

# Crew/Automation Interaction in Space Transportation Systems: Lessons Learned from the Glass Cockpit

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## Abstract

The progressive integration of automation technologies in commercial transport aircraft flight decks -- the “glass cockpit” -- has had a major, and generally positive, impact on flight crew operations. Flight deck automation has provided significant benefits, such as economic efficiency, increased precision and safety, and enhanced functionality within the crew interface. These enhancements, however, may have been accrued at a price, such as complexity added to crew/automation interaction that has been implicated in a number of aircraft incidents and accidents. This report briefly describes “glass cockpit” evolution. Some relevant aircraft accidents and incidents are described, followed by a more detailed description of human/automation issues and problems (e.g., crew error, monitoring, modes, command authority, crew coordination, workload, and training). This paper concludes with example principles and guidelines for considering “glass cockpit” human/automation integration within space transportation systems.

## Introduction and Background

The progressive integration of automation technologies, Flight Management Systems (FMS), and enhanced displays in commercial transport aircraft flight decks -- the “glass cockpit” -- has had a major, and generally positive, impact on flight crew operations. For example, these technologies have increased safety and have provided enhanced crew interface features and use of limited cockpit “real estate,” more efficient flight path control and management, and a general reduction in crew workload.

It is anticipated that significant automation technologies will be considered for integration into the next generation reusable human-rated space transportation system. This automation has the potential to enhance such functions as launch, ascent, and orbit insertion; rendezvous and proximity operations (e.g., during ISS resupply missions, for satellite retrieval and repair); detection and actuation of escape systems; on-orbit payload operations; and de-orbit, entry, descent, approach, and landing (especially with a deconditioned crew). Automation has provided a number of benefits on aircraft flight decks and could provide similar benefits to a Reusable Launch Vehicle (RLV). Some of these benefits are:

- **Economic Efficiencies:** Automation has provided savings in a number of domains, by enhancing efficiencies (e.g., in fuel use) and by reducing operating costs (e.g., by enhanced reliability, reduced maintenance requirements, and reduced crew size);

- Enhanced precision: Automation allows more precise guidance and navigation, enhanced vehicle position control, and better energy management;
- Enhanced safety: Automation enhances safety by providing for the rapid detection and actuation of emergency systems beyond the performance capabilities of the crew.
- Economy of cockpit space and enhanced information display: The glass cockpit has allowed increased information integration while also affording new information display methods and simplifying crew operations (e.g., number of procedures and procedure steps).
- Reduced crew workload: Automation reduced workload such that the flight crew could be reduced from three to two. Automation also removed crew responsibility for many tedious, time-consuming, and potentially interfering tasks (e.g., auto-tuning radios).

These enhancements, however, may have been accrued at a price. With increased automation, significant complexity has also been introduced into crew/automation interaction that has been implicated in a number of aircraft incidents and accidents (see, for example, Wiener, 1988 and Special Report, 1995). A seminal report by Wiener & Curry (1980) foreshadowed crew/automation interaction problems. Concerns with pilot interaction with flight deck automation has prompted research (e.g., Wiener, 1989; Sarter & Woods, 1991, 1992a, 1992b; Rudisill, 1994, 1995, 2000) and an in-depth review of the situation (with recommendations) by the FAA (Human Factors Team, 1996). In addition, several researchers have proposed sets of “human-centered” guidelines and principles for the design of highly automated crewed systems (e.g., Bergeron & Hinton, 1985; Billings, 1991, 1997; Dwyer, 1994).

This report will include an overview of the evolution of the “glass cockpit” and flight deck automation. Some accidents & incidents related to flight crew interaction with automation on the flight deck are described, followed by an exploration of crew/automation integration issues that have been identified within the aviation domain, which could have application to an RLV. Some example crew/automation integration guidelines are provided, as well as a description of planned work to develop guidelines for the design of crew/automated systems for consideration on the next generation RLV.

### *Evolution of the Glass Cockpit and Flight Deck Automation*

For a detailed description of flight deck evolution, see Billings (1991, 1997). Early automated flight decks had simple electromechanical flight and navigation instruments, with a first generation autopilot and Flight Director (FD). Vehicle information was distributed across individual displays. The pilot had primary responsibility for manually controlling the vehicle and monitoring the flight profile with rudimentary computer support. Next generation aircraft provided Performance Management Systems (PMS) with some rudimentary autoflight modes and a basic auto-touchdown function. The FD was integrated with rudimentary computer-based navigation support. Some functions were grouped within a common Mode Control Panel (MCP) and first generation autothrottles and autobrakes appeared.

