WHAT'S IT DOING NOW ?:
TAKING THE COVERS OFF AUTOPILOT BEHAVIOR

Lance Sherry
Honeywell
Lance.sherry@honeywell.com

Michael Feary
SJSU/NASA
mfeary@mail.arc.nasa.gov

Peter Polson
University of Colorado
ppolson@psych.colorado.edu

Everett Palmer
NASA
epalmer@mail.arc.nasa.gov

ABSTRACT:

Automation surprises in a modern "glass cockpit" can be attributed to the absence of a shared understanding of the intentions of the automation by the pilot/automation system. This paper demonstrates, using a formal modeling technique, how cockpit Flight Mode Annunciation (FMA) and Primary Flight Displays (PFD) fail to distinguish between distinct autopilot control behaviors. When the "covers are taken off" the autopilot behavior, it is observed that a single FMA configuration represents more than one autopilot behavior. This paper also describes how the contents of the formal model can be used to develop training and to set certification criteria.

Keywords:

Automation surprise, flight mode annunciation, goal-based model, human factors, certification criteria.

INTRODUCTION

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 (FAA, 1996; BASI, 1999). In fact 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).

Several researchers have provided case studies of specific automation surprises that occurred with pilot interaction with the mode control panel (MCP) vertical speed wheel (Palmer, 1995), altitude knob (Degani & Heymann, in press) and go around button (Javaux, 1998). An automation surprise was also documented in a recent National Transportation Safety Board (NTSB) Safety Recommendation (NTSB, 1999). In each of the case studies the pilot *was surprised by the trajectory of the aircraft as commanded by the autopilot*.

> **Representative example:** "When flight xxx was cleared to descend to 20,000 ft, the first officer initiated a descent via the autopilot. With approximately 1,200 ft left in the descent, <u>the captain became concerned the airplane might not level off at the assigned altitude</u> <u>and instructed the first officer to slow the descent rate. The first officer adjusted the MCP vertical speed wheel several times; however this maneuver proved ineffective</u>. The captain then took manual control of the airplane, and disconnected the autopilot …"

This example, highlights two prominent issues in the design, training, and operation of complex automation:

(1) <u>What is it doing now ? What is it going to do next ?:</u> "…the captain became concerned the airplane might not level off at the assigned altitude," describes a phenomenon in which operators were confused by the behavior of the automation and question what the system was doing, and more importantly, what it was going to do next. In this case the pilot/automation system failed to establish *a shared understanding of the intention of the automation*.

(2) <u>How do I convey pilot goals to the automation ?:</u> "…the captain …instructed the first officer to slow the rate of descent. The first officer adjusted the MCP vertical speed wheel several times; however this maneuver proved ineffective," describes a phenomenon in which the crew were unable to convey their trajectory goals to the automation. In this case the interface between the pilot and automation failed to provide *adequate affordances for the pilot to convey their goals to the autopilot.*

This paper describes a formal method to identify ambiguous feedback of the behavior of an autopilot that contributes to the breakdown of pilot understanding of the intentions of the autopilot. The paper also demonstrates how the contents of the formal model provide the basis for training pilots to recognize different autopilot behaviors that have the same FMA.

AUTOMATION SURPRISES & APPROXIMATE MENTAL MODELS

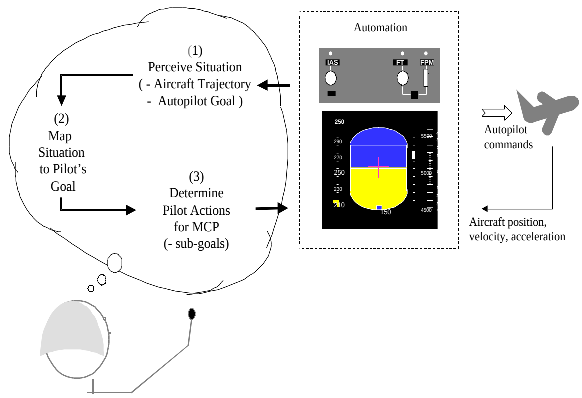
Norman (1988) proposed that operators of automated systems form "mental models" of the way the system behaves and use these models to guide their interaction with the system. This interaction with the automation (and much other human behavior) can be thought of as a continuous process of cyclic interaction (Monk, 1999). 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. This model of cyclic interaction is at the root of most modern models of cognition, for example; Card, Moran, & Newell's (1983) recognize-act cycle, Norman's (1988) seven stage cycle, and Anderson's (1993) ACT-R model.

