# Cognitive Demands of Staying in Control on Highly Automated Aircraft When Faced with Surprise

Shawn Pruchnicki [1], David Woods[1]
[1] The Ohio State University, USA

Pruchnicki.4@osu.edu Woods.2@osu.edu

**Abstract.** The pilots of today's modern aircraft are much more information and resource managers as opposed to direct controllers of the aircraft. Failures can result in conflicting or erroneous information flowing to automatic systems and flight deck displays complicating control and management tasks. The initiating or triggering event produces a kind of surprise situation where flight crews must recognize that the state of control of the aircraft has changed, scan information sources, understand the changed situation, priortize and decide on new courses of action. It is not well understood how pilots handle such surprises including factors that influence how they recognize the event, update their understanding of the situation and priorities, and develop/revise a course of action. We are interested in cognitive demands and difficulties that arise in the short interval immediately following the symptoms produced by the initiating event. By examining the demands of the tasks that flow from the initiating event -- how it is manifested in instrumentation, how different automated systems respond, and how aircraft behavior changes, how the event changes tempo, how the event changes priorities, and how the event changes what are critical and constructive courses of action -- we can better understand how pilots successfully accomplish this task and risks of breakdowns when these situations arise.

## 1 INTRODUCTION

In today's modern aircraft, the majority of flight time is spent at cruise where decision making is typically light and flight crew members are interacting with automation in a supervisory mode. That is to say, crew members are watching automation "fly" the aircraft and are adjusting various systems as needed. Additionally, during these times, event tempo is low and crew members have a clear understanding of what to expect next. They have sufficient time to recognize changes, understand the new situation and re-adjust the systems that handle the aircraft. The flight crew has the capability to stay in control of the aircraft and manage the automated systems.

But what happens when an initiating event occur in other phases of flight and when the failures result in conflicting or erroneous information flowing to automatic systems and flight deck displays? The flightcrew as resource manager and supervisor experiences new cognitive demands at the same time that tempo increases and actions become more critical for safety.

The initiating or triggering event produces a kind of surprise situation where, in the short interval immediately following the symptoms produced by the initiating event, flight crews must

- recognize that the state of control of the aircraft has changed,
- scan multiple information sources, and integrate information gathered to understand the changed situation,
- priortize and decide on new courses of action.

We understand too little about pilots' ability to able handle such surprises, the difficulties involved in the cognitive activities, the risks for how tasks could breakdown, and the support mechanisms that ensure the tasks can be done successfully and reliably despite the difficulties and given the criticality (Woods and Sarter, 2000). A variety of factors could influence how flight crews recognize the event, update their understanding of the situation and priorities, and develop/revise a course of action. It is particularly critical to measure the cognitive demands and difficulties that flow from the initiating event -- how it is manifested in instrumentation, how different automated systems respond, and how aircraft behavior changes, how the event changes tempo, how the event changes priorities, and how the event changes what are critical and constructive courses of action.

In this paper we describe a line of research underway to examine the above issues. As a hallmark of resilient systems, we are interested in how flight crews reassess, reconsider and revise their perceptions and understanding following the initiating event. How do they gather and integrate information across multiple data sources to make sense of the situation quickly? How do they decide on decisive and constructive actions despite the time pressure, criticality and uncertainties? The end result of this line of inquiry will contribute to a new kind of assessment of what it means to be in control, including risks and support requirements (Hollnagel, 1993).

## 2 BEING IN CONTROL

> Vignette 1: "My new first officer had been doing a great job flying the jet on previous legs. However, on the next leg as we lifted off the runway to fly a complicated departure procedure, I could see and hear that he was becoming focused solely on aircraft heading to the exclusion of other flight parameters. He was trying to hand fly a departure that not only required a rapid level off, but also a turn to stay within a close by airspace boundary. Additionally, we were assigned an speed well below normal our normal departure airspeed. I could see that because of his narrow focus on aircraft

> heading, our rapidly increasing airspeed & climb rate would soon result in multiple violations; thus I assumed control to prevent an excursion."