The next generation aircraft witnessed a major evolutionary step in automated capabilities, due to increased computer memory and processing speeds. Previously independent systems were integrated with autopilots to provide a “Flight Management System (FMS),” enabling automated control of the entire flight. New autoflight modes appeared and were integrated into a next generation MCP. Information was displayed on “glass.” The fully automated FMS had programmable navigation/flight profiles with supporting navigation databases using accurate Inertial Reference Systems (IRS) and integrated performance calculations (e.g., fuel usage). The crew interface was provided by a Primary Flight Display (PFD), an Electronic Flight Instrumentation System (EFIS), and a Map display for lateral navigation. Automated landing capabilities increased.

Modern transport aircraft have (multiple) complex and refined FMS’s, with larger and more sophisticated navigation databases, new autoflight modes, GPS-based navigation, digital autothrottles, and enhanced MCP’s. Autopilots with three-axis control allow enhanced guidance and crosswind landing capabilities. “System automation” (e.g, EICAS, Engine Indication Caution and Alerting System) with associated system displays and crew support (e.g., electronic procedures) appeared. The most recent aircraft have taken the next step with the introduction of automated failure mode handling. Sophisticated “fly-by-wire” control systems appeared, and some aircraft introduced active “envelope protection.”

#### *Crew/Automation Interaction Accidents & Incidents in the Aviation Domain*

Following is a brief description of a sample of incidents and accidents involving flight crew interaction with the automation on their aircraft. These examples are indicative of the types of problems that have been associated with the progressive introduction and use of automation on commercial transport flight decks.

- “Strong and silent” automation, feedback, and information display. Automation has been called “strong and silent” in that it has significant capability to control the vehicle, but often provides little feedback to the crew concerning its present state and its operation. For example, in 1985, a China Airlines flight crew lost power in one engine during automated flight of a Boeing B747. The automation compensated for failing engine performance until its control limits were reached, at which point the automation failed and the aircraft went into an uncontrolled dive. The pilot was ultimately able to disengage the automation and recover the aircraft. The automation essentially masked the approaching onset of its control limits and the impending loss of control of the vehicle.

In 1990, a British Midland Airways flight crew flying a B737-400 throttled back engine No. 2 in response to significant engine vibration, noise, and shuddering. However, engine No. 1 was on fire (difficult to discern from the re-designed glass “engine display,” particularly given the emergency circumstances); the engine suffered loss of thrust on final approach and crashed with significant fatalities. The accident investigation board questioned the methods used to evaluate and certify the new engine display, which was later improved by the manufacturer.

- Pilots as “system monitors” and crew over-confidence in automation capabilities. The pilot’s role has changed with automation, from “direct controller” to “system monitor.” At times, pilots have become complacent and have over-depended on their automation.

In 1988, at the Habsheim airshow, an Air France flight crew was demonstrating the “low, slow flyover” capabilities of the Airbus A320. The aircraft lost energy and flew into the trees, killing all persons on board. The crew was confident of the automated “envelope protection” features of the aircraft.

In 1996, an American Airlines B757 crashed in Cali, Colombia, killing all onboard. There were a number of underlying causes for this accident, many of which related to the automation and the flight crew’s training. The root causes of this accident included:

- inadequacy of the navigational database used by the automated FMC;
- the flight crew’s failure to maintain navigation situation awareness;
- the flight crew’s misprogramming of a navigational waypoint;
- crew task overload caused by unexpected runway changes (and the task load associated with re-programming the FMC);
- crew training that emphasized automation use at the expense of maintaining crew manual control and navigation skills; and
- language difficulties.

As Phillips (1996) noted, this accident was, “a textbook case of pilots depending on automation to solve a problem rather than taking manual control... [The vehicle’s] computer did exactly what it was told to do.” As a result of this accident, the airline changed its policy with regard to crew use of automation and has followed other airlines in training its pilots to “turn off” the automation and rely on their manual skills during an in-flight anomaly.