This cyclic interaction is abstracted in the picto-gram illustrating a pilot's interaction with the cockpit automation (Figure 1). 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 pilot actions on the MCP (block 3). In many cases, the sequence of pilot actions on the MCP 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 the blocks in the picto-gram, requires knowledge that must be trained and maintained.

The focus of this paper is the pilot's failure to map information about the situation of the aircraft and information about the state of the automation into an understanding of the autopilot's behavior. This failure may be due to the absence of appropriate knowledge in the pilot's head (block 1), or when the knowledge is present, a failure in cognition described by Reason (1987) as a "mistake." Incomplete and inaccurate training material results in gaps in a pilot's knowledge. Inadequate feedback on the user-interface fails to provide the necessary information to reinforce correct pilot mental models. These omission results in mistakes.

Inferring Autopilot Behavior from Cockpit Displays

The primary source of information in the cockpit for the state of the aircraft is derived from the PFD speed tape, altitude tape, vertical speed tape, and horizontal situation indicator. Despite the availability of FMA, pilots are more likely to use this aircraft trajectory information to determine the state of the automation (Woods, et. al., 1994). In a study of fixation time in approaches, (Huettig, Anders, & Tautz, 1999) found that pilots use the FMA 4.7% percent of the time even in the presence of abnormal



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

operations. Sarter (1995) suggested that pilots scan the cockpit displays to gather information to answer specific question pilots ask themselves.

There are a number of explanations for the lack of use of FMA. One premise is that pilots, despite their role as supervisor of cockpit automation, are still flying the aircraft through a surrogate - the automation (UAL, 2000). The current content of the FMA, control modes, provides little value to the task of managing thrust and pitch to achieve the desired trajectory. One implication of this premise is that the FMA is not designed to allow pilots to "fly" the aircraft through the autopilot surrogate. Another explanation is that the FMA is poorly located. One of the goals of the Integrated Mode Management Interface (IMMI) designed by Hutchins (1994) is provide confirmation of pilot activated mode change at the location of the pilots hand action. The physical separation of the MCP and PFD has been cited by several pilots as inappropriate. In fact, several MD-11 instructors have been observed to tape over the MCP windows to force their students to focus on the PFD were the pilot entries are confirmed by the automation and result in mode changes (Feary, 1999).

Inferring the state of the automation from aircraft trajectory information requires the pilot to "have knowledge in their heads" (Norman, 1988) that maps information from the scan to autopilot behavior. Placing "knowledge in the world" can eliminate the requirement for "knowledge in the head". One implementation of this strategy is to supplement the existing FMA, or replace the existing FMA with explicit annunciation of the autopilot behavior. The explicit display of VNAV behavior, proposed by Sherry & Polson (1999), resulted in improved pilot performance ($p > 0.03$) (Feary et. al., 1999).

Inferring Autopilot Behavior from Knowledge in the Head

In the absence of simple, consistent, and communicable descriptions of the behavior of the cockpit automation, pilots will (and do) create their own models of this behavior (Vakil & Hansmann, 1999). These ad-hoc mental models are, at best, approximations of the behavior of the actual avionics and directly contribute to automation surprises by providing predictions that are different than the actual behavior of the automation.

The mental models of pilots are approximations for three reasons. First the training materials provided in the form of Flight Crew Operating manuals (FCOMs) provided by the manufacturers and airlines are incomplete and do not reflect the underlying conceptual model of the behavior (Vakil & Hansmann, 1999). Second, the content of the cockpit displays does not provide sufficient information to infer the behavior of the automation even when it is trained completely (Hutchins, 1994). Third, pilots develop approximate models of the behavior of the automation due to naturally occurring cognitive processes that simplify and generalize rules in memory (Javaux, 1998). This simplification of the rules takes place as a result of infrequent use and generalization of similar behaviors.

