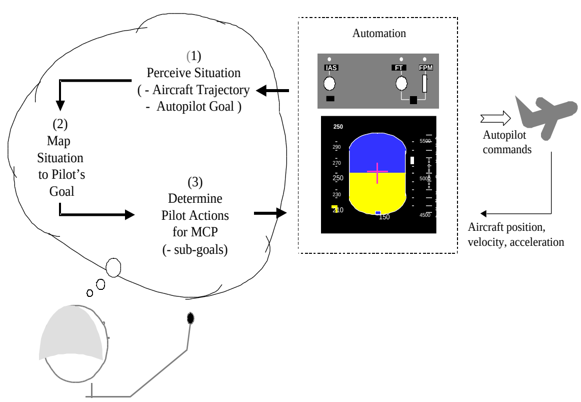
Norman (1988) proposed that operators of automated systems form "mental models" of the way the system behaves and use these models to guide their interaction with the system. This interaction with the automation (and much other human behavior) can be thought of as a continuous process of cyclic interaction (Monk, 1999; Card, Moran & Newell, 1983; Norman, 1988; and Anderson & Lebiere, 1998). To achieve a trajectory goal, the pilot performs a set of actions that lead to changes in the automation, that in turn causes changes in the environment. Evaluation of the state of the environment leads to reformulation of the pilot's goals and further action, leading to a new state of the environment, and so on.

Figure 1 illustrates the cycle for a pilot's interaction with the cockpit automation (Sherry et. al, in press –a). Based on information from the environment, the pilot formulates a definition of the perceived situation (block 1). This situation is used to determine appropriate goals (block 2). The goals are mapped to a sequence of actions on the MCP (block 3). In many cases, the sequence of actions themselves lead to the formulation of sub-goals and sub-actions as described in hierarchical task models such as GOMS (Johns & Kieras, 1996) and OFM (Callantine & Mitchell, 1999). Each of these cognitive activities, represented by function blocks in the picto-gram, requires knowledge that must be trained and maintained.

What is the Autopilot Doing Now ?

When the pilot delegates responsibility for performing specific tasks to the automation, it is critical that the pilot be cognizant of the behavior of the automation at all times. A subset of the pilot task of assessing the situation, block 1 in Figure 1, is assessing the behavior of the automation.

Sherry et. al. (in press - a) define autopilot behavior as the legal combinations of the values/actions for the autopilot output parameters; pitch control mode, throttle control mode, altitude target, speed target, and vertical speed target (see Table 1).



(1) Situation, (2) goal, and (3) action sequence of pilot interaction with automation. Boxes represent knowledge required by the pilot.
Figure 1

Autopilot Commands	Possible values
Altitude target	- MCP window - Current altitude - None
Speed target	- MCP speed window - Current speed - Max speed - Min speed
Vertical speed target	- MCP vertical speed window - Current vertical speed - None
Thrust control mode	- Max thrust - Idle thrust - Close loop on speed
Pitch control mode	- Close loop on speed - Close loop on vertical speed - Close loop on altitude

Autopilot behavior is defined by the legal combinations of values for the five autopilot commands in the left column. Possible values for each command are listed in the right column.
Table 1

Unique autopilot behaviors, defined by the legal combinations of these autopilot outputs are not uniquely annunciated on the PFD/FMA. For example, the FMA displays THRUST || VS for combinations of autopilot commands that will climb/descend and capture the assigned altitude and combinations of autopilot commands that will *fly away* from the assigned altitude.

To effectively monitor the autopilot, the pilot must be trained to map the FMA and PFD cues to identify each unique autopilot behavior. This knowledge is explicitly trained in the Autopilot Tutor.

Why Won't the Autopilot Take My Command ?

When the pilot decides on trajectory goal for the aircraft, the pilot must be able to convert the pilot goal into a set of pilot MCP actions that convey the pilot goal to the autopilot – block 3 in Figure 1.

Palmer (1995), Degani & Heymann (in press) and Sherry, Feary, Polson, & Palmer (in press - b) describe several examples MCP control devices conveying different pilot commands to the autopilot depending on the current context. For example, rotating the MCP vertical speed wheel when the autopilot is not actively capturing the MCP altitude, conveys a pilot command to *climb/descend to the MCP altitude* at the pilot selected rate of climb/descent. Rotating the MCP vertical speed wheel when the autopilot is actively capturing the MCP altitude conveys a pilot command to *fly away from the MCP altitude* (i.e. "kill the capture"). The different behaviors invoked by pilot action on the same MCP control device is not annunciated on the MCP and must be learned by the pilot.