- Crew interaction with complex automated flight modes. Automated flight modes have become increasingly sophisticated and complex. Crew mode confusion underlies a number of incidents and accidents.

In 1992, an A320 crashed on final approach to Strasbourg, France airport, killing 87 of the passengers and crew. On investigation, it was determined that the autoflight system was set to the Vertical Speed (V/S) mode rather than the typical Flight Path Angle (FPA) mode. The display read, “3.3”; when in V/S mode, this indicates a descent rate of 3,300 feet per minute on final approach (four times the published descent rate) rather than a descent angle of 3.3 degrees in FPA mode (translating into a descent rate of about 1,000 feet per minute). It was a night flight through poor weather and, again, late instructions from ATC required the pilots to re-program their FMC, increasing their workload beyond a level they could handle safely. Apparently a similar incident had occurred on approach into San Diego airport in 1990, but the aircraft’s Ground Proximity Warning System (GPWS), not present on the Strasbourg flight, warned the pilots in time to disengage the automation and take manual control of the aircraft. As a result of the Strasbourg accident, the manufacturer redesigned the display panel to prevent such mode confusion.

There have also been accidents and incidents related to automation-commanded mode transitions (i.e., mode transitions not commanded by the crew) and the resulting changes in autoflight logic behavior. For example, an “uncommanded” (i.e., by crew) mode transition during a simulated engine failure on take-off contributed to the fatal crash of an A330 in Toulouse, France in 1994. During takeoff, the aircraft automatically transitioned to an automode; with no pitch authority limitations in this particular mode, the automation pitched the aircraft to 32 degrees nose high and maintained an excessive climb rate, causing the aircraft to lose airspeed and stall before the crew could disengage the automation and take manual control. The dynamic conditions in this situation were beyond the control logic capabilities of the particular autoflight mode, and the manufacturer has since changed the mode logic such that pitch authority is limited.

Other autoflight mode accidents and incidents have been related to crew confusion with regard to the automated mode, perhaps exacerbated by non-standard mode disconnects and lack of automation feedback to the crew. In two cases (Moscow, 1991 and Nagoya, Japan, 1994), an autoflight mode commanded nose-up pitch while the pilot commanded nose-down pitch during an autopilot-coupled go-around. In the Moscow incident, the airplane went through a number of extreme pitch oscillations until the crew was able to disconnect the automation and gain control. In Nagoya, the crew inadvertently activated the go-around mode during a normal approach. The crew attempted to reacquire the glide slope by commanding nose down elevator, but this conflicted with the autoflight mode’s logic and pitch up commands. In addition, the automated stabilizer system had trimmed the aircraft to maximum nose-up, following its go-around logic (which may not have been clearly annunciated to the crew). The crew should have allowed the automated flight mode to control the aircraft, or should have completely disconnected the automation. That is, the situation was recoverable, but the crew, interacting with the automation (and in the presence of reduced feedback), put the aircraft into an unrecoverable position. An underlying issue relates to the mechanism enabling a pilot to disconnect the autoflight mode and regain manual control. The autopilot was designed to not disconnect using the standard control column force when in go-around mode below a specific altitude (for protection), and needed to be disconnected by an alternate mode; the crew may have believed they disconnected the autopilot and were manually controlling the aircraft when, in fact, the automation was still operating. Ultimately, the automated flight mode dominated and the aircraft pitched up, stalled and crashed.

### Crew/Automation Interaction Issues & Problems

As shown by the brief descriptions of automation-related incidents and accidents, with the benefits accrued by automation came a number of unexpected problems. This has generated research exploring crew interaction with automation. General categories of crew/automation interaction problems and issues are identified and briefly described below.

- Safety and Crew Error

Pilots maintain that automation has generally enhanced overall safety. Automation has freed the crew from many “mundane and time consuming” tasks, thereby allowing them more time for monitoring and decision making. However, automation may also lend a false sense of security. The majority of aircraft accidents are still attributed to human error (approximately 70%); it has been assumed that automating functions removed the source of this error (i.e., the human crew),

although this assumption is now in debate. More likely, automation relocated, rather than reduced, crew error (for example, crew must still monitor the automated systems, so automation generally does not operate without some crew input and interaction). Automation may have decreased some forms of crew error while creating opportunities for new error types. And these new error types may be more serious, since (1) the automation can often quietly compensate, then fail at the boundaries of the problem, from which it is more difficult to recover (and, in fact, may be unrecoverable at this point), and (2) crew may be “out-of-the-control loop” while automation is in command, making it more difficult for them to become sufficiently involved quickly enough to effect a recovery.

