RULES FOR FIGHTER COCKPIT AUTOMATION

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ABSTRACT

This paper discusses the issues and special problems associated with the automation of functions in the fighter cockpit. The fighter cockpit has unique design requirements as a result of being a combat aircraft. Digital avionics permit additional capability, but at a cost of additional workload for the pilot and perhaps even lower reliability and operability. Automation is increasingly seen as the solution to this problem. Automation is defined on a continuum with ten generic levels of delegated functionality. The higher levels are more appropriate for highly reliable, low criticality functions. Sixteen rules for automation of fighter cockpits are presented and discussed. While these rules are preliminary, they can serve as a framework for a systematic approach to the automation design problem.

INTRODUCTION

This report discusses the issues for automation and offers a preliminary guide to aid the cockpit designer in automating and integrating a digital cockpit of a fighter aircraft. It is generic in the sense that it does not endorse any particular emerging technologies or development programs.

The purpose of this paper is to define automation and provide preliminary rules for automating functions in a fighter cockpit. It will define methods for automating subsystems, defining redundancy, identifying and defining appropriate manual back-up mechanisms for automated cockpit features. The pilot must be able to use the automated functions in a consistent and reliable manner, including manual backup and override functions.

Three ideas are introduced in this paper. First, automation has become a significant issue in cockpit design, and needs to be dealt with in an organized manner when integrating the pilot-vehicle interface. Second, automation is not a unitary concept, but has many levels or degrees along a continuum of delegated functionality. Third, a set of preliminary "rules" are offered for consideration. After such "rules" are improved and expanded by research and experience, they may serve as the foundation for future design standards.

PROBLEM

Currently, philosophies and techniques for automating fighter aircraft cockpits are vaguely stated and scattered throughout a variety of documents. One reason for this vagueness is the lack of willingness on the parts of the pilots of aircraft and the designers of aircraft to accept the other's point of view. This disagreement is fueled by two events which are not under the control of either party. First, the evolution of a more capable threat demands enhancements to the capabilities of fighter aircraft. Second, the evolution of the digital avionics permits enhanced capabilities, but with the consequence of added complexity of operation. At the same time, high speeds of modern fighter aircraft allows only seconds for the pilot to execute the entire fighting part of the mission.

The designer's solution to this situation has been the promotion of a concept which redefines the role of the pilot as a aircraft system manager rather than an aircraft controller. Carried to its ultimate conclusion, this concept would automate the flight path control of the aircraft in order to free the pilot to perform other mission critical tasks which cannot be automated. Pilots reject this concept because the current automation technology cannot perform the flight control function as well or as reliably as the pilot.

According to Gen. Robert Russ (1988), Commander of the Tactical Air Command, the reliability of avionics is a major problem. He feels that integration and software are becoming too complex and expensive. Part of the problem is due to the rapid evolution of digital systems, with a complete new generation turning over ever few years. The rush to automate and enhance before the utility and reliability of avionics has been established is actually degrading overall system performance, while increasing costs to unacceptable levels.

In a design study of commercial aircraft, Chambers and Nagel (1985) concluded that a totally automatic cockpit (with the pilot acting as a passive system monitor) would not be desirable and that a partially automated cockpit (with the pilot doing planning and procedural tasks) would be more reliable. They claim that "humans make relatively poor (or at least unreliable) passive monitors, subject to lapses of attention and sensitivity".

When the pilot is monitoring an automated system, he is acting as a backup system. In this configuration, the reliability of the total system is increased. However, humans do not make very reliable monitors, according to Wiener (1987) summarizing 45 years of vigilance research. If the human monitor is distracted or has attention captured by any happening, the human usually ceases to be an effective system monitor. There are many catastrophic examples in aviation history similar to the following. A L-1011 commercial transport descending on autopilot flew into a Florida swamp while the flight crew was occupied with a defective warning light bulb, despite indications of cockpit instruments and alarms, (NTSB, 1973). A Boeing 747, flying on autopilot at 47,000 feet experienced loss of power on one engine over the Pacific, rolled out of control and fell 30,000 feet before recovery. The flight crew ignored instruments and alarms (later said they thought these had failed) preceding the incident while attending to the ailing engine (NTSB, 1986). A DC-10 ran off the end of the runway at Kennedy airport as a result of an autothrottle failure and the crew's failure to notice the excessive speed (NTSB, 1984).