This notional example considers how one person monitors how well another human is controlling a process, anticipates risks of loss of control, and intervenes constructively and decisively before control of the situation deteriorates too far (Woods, 2011; Woods and Branlat, 2011). In this example we see how an experienced Captain stays in control as initial signs of loss of control emerge when she is monitoring the activities of the First Officer as pilot flying, The example illustrates the combination of factors that led the Captain to anticipate the need to intervene and to transfer control bumplessly to avoid difficulties. She considered the difficulty of the task (a complicated departure procedure), workload trend (going up), the difficulties ahead (increasing), and the risks of to task performance. (getting closer to limits on criteria for successful performance), all, relative to the abilities of the First Officer to handle the multiple demands. To consider these factors, she knew what indicators to scan, how to integrate the information she gathered and how to combine them with expectations about to what lay immediately ahead in order (a) to understand the trend on the risk of loss of control and (b) to see how and where to take decisive and constructive action to maintain control.

> Vignette 2: "We had the autopilot engaged upon beginning our initial descent towards our crossing restriction. As we were completing the descent checklist, I noticed something flashing while scanning across the displays to ensure ATC path compliance. As I searched the moving map and FMS indications, I recognized that the FMS had gone into dead reckoning mode and the rest of our route had disappeared from the map display. I was puzzled as to what could have produced this change? I soon recognized that this change in mode meant the aircraft was not only drifting off course, but also, that our crossing restriction had been removed. I directed the First Officer to advise ATC, while I quickly inserted the next waypoint, re-established the crossing restriction, and shifted autopilot modes to regain control of the situation."

The second notional example considers how one person monitors how well automated systems are controlling a process. The example illustrates an automation surprise (Woods and Sarter, 2000) triggered by an indirect mode transition (Sarter and Woods, 1995). Whereas in vignette 1 the situation developed rapidly but continuously, in vignette 2 the initiating event introduces a sudden change. The Captain needs to recognize that a change in control has occurred and that the automated systems have changed their configuration, and therefore how they will control the aircraft relative to targets, constraints, and plans has changed. Upon noticing an unexpected indication while scanning the cockpit displays, we can easily imagine the basic questions of an automation surprise (Sarter and Woods, 1995) running through the Captain's head: what just happened, what are the automated systems doing and going to do next, how did we get into that mode. Also note in this example, the absence of an indication provides relevant information, i.e., the absence of route indication, the loss of he crossing restriction.

These situations occur under time pressure, so that scanning displays and integrating data gathered to answer how and why questions is insufficient -- constructive interventions to maintain control are needed. One could spend too much of the limited time available for information processing and decision making answering the questions of how and why did we get into this situation, when staying in control demands timely identification of what to do next and the ability to commit to decisive intervention despite the time pressure (and potentially uncertainty).

The shift to monitoring automated systems for risk of loss of control introduces some differences and new difficulties as contrasted with the human to human case illustrated in vignette 1. The Captain directly can observe directly how well the First Officer is handling demands, and can project how the First Officer will handle upcoming demands based on shared knowledge and experiences as professional pilots. Understanding changes in automation configuration, how the automation will handle the aircraft following the change, projecting how automated systems will behave next, and judging how these changes effect the risk of loss of control is quite different and presents new kinds of difficulties (Sarter and Woods, 2000).

> Vignette 3: “We had just lowered the gear and were starting down the nighttime ILS to minimums when I noticed that, despite the auto-throttle being engaged, the airspeed was too fast for lowering final flaps. I still tried to lower flaps but the aircraft’s programmed protection refused to comply. I manually extended the spoilers in an attempt to bleed off airspeed so that once corrected we could lower the flaps. With the spoilers extended the aircraft climbed above the glideslope and then surprisingly pitched down. I retracted the spoilers as we descend below the glideslope and the aircraft responded by pitching up and the auto-throttle began to spool up the engines. However, given that the rate of applied thrust was insufficient to regain the lost airspeed, we started to descend further below the glideslope. It almost seemed as if the auto-throttle was not working correctly in conjunction with the autopilot that was flying the ILS. Things were happening very fast. When we received the first “pull-up” terrain warning I took control of the aircraft, turned off the automation and hand flew a missed approach. We still don’t understand how we became so unstabilized and why the autopilot could not regain stability and path control after the slight initial airspeed excursion.”

The third notional example introduces new complexities as there are interactions across multiple automatic systems, and two automated systems appear to be working at cross-purposes. In this example, time pressure to intervene is high limiting the amount of time available for scanning and interpretation. But uncertainty is high: each action is followed by unexpected behaviors of automated systems and aircraft behavior. Each cycle of information gathering and situation assessment leads to control surface adjustments but instead of improving control of the situation they introduce new demands for information gathering, situation assessment, and intervention. Ultimately, the resolution is to fly a go-around maneuver.