- The Pilot as System Monitor

The role of the crew on the flight deck has changed from “direct (manual) controller” to “system monitor and supervisor.” The crew must be supported in this role, especially if automation is “opaque” with regard to its state. “Silent” automation is more difficult to monitor and more difficult to recover from when it fails. Norman (1989) maintains that the primary problem with crew interaction with automation is lack of feedback and poor human/automation interaction.

Some pilots report discomfort with a monitoring role: they are given responsibility for the flight/mission, but essentially give control to a silent and powerful controller. Automation technology should be viewed as a tool to be used by the crew as they require. Also, pilots report that automation requires more self-discipline -- it is easy to depend on the automation and lose sight of the vehicle, becoming a “spectator” while automation does its job, rather than the vehicle commander. As evidenced by “Controlled Flight Into Terrain” (CFIT) accidents, a non-human computer controller will fly an aircraft into a mountain if it is instructed (i.e., programmed) to do so, with little regard to its “personal safety.”

- Automation Complexity and Modes

Automated systems have become quite complex and often the complexity has been coupled with little feedback about the actual state of the automated system. Pilots are generally positive about their automation, reporting that automation “allows them to concentrate on the real world outside the vehicle.” They particularly appreciate automated navigation support. But there is also a sense of “over-automation,” that automation technology was unnecessarily included on the flight deck, with little consideration of an actual requirement for it.

One particular problem with automation complexity relates to “autoflight modes.” Multiple complex flight modes have, at times, reduced crew mode and situation awareness and understanding of automation and the energy state of the vehicle. Wiener (1989) established the “what’s it doing now?” syndrome, indicating the complexity of human/automation interaction. He reported that the most common questions pilots ask with regard to flight deck automation are: “What’s it doing now?”, “Why did it do that?”, and “What will it do next?”

Exacerbating the mode complexity problem are “uncommanded mode changes” (i.e., automation, rather than crew, changing the flight mode with little or no annunciation), that effectively and silently change the control logic operating at the time, couched within a framework of little or no feedback about the automation’s activities. Mode problems have generated a significant amount of research, most notably work by Sarter and Woods (see, for

example, Sarter & Woods, 1991, 1992a, 1992b). From an automation survey they conducted, the authors reported that a significant number of pilots experience “FMS surprises” and do not understand all of the FMS modes and functions, even after one year of flight experience. These “surprises” were reported with such automated functions as vertical navigation logic, data entry, infrequently used features & modes, the FD, data propagation, and partial system failures.

- **Distancing**

Automation has placed a “layer” between the crew and the physical vehicle; that is, the crew no longer effects changes on the vehicle directly, but controls the vehicle “through” the automation. Pilots report feeling “isolated” and “distanced” from the physical vehicle and its energy state. Layering can make it more difficult to maintain situation awareness, it may foster a “crew out-of-the-loop” situation, and make it more difficult for the crew to anticipate vehicle behavior.

- **Command and Authority**

The increasing capabilities of automation have at times produced a situation where it is unclear “who is in charge.” Decisions (made, essentially, by the designer of the automation) can be implemented without crew consent and restrictions on crew capabilities can be instituted (e.g., “automated envelope protection” actively restricts the flight crew from performing flight maneuvers considered outside the operating envelope of an aircraft, even during an emergency). In addition, some pilots have noted that automation effectively alters command structure and “muddies” command authority by allowing either crewmember to manage the flight through the powerful FMS.

- **Crew Interaction & Cockpit Resource Management**

The visual nature of automation increases the need for crew communication and cooperation; flight decisions are made and programmed into the FMC but are not necessarily reflected in the displayed information, effectively removing one crewmember from the “decision loop.” Automation requires crew discipline (with regard to communication) and new operating procedures: at times, pilots are left to operate highly computerized equipment with procedures designed for electromechanical instruments.