This paper demonstrates that the FMA on modern "glass" aircraft does not provide pilots with sufficient information to infer unique autopilot behaviors. Unique autopilot behavior, labeled as autopilot goals in this paper, can be derived from a formal model of the behavior of the autopilot. These goals can be introduced into the cockpit displays, and/or used as the basis for pilot training on autopilot behavior.

METHOD OF ANALAYIS: SGA MODEL

The SGA model, a variation of the Operational Procedure Model (Sherry, 1995), layers a semantic goal model over a formal situation-action model of a finite state machine:

Situation = *f* (state of env. from system inputs) (a)
Goal = *f* (situation) (b)
Outputs = *f* (goal, actions) (c)

The behavior of a system under analysis is defined by the values of the output parameters over time. The output values are derived by executing a set of actions (or functions) that are selected based on the active goal (equation c). The goal is determined by the situation (equation b). The situation is determined by the conditions of the input parameters to the system (equation c).

Using this model, the behavior of the system can be defined by the *legal combinations of functions used to generate outputs at any given time.* The behavior of a modern autopilot can be defined by the combinations of functions used to generate the values of outputs in Table 1. For example, the autopilot behavior "climb and maintain the MCP altitude" is defined by autopilot altitude target set to the MCP altitude, autopilot speed target set to the MCP speed, pitch control mode closing the loop on aircraft speed, and thrust set to the climb thrust rating.

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

Analyzing User-Interfaces Using SGA model

The user-interface of the automation provides feedback to the pilot on the behavior of the automation. By definition of the SGA model, each unique system behavior should be annunciated unambiguously to the operator. The SGA model of a device can be used to identify potential ambiguous displays when:

- *the same annunciation for different autopilot behaviors*
- *different annunciations for the same autopilot behavior.*

When unique displays cannot be eliminated from the design, the situation definitions in the SGA model can be used to ensure sufficient information is displayed so that the pilot can distinguish between the different autopilot behaviors. The SGA model also provides the content for pilot training and an executable model that can be used in a web-based interactive training device that allows the pilot to build and maintain proficiency in the operation of the autopilot.

CASE STUDY: ANALYSIS OF MODERN AUTOPILOT MODE CONTROL PANEL

An SGA model of a modern autopilot was constructed and used to analyze the effectiveness of the MCP of the NASA Research Autopilot (Sherry, Feary, Polson, & Palmer, 1997). The possible combinations of pitch mode, thrust mode, altitude target, speed target, and vertical speed target were also identified by analysis of the software and the design documentation. The combinations of output functions were labeled with an operationally meaningful *autopilot goal*. Where possible, the goal description reflected Air Traffic Control nomenclature, such as “climb and maintain XXX thousand feet.”

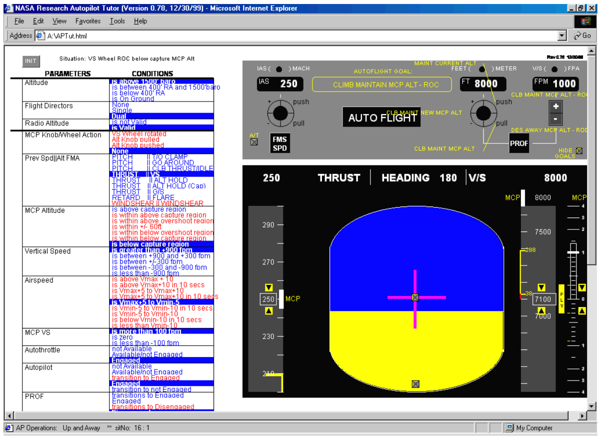
A sample of the autopilot goals for up-and-away operations (above 1500 ft) for the autopilot are listed below. The legal combinations of output functions are listed on each row on the right-hand-side of Table 1. The left-most column of Table 2 lists the autopilot goal assigned to each unique autopilot behavior.