These and other accidents have a common recipe: the human operator ceases monitoring an automated system as a result of attention being captured by another event. The above accidents also illustrate the almost fatal weakness humans have toward focusing their attention on one problem, while allowing a more serious problem to develop unnoticed. In all the cases cited above, the cockpit had a crew of three. One, or even two, easily could have been given the responsibility of dealing with the initial problem while the third continued to monitor the system and fly the aircraft. In case after case, the entire crew allowed their attention to be captured by a single problem.

The fighter aircraft has characteristics and missions which require special consideration when designing automation. Because the system is an aircraft, its design must consider the safety-of-flight issues. Because it is a weapon system, it operates in a deliberately hostile situation, and must consider both offensive and defensive design issues to succeed in performing the mission. Because the mission involves the use of lethal weapons, the pilot has unique, delegated authorities and responsibilities which must be considered in the design. The use of lethal weapons requires the judgment of the human operator and cannot be further delegated to automation.

The advent of computerized cockpits has radically changed their appearance. Fighters like the F-4 were cluttered with knobs and dials. The sheer number of controls and displays was intimidating. By comparison, future fighters will have few controls and displays. However, this uncluttered appearance is deceptive. The operation of the new cockpit is actually more complicated. In the busy F-4 cockpit, each control and each display had a single function. To operate any control, the pilot would operate a single purpose control, and the task was finished. Displays were also dedicated and simple. Even the switch handles served as displays of the current status.

In future cockpits, controls and displays will be multi-function. The pilot may have to push several buttons to step through a series of menus to cause the desired information to be displayed, or the desired function to be activated. Because the cockpit space available for controls and displays is limited, it will not be possible for all information to be displayed all the time. The use of multifunction controls and displays results in longer execution times. Because the aircraft flies at a faster speed, the time available to perform these operations is reduced. So the pilot will have more work to do and less time to do it.

Even the aircraft itself is becoming multifunction. Because of the increasing cost of aircraft and because digital systems permit the flexibility, a single future fighter aircraft may be able to perform all the combat missions. This of course would increase the complexity of the cockpit, make the multifunction displays and controls even more complex and increase the taskload on the pilot.

It is ironic that many of the "enhancements" to cockpits achieved with automation and computer aids to the pilot have sometimes resulted in catastrophic accidents. In addition to performing useful work, computers are also capable of generating and compounding errors. The use of computers requires the entering of larger quantities of data than before, with the consequence of more data entry errors. Some data is entered directly from sensors on board the aircraft, sensors which are not always accurate. The accidents resulting from such errors are too numerous to describe here, but suffice it to say that pilots have learned not to trust these systems, to check them constantly, and to resist attempts to design new aircraft with critical functions totally automated. While digital systems generally have a higher reliability and are easier to maintain, when failures do occur, they tend to be more sever (often total) and sometimes are momentary, so that the faults cannot be duplicated during maintenance test.

BACKGROUND

Automation Issues

Traditionally, the purposes of automation in the civilian sector are to reduce costs, increase production, and remove human workers from hazardous environments. In the case of the fighter aircraft of the future, the purpose of automation is to improve the total system performance. The cost will likely be greater and the pilot must still work in a hazardous environment.

Although one reason for automation is to keep pilot workload manageable, automation does not necessarily reduce pilot workload. There are many cases where the pilot must still interact with the automation. In some cases, the pilot must monitor an automated function to verify its correct functioning, interrupt the function in progress (with manual override if necessary), enter data or choices, enable an automated function, or monitor the operation to determine when it is complete.

Is automation a generic process, or should special consideration be given to fighter aircraft? This author believes that fighter aircraft represent the worst-case design problem and deserves special consideration. It may well be that an automation procedure that works for fighter aircraft will also work for other systems, but the converse does not appear to be true. One reason is that the fighter aircraft is undoubtedly the most complex machine ever built for a single operator. Even other aircraft are simple, by comparison. In transport aircraft on long flights, for example, the lack of workload is seen as a severe problem. Northwest airline recently expressed concerns that boredom is degrading crew performance on trans-Pacific flights (AW&ST, 1986). What ever else it may be, air combat is not boring.

Design Philosophy

Traditional design philosophy says we should automate functions which the system can do better and faster than the operator. On the other hand, we should leave to the pilot those things which he can do best. The pilot excels in assessment of complex situations, decision making in complex situations, intuitive judgment, and complex pattern recognition (Eggleston, 1987). It goes without saying that the automation must be both technically and economically feasible, and that the automation must be acceptable to pilots.

In the future, integrated digital avionics will have the capacity to produce more information than the pilot needs or can use. To develop a usable system, even minor functions may have to be automated for the sole purpose of keeping pilot workload at a manageable level, and so that the pilot may attend to more important or more critical tasks, or attend to functions which cannot feasibly be accomplished by automation. Traditional design philosophy may, therefore, have to be replaced by one that emphasizes automating functions on the basis of their effect on system capability, reliability, and effectiveness.