- **Crew Workload**

With the glass cockpit, an “automation paradox” appeared (Wiener, 1989): automation reduces workload in low workload flight phases (e.g., cruise), but often increases workload during high workload flight phase (e.g., approach and landing). This increased workload is primarily caused by difficulties associated with interacting with the automation through the crew interface, that is, programming the FMS. This is especially true if there are changes in the flight plan that must be effected while controlling the vehicle. Workload also may significantly increase during an abnormal or emergency situation. In addition, automation has reduced manual workload, but has increased “cognitive” workload (e.g., planning and monitoring) and has introduced an “interface management task” in addition to the pilot tasks of “aviate, navigate, communicate.” Pilots report that it is often easier to turn off the automation and control the vehicle manually than to reprogram the automation during high workload situations.

- Display and Control Design

The “glass cockpit” provides significant enhancements to the display of information to the flight crew. In particular, (1) integration of information onto a single Primary Flight Display (PFD)/Electronic Flight Instrumentation System (EFIS) display and (2) display of lateral navigation information on a “Map Display,” has significantly enhanced crew operations. But the glass cockpit also created new opportunities for clutter and the different organization of information may have also altered well-learned scan patterns; the new displays “take some getting used to” (e.g., reading an airspeed and altimeter “strip”).

Automated controls are also well received, with “fly-by-wire” control systems highly regarded. However, one area of concern has emerged: some pilots believe that the lack of back-driving and lack of cross-coupling of some control systems removes a significant type of feedback that crew uses to maintain situation awareness of the vehicle. In addition, some implementations of automated control have “smoothed the boundaries,” effectively removing the “seat of the pants” feel that pilots use.

- Fatigue, Stress, Complacency, & Boredom

Automation generally reduces fatigue and stress. But pilots also report that they’ve observed an over-reliance on the automation, where they become complacent and can be lulled into a “false sense of security.” This appears to be particularly true with less experienced pilots, who may feel more comfortable depending on the computer to the point where they may “fixate” on the automation. Boredom associated with complacency may reduce their situation awareness and their ability to intervene during an emergency. This problem may be reduced by training, experience, and operating procedures that dictate decreased reliance on automated support and regular cross-checking of raw data.

- Loss of Manual Skills

Some pilots report degradation of, and decreased confidence in, their manual control skills with significant automation use, decreasing safety when crew is used as the “back up” to a failed automated control system. Automation has not changed the fundamentals of airmanship; understanding this, some pilots regularly turn off the automation and fly manually to maintain their skills.

- Crew Training and the Automation “Mental Model”

Transitioning to a glass cockpit is often difficult; this “new way of flying” requires significant learning and a significant change in the pilot’s “mental model” concerning how the vehicle is operated. Training needs to provide sufficient vehicle and system knowledge to allow crews to understand the automation and solve problems when they arise. They need hands-on practice to feel comfortable programming the automated systems (and efficiently re-programming if the situation arises). How and when to use the automation effectively should be emphasized. And training needs to be coupled with procedures and an “automation operating philosophy” that accounts for the difficulties described here.

- Level of Capability

At its present level of capability, automation is able to perform numerous tasks formerly only performed by human crew, with high levels of precision (particularly, navigation and flight

control tasks). But automation is not yet capable enough to completely replace a human crewmember; there are flight situations (e.g., significant crosswinds) where an automated controller cannot operate. In particular, automation cannot yet perform well under those circumstances where humans excel, such as operating under uncertainty, with little or no information, and operating under new (i.e., untrained or “unprogrammed”) circumstances. For the near future, combined human/automation systems are to be expected.

## Space Transportation & Human-Centered Automation

This aviation experience base provides a set of “lessons learned” that may be applied to the design of future human-rated Space Transportation Systems. To enhance crew effectiveness and to prevent these types of crew/automation problems in a next generation RLV, a human-centered approach to automation design must be followed. This includes developing and following a set of human-centered principles, rules, and standards that define, and guide the design of, crew/automation systems. The potential problems defined in this report have implications both for design of the crew/vehicle interface throughout the vehicle and for crew operations (e.g., training, operating procedures, flight rules); therefore, design principles and guidelines should be defined for all of these areas.