The pilot can invoke the first 7 goals through actions on the MCP. Goal pairs 1 & 2 perform flight level change with max thrust and idle thrust respectively. Goals 3 & 4 provide climb and descent with pilot selected rate of climb/descent. Goals 5 & 6 reflect a feature implemented in this autopilot that allows the pilot to “kill the capture” to the MCP altitude. Goal 7 is for immediate level-off at current altitude. Goals 8 -12 are invoked autonomously by the autopilot without any pilot confirmation. Goals 12 & 13 may be invoked automatically by the autopilot 2 seconds after autopilot goals 5 or 6 are selected by the

Autopilot Goal	Unique Autopilot Behaviors				
	Speed FMA	**Alt FMA**	**PFD Alt Bug**	**PFD Spd Bug**	**PFD VS Bug**
1. CLIMB MAINTAIN MCP ALT	PITCH	CLB THRUST	MCP Alt window	MCP speed window	N/A
2. DESCEND MAINTAIN MCP ALT	PITCH	IDLE	MCP Alt window	MCP speed window	N/A
3. CLIMB MAINTAIN MCP ALT - ROC	THRUST	VS	MCP Alt window	MCP speed window	MCP VS window
4. DESCEND MAINTAIN MCP ALT – ROD	THRUST	VS	MCP Alt window	MCP speed window	MCP VS window
5. CLIMB AWAY MCP ALT – ROC (2 SECS)	THRUST	VS	N/A	MCP speed window	MCP VS window
6. DESCEND AWAY MCP ALT – ROD (2 SECS)	THRUST	VS	N/A	MCP speed window	MCP VS window
7. MAINTAIN CURRENT ALT	THRUST	HOLD	Current Altitude	MCP speed window	N/A
8. CLIMB MAINTAIN MCP ALT - CAP	THRUST	HOLD	MCP alt window	MCP speed window	N/A
9. DESCEND MAINTAIN MCP ALT - CAP	THRUST	HOLD	MCP alt window	MCP speed window	N/A
10. MAINTAIN MCP ALT	THRUST	HOLD	MCP Alt window	MCP speed window	N/A
11. PROTECT SPEED ENVELOPE	PITCH	IDLE	MCP Alt window	MCP speed window	N/A
	PITCH	MCT	MCP Alt window	MCP speed window	N/A
	THRUST	VS	N/A	MCP speed window	Current VS
12. CLIMB AWAY MCP ALT – ROC (2 SECS)	THRUST	VS	N/A	MCP speed window	MCP VS window
13. DESCEND AWAY MCP ALT – ROD (2 SECS)	THRUST	VS	N/A	MCP speed window	MCP VS window
14. MAINTAIN CURRENT ATTITUDE/SPEED	THRUST	VS	MCP Alt window	Current speed	Current VS

Autopilot behavior is defined by the legal combinations of autopilot commands for altitude control (FMA), speed control (FMA), altitude, speed ,and vertical speed. Each legal combination is labeled with an operationally meaningful autopilot goal.

Table 2



Autopilot Tutor. Trains pilots on situations-goals-actions of autpilot. Training requires students to execute ATC instructions in a LOFT. Training scaffolding and reinforcing feedback is provided.
Figure 2

pilot.

Table 2 illustrates two potential ambiguities in the annunciation of the autopilot behavior.

Same Annunciation for Different Autopilot Behaviors

The labeling of the Speed || Altitude FMA does not provide unique labels for all of the possible autopilot goals. For example THRUST || VS appears 6 times in the table. It represents the following goals:

3&4) CLIMB/DESCEND MAINTAIN MCP ALT – ROC/ROD
5&6) CLIMB/DESCEND AWAY MCP ALT – ROC/ROD (2 SECS)
12&13) CLIMB/DESCEND AWAY MCP ALT – ROC/ROD
11) PROTECT SPEED ENVELOPE
14) MAINTAIN CURRENT ATTITUDE/SPEED

Distinguishing autopilot behaviors that climb/descend and maintain the assigned altitude, from behaviors that fly *away* from the assigned altitude are critical. Furthermore, distinguishing pilot invoked autopilot goals from those invoked autonomously by the autopilot, such as PROTECT SPEED ENVELOPE and MAINTAIN CURRENT ATTITUDE/SPEED, can eliminate automation surprises.