These notional cases illustrate the need to study and model the cognitive demands and risks associated with staying in control on highly automated aircraft. To do this we need to analyze the cognitive processes required while moving through time from initiating event and associated indications, through information search and integration, to committing to new courses of action, and looping through combinations:

- Background: What is the state and trajectory of control just prior to the initiating or surprise event?

- Initiating event and manifestation in displays, alerts, automation system changes and behaviors, and aircraft behavior: How do events change control and change risks of loss of control? How are the events and the change in control signaled to flight crew? Does the event generate conflicting indications or other challenges?

- Scan patterns and information gathering: What are effective scan patterns? What are the *costs* (e.g., time delays), *difficulties* (e.g., recognizing the absence of an expected indication; detecting state changes with poor display of events) and *risks of breakdown* (e.g., fragmented scan pattern; missing indirect mode changes, missing dropped constraints)

- Integration and assessment: What is necessary to resolve uncertainty and conflicts between indications (analysts must be sure to escape from hindsight bias to address this question)? What is needed to anticipate upcoming events and constraints? What are the *costs*, *difficulties* (e.g., what is the role of anticipation), and *risks of breakdown* (e.g., getting stuck on this cognitive activity delaying intervention decisions) associated with integration and assessment?

- Interventions and commitment to course of action: How to identify constructive interventions and commit to a course of action despite uncertainty and risk? How to generate possible approaches? How to focus on key priorities? what are the *costs*, *difficulties* (e.g., how to decide on interventions when data conflicts), and *risks of breakdown* (e.g., over-relying on automated systems to handle non-normal situations; delays due to resolving uncertainties, inability to prioritize, bumpy transfer of control) associated with identifying and committing to constructive interventions?

- Dynamic interplay across these events and activities: how to manage tempo, time pressure, and workload to keep up with the pace of events? What are the *costs*, *difficulties*, and *risks of breakdown* in managing workload in time as a situation threatens to cascade out of control?

The cognitive demands above can be address by observing how professional crews in advanced turbojet aircraft simulators handle the general challenges imposed by different specific instances of surprise that challenge the ability to stay in control. The data can be analyzed as a process tracing of the detailed cognitive flow as organized around the above points (Woods, 2003). Analysis can extract results on questions such as:

- What factors delay information gathering and integration when the surprise is first manifested or recognized?

- What kinds of scan patterns do pilots use? Are these ad hoc or systematic? Are some scan patterns more useful and robust in these situations?
- How do current displays hinder or facilitate information gathering and integration?
- What factors produce bumpy transfers of control or control conflicts between the interacting automated systems and flight crew?
- How do crews resolve conflicts between data and interpret unexpected automated systems responses?
- How do some failures complicate flight crew control and management tasks when conflicting or erroneous information flows to automatic systems?
- What factors delay or undermine the ability to take decisive and constructive actions despite uncertainty?

The initial model of the cognitive demands of staying in control following a surprise event provides the structure for future data collection and analysis to identify what is particularly difficult, what breakdowns are likely, and what support mechanisms can increase the ability to stay in control in demanding situations.

# 3 RESILIENCE AND STAYING IN CONTROL

Staying in control in this setting (aviation flight decks), for this joint cognitive system (multiple automated systems and flight crew), and for key dynamics associated with keeping pace with a changing situation represents a kind of natural laboratory (Woods, 2003) for Resilience Engineering to investigate key concepts about how systems respond to challenge situations (Woods and Branlat, 2010).

First, staying in control following a surprise is subject to significant risk of the adaptive system breakdown pattern - *decompensation* which occurs when challenges grow and cascade faster than responses can be decided on and deployed to effect (Woods and Branlat, 2011). The ability to continue to control saturates so that there is little or no capacity to adapt as challenges cascade and new events occur (Cook and Rasmussen, 2005).

Second, staying in control following a surprise when managing a set of partially autonomous resources (the different parts of flight deck automation) is subject to significant risk of the adaptive system breakdown pattern - *working at cross-purposes* which occurs when there is inability of different agents at different echelons to coordinate their activities given uncertainty, risk, and the potential for goal conflicts (Woods and Branlat, 2011). Automated systems may work at cross purposes as is indicated in vignette 3, especially following sensor failures, and flight crew and automated systems may and have miscoordinated their activities (Sarter and Woods, 2000; Woods and Sarter, 2000).

Both kinds of breakdowns are risks when flight crews need to stay in control following a surprise, and this risk of a failure to control is captured in the parameter *brittleness* of a complex adaptive system (Woods and Wreathall, 2008). Estimates of brittleness or change in brittleness can be used to drive investment in training and design improvements.