From a review of the aviation experience base, an initial set of categories for crew/automation design principles and guidelines for space transportation systems has been developed (see Appendix A). These principles and guidelines will address such factors as: philosophy of automation use; crew vs. automation roles and responsibilities; the crew interface to automation; automation feedback; automated flight management; automated modes; crew workload; confidence and complacency; predictability, reliability, and trust; automation training content and approach; cockpit operations and crew coordination; personal factors; failures and off-nominal situations; and crew skills maintenance.

As a beginning point, principles and guidelines for the design of human/automation systems derived from aviation experience have been defined by a number of researchers and can be adapted to the space transportation domain. For example, Wiener & Curry (1980) provided guidelines for the support of control and monitoring tasks. Billings (1991, 1997) published a number of guidelines and principles for the design of human/automated systems in the areas of control, information, and management automation. He maintains that, ultimately, human-centered automation is accountable, subordinate, predictable, adaptable, comprehensible, simple, flexible, dependable, informative, error resistant, and error tolerant. In addition, Billings provided high level guidelines dictating interactions within a combined human/automation system (e.g., the human operator must be in command; automated systems must be predictable; and functions should be automated only if there is a good reason for doing so.)

Dwyer (1994) published general and specific guidelines for designing the automated system (operational and adaptive capabilities), system interface and operational considerations (controls, displays, and formats; information), and artificially intelligent processing. Rudisill (1995) described guidelines for design (e.g., displays, controls), for enhancing crew understanding and automation use, for enhancing crew operations with automation, and for managing crew personal factors (e.g., complacency).

A design philosophy and principles for human/automation integration were provided by Palmer, Rogers, Press, Latorella, and Abbott (1995). Their crew-centered design philosophy is defined by a set of over-riding philosophy statements, and a set of design principles are organized by consideration of the crewmember as a team member, as a commander of the mission, as an individual operator, and as a vehicle occupant. The FAA's Human Factors Team, in their review of the interfaces between flight crews and modern flight decks (1996) stated a number of guiding design principles and recommendations for the design of human/automation systems.

## Conclusions

The next generation human-rated RLVs will witness significant increases in automation technologies. Typical operations will involve significant crew interaction with this automation. The space transportation community would be served in developing principles, guidelines and standards, based on lessons learned from the aviation community, to guide the design and use of automation on these types of vehicles. In providing information for this task, (1) an initial review of the aviation automation research literature has been conducted, (2) crew/automation integration categories have been identified, (3) an outline for principles, guidelines, and standards has been generated, and (4) a project overview and roadmap is under development within the NASA Integrated Space Transportation Project Plan for guiding this effort.

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## Appendix A

### Outline

#### Principles, Guidelines, and Standards for Crew/Automation Integration In a Space Transportation System

- Philosophy of Automation Use
  - Crew role & automation role
  - Automation technology
  - Crew / automation integration and interaction
  
- Automation and the Crew Interface
  - Displays and instruments
  - Information density, relevance, and “truthfulness”
  - Automation feedback to the crew
  - Making failures obvious and understandable
  - Mode errors
  - Integration and standardization
  - System response time
  - Crew information input
  
- Flight Management Automation (FMA)
  - Predictability of automation operation
  - Complexity of interaction
  - Flight Management programming
  - “Correctness” and the crew mental model
  - Specific problems with FMA
  - Pre-occupation
  - Detecting and understanding system problems
  - Distancing through technology layers
  
- Crew Workload and Automation
  - During failures
  - During emergencies and off-nominal operations
  - Relative to flight phase
  - Relative to crew roles
  - Relative to flight conditions
  
- Crew Confidence in Automation
  - Level of trust and reliance
  - Technology maturity & reliability automation
  - Risk Perception
  
- Training and Automation
  - Amount of automation-specific training
  - Depth of training

Training content  
Approach to automation training  
Learning curve with automation  
Recurrent training & skill maintenance  
Handling skills  
Airmanship  
Scan pattern  
Situation and position awareness

- Cockpit Operations Management  
Cockpit management, crew coordination, division of labor  
Vigilance and monitoring  
Cockpit crew communication  
Interacting and coordinating with MCC  
Standard operating procedures and policies for automation use  
Supporting documentation
- Crew Personal Factors  
Experience  
Self-discipline  
Stress  
Fatigue