Different Annunciation for the Same Autopilot Behavior

The labeling of the FMA also uses different FMA for the same autopilot goal. Autopilot goal PROTECT SPEED ENVELOPE has three combinations of FMA:

- PITCH || CLB THRUST
- PITCH || IDLE THRUST
- THRUST || VS.

Scenarios may occur when the FMA does not change following autonomous intervention by the autopilot.

MITIGATING "HIDDEN" AUTOPILOT BEHAVIOR

There are two ways in which autopilot behavior hidden by the FMA can be addressed.

Place Knowledge in the World: Display Autopilot Goal

The simplest way to solve this type of automation surprise is to place knowledge in the world that makes the pilot task of inferring the autopilot goal intuitive. One implementation is to display the autopilot goal on the MCP or on the PFD/FMA (Sherry & Polson, 1999; Feary et. al. 1998). As in the design of all user-interface components, the content and form of these goal displays should be considered carefully.

Place all Knowledge in the Pilots Head to Infer Autopilot Goals

When it is not possible to design the user-interface to place all the knowledge in the world, or when the system is already in place, it is necessary to train the operator. This training must explicitly define all of the autopilot behaviors and the set of cues that should be used to infer these goals.

Sherry, Feary, Polson, and Palmer (1999) developed a web-based Autopilot Tutor using the SGA model of the autopilot (Figure 2). Since the SGA model is created from the actual autopilot software it reflects the exact operation of the actual autopilot. Accompanying the tutor is a workbook with the definition of the autopilot goals, situations and behaviors. The workbook also includes LOFTs designed to invoke all of the features and behaviors of the autopilot as defined in the SGA.

Two pedagogical features of the tutor that are worth noting are:

- The tutor/workbook require the student to "solve problems" using the MCP by executing ATC instructions. This provides context for memory retrieval (Anderson, 1993).
- Training scaffolding overlays additional icons on the Primary Flight Display. The scaffolding aids 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 in the SGA. Display of the autopilot goal on the MCP provides immediate feedback to the student on the active autopilot goal. Scaffolding is faded as the training progresses to allow the student to transition to the actual cockpit.

CONCLUSIONS & RECOMMENDATIONS

The formal SGA model of the modern autopilot provides the basis for evaluating the pilot/autopilot interaction. For example in the automation surprise described at the beginning of the paper, the SCG model identified that the ambiguous FMA "hides" more than one autopilot behavior behind the same FMA - THRUST || VS. Both autopilot goals DESCEND MAINTAIN MCP ALT and DESCEND AWAY MCP ALT - ROD (2 SECS) share this annunciation. By adjusting the MCP vertical speed wheel every few seconds, the first-officer unwittingly "killed the capture" and caused the aircraft to *fly away from*, not capture the assigned altitude. Hence the automation surprise.

Solutions to the hidden autopilot behavior can be addressed by: (1) use of unique labels for each autopilot behavior, and (2) explicit pilot training to recognize the unique autopilot behaviors and the autopilot goals (Sherry, Feary, Polson, Palmer, in press).

Recommendation for Certification

The SGA analysis provides a formal method for defining the behavior of the avionics device. The model can be used by manufacturers to demonstrate to the certification authorities, that unique labels are used for display of all autopilot behaviors.

Acknowledgements:

This research was supported by the National Aeronautics and Space Administration (NASA) under contract NAS1-20219 to Honeywell Air Transport Systems (COTR: Ev Palmer) and cooperative agreement NCC 2-904 with the University of Colorado (COTR: Ev Palmer) Special thanks for several technical contributions and support: Mike Palmer (NASA – Langley), Steve Quarry, Dan McCrobie, Jim Martin, John Kilroy (Honeywell), Marty Alkin (FedEx), John Powers (UAL).

References:

Anderson, J. (1993) *Rules of the Mind.* L. Erlbaum and Associated: Hillsdale, New Jersey.