COGNITIVE TUTORS

Cognitive tutors have the ambitious goal of serving as human tutors by engaging the student in sustained reasoning activities on specific topics (Anderson & Lebiere, 1998). They are specifically designed to build and train competence in procedural tasks, in which the student will solve problems by a sequence of steps. Like it's human counterpart, cognitive tutors guide the student through the material and provide immediate feedback to reinforce correct behavior and rectify incorrect behavior.

The cognitive tutor sets up real-world problems using the graphical user-interface of a computer. The student is posed a problem. The tutor initially guides the student through the steps to solve the problem. As the student gains competence, the tutor simply provides feedback to reinforce good behavior and rectify incorrect behavior. Through repetitive problem solving the tutor helps students convert facts about how to solve the problem (known as declarative knowledge) to mental production rules that determine behavior (known as procedural knowledge).

At the heart of the cognitive tutor is a model of the desired behavior. This explicit definition of the steps to solve the problem is used as content of the training material to build a student's knowledge of the facts (declarative knowledge) and as the mechanism in the tutor to provide real-time feedback to the student as the student repetitively solves problems. The repetitive problem solving with feedback is critical to a student "compiling" complete and accurate procedural knowledge.

Corbett, Koedinger, & Anderson (1997) summarize the characteristics of cognitive tutors with the following eight principles:

(1) train behavior using goal structures
(2) train behavior using production rules organized by goals
(3) reinforce correct behavior/rectify incorrect behavior immediately
(4) provide instruction in context of the real world problems solving the student will have to do
(5) minimize the load on a student's working memory so they can focus attention on the main task
(6) adjust grain size by starting with basic goals/production rules that provide the foundation for more complex goals/production rules
(7) provide for successive approximation to competence by fading support as the student's skills improve

THE AUTOPILOT TUTOR

The Autopilot Tutor is a web-based tool designed to build and maintain pilot competence using the characteristics of cognitive tutors described above. The Autopilot Tutor is explicitly designed to train pilots to:

a) map FMA and other PFD cues to autopilot goals
b) map pilot goals to pilot MCP actions

The tutor provides the pilot with ATC instructions that must be executed. Correct pilot behavior is reinforced by the tutor in real-time. Incorrect pilot behavior is flagged in real-time.

The tutor consists of three components; (1) the tutor user-interface, (2) the underlying model of the autopilot behavior, and (3) the workbook.

The Tutor User-interface

The Autopilot Tutor user-interface includes a MCP and PFD (Figure 2). The MCP knobs, wheels and buttons are active and may be selected to dial values into the windows, and engage/disengage modes. The PFD includes the FMA, speed tape, horizontal situation indicator, altitude tape, and vertical speed tape.

Training scaffolding is layered over the MCP and PFD to provide declarative knowledge, highlight critical parameters, draw attention to changes that are not annunciated in the cockpit displays, and provide immediate feedback to the pilot. The scaffolding includes labels for each of the MCP control devices to identify what autopilot goal will be invoked when the control device is selected. These labels change as a function of the state of the aircraft relative to the MCP altitude and speed envelope (see Sherry, Feary, Polson, & Palmer, in press – b). Training scaffolding on the MCP also includes annunciation of the autopilot goal that is currently active. This scaffolding is used by the pilot to confirm autopilot acceptance of pilot actions, and to alert the pilot to autonomous changes in autopilot goals.

Training scaffolding overlays additional icons on the PFD to aid the student in learning what parameters are important and in building rich indexing schemes into long-term memory to retrieve patterns of the PFD for each situation-goal-action. An example of the scaffolding on the PFD is the display of the capture region to the MCP Altitude. This dynamic display of the 0,03g circular path capture region allows pilot to learn where the aircraft will initiate a capture to the MCP altitude for different vertical speeds. This scaffolding also helps pilots learn the contour of normal capture trajectories.

The training scaffolding is incrementally faded as the training progresses to allow the student to transition to the actual cockpit.