Staying in control following a surprise represents another kind of opportunity for Resilience Engineering - a potential demonstration of the engineering potential of the field. As specific factors are identified that drive the risk of these breakdowns, specific improvements can be developed and tested. For example, one approach is the development of new training approaches that develop pilot skills to manage surprise events (Dekker and Lundström, 2006). Another is the role of tactile displays which have been shown to improve dramatically pilots' accuracy to recognize relevant indirect mode transitions (Sarter, 2002; Nikolic et al., 2004; Ho, et al., 2004). The data gathered on staying in control following surprise may point to vulnerabilities in different areas with different implications for practical and measurable improvements: if a vulnerability is inconsistent and fragmented scan patterns, then new part-task training programs can be developed to reinforce effective scan patterns; if the vulnerability is inherent difficulties associated with resolving data conflicts, then new heuristic procedures for resolving data conflicts can be innovated (Lipshitz, 1997); if interruptions and multi-tasking are a key vulnerability, then attention directing displays can produce significant performance improvements (Sarter, 2002).

## 4 REFERENCES

Dekker, S., & Lundström, J. (2006). From Threat and Error Management (TEM) to Resilience. *Human Factors and Aerospace Safety*, 6(3), 261–273.

Cook, R. and Rasmussen, J. (2005). "Going Solid": A model of system dynamics and consequences for patient safety. *Quality and Safety in Health Care*, 14, 130-134.

Ho, C-Y, Nikolic. M., Waters, M., and Sarter, N.B. (2004). Not now: Supporting interruption management by indicating the modality and urgency of pending tasks. *Human Factors*, 46(3), 399-409.

Hollnagel, E. (1993). *Human reliability analysis: context and control*. Academic Press, London.

Lipshitz, R. (1997). Coping with uncertainty: Beyond the reduce, quantify and plug heuristic. In R. Flin, E. Sala, M., Strub, & L., Martin (Eds.), *Decision making under stress: Emerging themes and applications.* (pp. 149-160). Aldershot, UK: Ashgate.

Nikolic, M.I., Orr, J.M., and Sarter, N.B. (2004). Why Pilots Miss the Green Box: How Display Context Undermines Attention Capture. *The International Journal of Aviation Psychology*, 14(1), 39-52.

Sarter, N. B. (2002). Multimodal Information Presentation in Support of Human Automation Communication and Coordination. In Eduardo Salas (Ed.), *Advances in Human Performance and Cognitive Engineering Research* (pp. 13-36), New York: JAI Press.

Sarter N. B. and Woods, D. D. (1995). "How in the world did we get into that mode?" Mode error and awareness in supervisory control. *Human Factors*, 37: 5-19.

Sarter, N. and Woods, D.D. (2000). Team Play with a Powerful and Independent Agent: A Full Mission Simulation. *Human Factors*, 42, 390—402.

Woods, D. D. (2003). Discovering How Distributed Cognitive Systems Work. In E. Hollnagel (ed.), *Handbook of Cognitive Task Design*. Erlbaum, pp. 37-54.

Woods, D. D. (2011). Resilience and the Ability to Anticipate. In E. Hollnagel, Paries, J., Woods, D.D., and Wreathall, J., Eds., *Resilience Engineering in Practice* (pp. 121-125). Ashgate, Aldershot, UK.

Woods, D. D. and Sarter, N. (2000). Learning from Automation Surprises and Going Sour Accidents. In N. Sarter and R. Amalberti (Eds.), *Cognitive Engineering in the Aviation Domain* (pp. 327-354). Erlbaum, Hillsdale NJ.

Woods, D. D., & Branlat, M. (2010). "Hollnagel's test: being 'in control' of highly interdependent multi-layered networked systems." *Cognition, Technology & Work* 12.2: 95-101.

Woods, D. D. and Branlat, M. (2011). How Adaptive Systems Fail. In E. Hollnagel, Paries, J., Woods, D.D., and Wreathall, J., Eds., *Resilience Engineering in Practice* (pp. 127-143). Ashgate, Aldershot, UK.

Woods, D. D., & Wreathall, J. (2008). Stress-Strain Plot as a Basis for Assessing System Resilience. In E. Hollnagel, C. Nemeth and S. W. A. Dekker, eds., *Resilience Engineering Perspectives 1: Remaining sensitive to the possibility of failure* (pp. 145-161). Ashgate, Aldershot, UK.