BASI (1998) Advanced Technology Aircraft Safety Survey Report. Report by Dept. of Transport and Regional Dev. Bureau of Air Safety Investigation. Available at http://www.basi.gov.au/sprog/advtek.htm

Card, S.K., T.P. Moran, & A. Newell (1983) *The psychology of human-computer interaction*. Lawrence Erlabaum: Hillsdale, N.J.

Callantine, T.J., & C.M. Mitchell (1999) *GT-CATS: Tracking Operator Activities in Complex Systems*. NASA/TM-1999-208788.

Degani, A,. & M. Heymann (in press) Some formal aspects of human-automation interaction.

FAA (1996) *The interface between flightcrews and modern flight deck system*. FAA human factors team. Federal Aviation Administration. Available at http://www.faa.gov/avr/afs/interface.pdf

Feary, M. (1999) personal communication.

Feary, M., M. Alkins, E. Palmer, L. Sherry, D. McCrobie, P. Polson (1997) Behavior-based vs. system-based training and displays for automated vertical guidance. Proceedings *Ninth International Aviation Psychology Symposium Conference,* Columbus, OH.

Huettig, G., G. Anders, A. Tautz (1999) Mode awareness in a modern glass cockpit: Attention allocation to mode information. *Proceedings of the 10th International Symposium on Aviation Psychology,* Columbus, OH.

Hutchins, E. (1994) An integrated mode management interface for training. Training for automation workshop, NASA-Ames Research Center, Moffet Field, CA.

Javaux, D. (1998) The cognitive complexity of pilot mode interaction: A possible explanation of Sarter & Woods classical results. Proceedings *HCI-Aero, International Conference on Human-Computer Interaction in Aeronautics,* Montreal, Canada.

John, B. & D. Kieras (1996) Using GOMS for User-interface design and evaluation: Which technique ?" *ACM transactions on Computer-Human Interaction* V 3, N 4. Pgs 287-319.

Monk, A. (1999) Modelling cyclic interaction. *Behavior & Information Technology,* Vol. 18, No. 2. Pgs 127-139.

Norman, D. A. (1988) *The Design of Everyday Things*. Doubleday: New York, N.Y.

NTSB (1999) Safety Recommendation. A-99-39 through 44

Palmer E. (1995) Oops, it did n't arm: A case study of two automation surprises." In proceedings *Eighth International Symposium on Aviation Psychology,* Colombus, OH, April, 1995. Pgs. 227-232.

Reason, J. (1987) The psychology of mistakes: A brief view of planning failures. In J. Rasmussen, K. Duncan, & J. leplat, eds, *New Technology and Human Error*. John Wiley: New Yor, N.Y. Pgs 45-52.

Sarter, N.B., D.D. Woods, & C.E. Billings (1997) Automation surprises. In G. Salvendy, editor, *Handbook of Human Factors and Ergonomics*. John Wiley & Sons, 2nd edition.

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

Sherry, L. M. Feary, P. Polson, & E. Palmer (1997) Analysis of the Behavior of a Modern Autopilot. Prepared for NASA under contract NAS1-20219. Honeywell Publication No. C69-5370-009.

Sherry, L.& P.Polson (1999) Shared models of flight management systems vertical guidance. In *The International Journal of Aviation Psychology – Special Issue: Aircraft Automation.* L. Erlbaum: N.Y.

Sherry, L., M. Feary, P. Polson, & E. Palmer (in press) Autopilot tutor: Building and maintaining autopilot skills.

UAL (2000) Personal communication with Boeing fleet captains at UAL.

Vakil, S. S. & R.J. Hansman (1999) Approaches to mitigating complexity-driven issues in commercial autoflight systems. In pre-proceedings *Human Error, Safety, and System Development,* Liege, Belgium. June 7-8, 1999.

Woods, D.D., Johannesen, L., Cook, R., N. Sarter (1994) Behind human error: Cognitive systems, computers, and hindsight. Wright Patterson Air Force Base, Dayton, O.H.: CSERIAC.