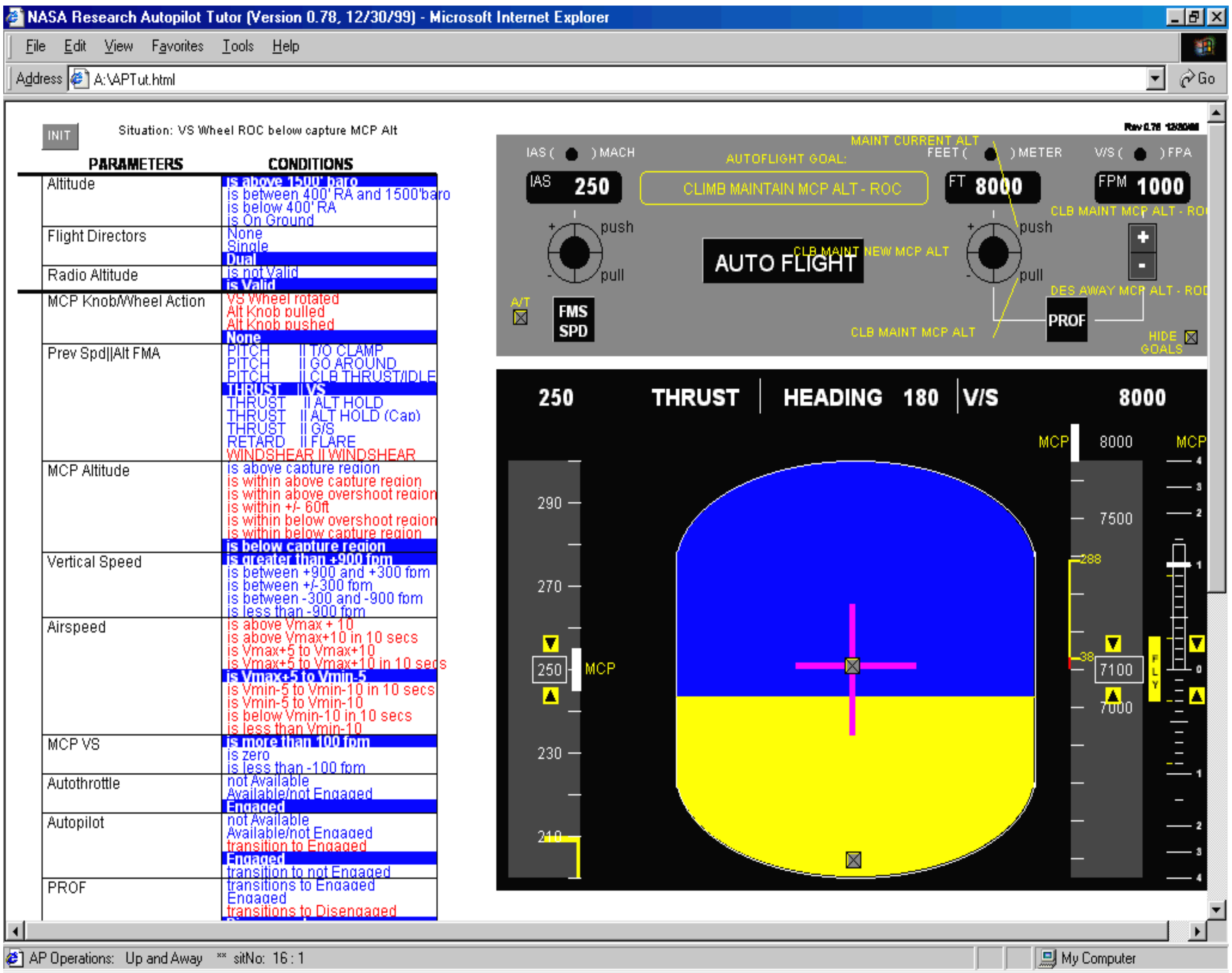
The Underlying Behavioral Model

As discussed above, the behavior of the tutor is based on a goal-based SGA model of the behavior the autopilot. The autopilot SGA model was derived from design logic diagrams and the actual autopilot software. Each combination of input conditions defines a *situation*. The possible combinations of pitch mode, thrust mode, altitude target, speed target, and vertical speed target define the *goals* (Sherry, Feary, Polson, & Palmer, 1997).

A dynamic representation of the SGA model is included on the user-interface. The active condition for each input is highlighted. Experts in autopilot operation have found the SGA model table useful during exploratory learning using the tool. The SGA model is not used by novice autopilot operators.

The Workbook

The workbook is used along with interactive user-interface. The workbook serves three purposes: it provides the declarative knowledge on autopilot behavior, it provides the practice drills that are critical in converting a pilot's declarative knowledge into procedural knowledge, and it provides the quizzes to determine competence.



Autopilot Tutor builds and maintains pilot competence to operate an autopilot. Training requires students to execute ATC instructions in a LOFT. Training scaffolding and reinforcing feedback is provided.
Figure 2

The desired pilot skills are defined in the workbook. The rules for the context-sensitive behavior of the MCP control devices and the rules for the inferring autopilot goals from the FMA and other PFD cues are explicitly defined and described by narrative and case studies. Figure 3 illustrates an excerpt that describes one aspect of the behavior of the MCP vertical speed wheel. The workbook explains this rule with diagrams of the MCP and PFD and narrative case study.

IF
- Pilot's goal is to decrease the rate of descent AND
- MCP altitude is within the 0.03g capture region AND
- aircraft speed is within the speed envelope AND
- aircraft is up-and-away (above 1500')
- autopilot is engaged
- PROF is not engaged

THEN
+ rotate the MCP vertical speed wheel up to a lower rate of descent

Contents of declarative rule describing task-action mapping to convert a pilot goal to pilot MCP actions.

The workbook also includes a set of practice drills that are critical in converting static pilot knowledge into rapid pilot stimulus-response behavior. The practice drills are all set up in real-world scenarios in which the pilot is required to respond to an event such as an ATC instruction. An example LOFT drill is included below. The quizzes to test competence take the same form as the drill.

Situation:

Departing PDX.

The aircraft is level at the MCP Altitude of 5000 ft at the MCP Airspeed of 250 knots.

The Speed || Altitude FMA reads THRUST || HOLD
The PFD Altitude Bug on the PFD Altitude Tape is at 5000'
The Autopilot goal is MAINTAIN MCP ALT

Event:

ATC: "NASA14, radar contact, climb maintain 6000' "

ANSWER THE FOLLOWING QUESTION

Question 1:
What pilot action on the MCP is required to meet the ATC instruction "climb and maintain 6000'"?

(Select one of the following)

- ❑ Dial up MCP Altitude to 6000
- ❑ Dial up MCP Altitude to 6000 and pull MCP Altitude Knob
- ❑ Rotate Vertical Speed Wheel to 800 fpm
- ❑ Push MCP Altitude Knob

ANSWER THE FOLLOWING QUESTION

Question 2
What SPEED || ALTITUDE FMA will be displayed ?

(Select one of the following)

- ❑ THRUST || HOLD
- ❑ PITCH || CLB THRUST
- ❑ THRUST || V/S
- ❑ PITCH || IDLE

What Autopilot goal will be invoked ?

(Select one of the following)

- ❑ MAINTAIN MCP ALT
- ❑ CLIMB MAINTAIN MCP ALT
- ❑ CLIMB MAINTAIN MCP ALT – ROC
- ❑ CLIMB MAINTAIN MCP ALT – CAP

Pilot Action:

Dial up the MCP Altitude to 6000 and pull the MCP Altitude Knob.

- · Monitor the Speed || Altitude FMA change to PITCH || CLB THRUST
- · Monitor the Altitude Bug on the PFD Altitude Tape change to 6000'
- · Monitor the Autopilot goal change to CLIMB MAINTAIN MCP ALT.

Pilot Action:

FLY the aircraft to 5600

Monitor the climb to 5600'

Situation:

The aircraft is ascending through 5600' with vertical speed of approx. 1100 fpm.

- The Autopilot goal is CLIMB MAINTAIN MCP ALT.
- The Speed || Altitude FMA reads PITCH || CLB

THRUST

- The Altitude Bug on the PFD Altitude Tape is at 6000'

CONCLUSIONS

The SGA model of autopilot behavior (Sherry, Feary, Polson, & Palmer, 1997) provides a fundamental source for knowledge required by pilots to operate the autopilot. This knowledge, organized as goals with situation-action rules, explicitly defines what the pilot needs to know about: (1) the context-sensitive dynamics of the MCP control devices and, (2) the behavior commanded by the autopilot for all combinations of FMA, altitude bug, speed bug, and vertical speed bug.

The Autopilot Tutor described in this paper, provides a part-task simulator to build and maintain this knowledge of autopilot. The user-interface and workbook provide the basic knowledge and the practice drills in which the student actively solves problems by executing ATC instructions. Immediate feedback is provided by the tutor to reinforce correct behavior and to rectify incorrect behavior.

The knowledge imparted to the students, the behavior of the MCP/PFD/autopilot, and the practice drills are all derived from a model of the actual software. This guarantees that the training is accurate, especially for "corner cases." The model is also critical in building LOFT practice drills that cover the flight regime and the autopilot "behavior space."

The tutor may also play a significant role in maintaining pilot competence in operation of the autopilot. By exercising the tutor during recurrent training, or on lay-overs the pilot will strengthen rules in their mental models that may have become weak and/or generalized by infrequent exposure in normal operation in revenue service or by natural inferrencing mechanisms of cognitive science as described by Javaux (1998).

Future Work

An experiment is planned to test the efficiency of the tutor in building and maintaining competence in the knowledge to operate the autopilot. Airline pilots will serve as subjects in the experiment. A control group will be trained using existing manufacturer/airline Flight Crew Operator Manuals (FCOM). An experimental group will be trained using the tutor. The performance of the groups will be tested by their ability to perform the correct pilot actions given an instruction and their ability to correctly predict the autopilot behavior in the course of a LOFT.

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