Other Attempts at Automation Guides

Later, this report will list and define various levels and rules for automation relevant to fighter aircraft. This is not the first attempt to do so. An Air Force Studies Board (1982) discussed the issues of automation and produced guidelines for automating fighter aircraft, including the levels of automation developed by Sheridan (1979). The levels of automation defined by Sheridan, however, were limited to automating the decision processes. The application was to automate the "cognitive content" of flying an aircraft and managing its weapons. While this has specific application to the use of "expert systems" and "artificial intelligence", it does not consider other relevant aspects of automation. As it applies to the fighter cockpit, there is no reason to limit automation to the single function of decision making.

A limitation in other automation methodologies is the restrictions placed on the definition of automation. Automation is the technique of making an apparatus, process, function, or system operate independent of external influence or control by an operator. Often, functions are thought of as automated or manual. However, complex functions can be divided into component subfunctions, which in turn can be candidates for allocation to automation. In this way, the operator can share in the function by performing some of the subfunctions. Allocating functions of decision making or choice making is only a small part of this. The designer also must allocate functions based on considerations of who (the operator or automation) implements, who consents, who analyzes, who creates choices, who prioritizes, who monitors, who proposes, who enables/disables, who delays, who informs, who predicts, and who perceives. These activities can be accomplished by the pilot or automated in any combination.

Some attempts at automation guides have been too general, defining every enhancement to the cockpit as automation. For example, substituting a color display for a monochrome display usually enhances operability, but this is not automation, because it does not accomplish a task previously undertaken by the pilot. If, on the other hand, information from two displays were combined on a single display so that information fusion were achieved, this would constitute automation.

As it applies to the fighter aircraft, the most important limitation common to other automation methodologies is the failure to consider the authorities which have been delegated to the pilot. The fighter aircraft crew system must be designed to maintain the pilot in command of the entire system. Any scheme to do otherwise will not be acceptable. According to Federal Aviation Regulation 91.3(a), the pilot-in-command of an aircraft is directly responsible for, and is the final authority as to, the operation of that aircraft. Because the weapon system is a special case, automation must be regarded as a delegation of authority by the pilot-in-command to a system or subsystem. As with any delegated authority, it is conditional on the continued acceptable performance of the delegated function and the dynamics of the situation. The one with the highest authority, in this case the pilot, must be able to override the delegated authority at will. The design philosophy for automating aircraft crew systems must embody the concept that the pilot is ultimately and legally in charge, and that there are no exceptions.

RULES FOR AUTOMATING FIGHTER COCKPITS

1. The pilot shall be provided the capability to override, disable, or disconnect automated functions.

2. The fighter pilot shall be provided the capability to determine the status of any function, state, or action either by continuous display to the pilot or upon command of the pilot.

3. The decision to fire weapons cannot be totally automated. As a minimum, the pilot must give informed consent to enable an otherwise automated process.

4. Every pilot input to the system must be acknowledged with a response observable by the pilot.

5. In the event of failure of an automated function, it should fail-safe (where subsystem failure does not cause a hazard to the system) and fail-soft (where the failure of one subsystem or function does not cause unnecessary degradation of another subsystem or function).

6. Before an automatic function can take over from an incapacitated pilot, the pilot must be queried and fail to respond.

7. If an aircraft has more than one automated function, the automation design must be consistent with respect to operation, feedback, and override characteristics.

8. When a pilot disables or selects manual backup, this status mode must be displayed to the pilot.

9. Automated systems will present only relevant information or data to the pilot. The information presented to the pilot should be relevant to the current mission segment, or a future segment (if intended to be a preview).

10. Automated systems will not present erroneous information to the pilot. If the accuracy of information is uncertain, it must be so identified or coded.

11. Critical functions which are automated must have a manual backup, and/or redundant automation, especially if the reaction time of the pilot is too long to be effective in all situations.

12. If a manual override exists, it must be continuously available for selection by the pilot. If the automated function is critical, the override shall be activated with a single control action.

13. If a system has one or more levels of redundancy, the number of levels available (i.e. unfailed) should be displayed to the pilot.

14. If a delay is involved, or if a time cue is relevant, the time remaining will be displayed to the pilot.

15. During the transition period, after overriding or interrupting an automated function but before the pilot's initial control input, the function will maintain a safe or neutral state until the pilot has taken control.

16. During the transition period, after a failure of an automated function but before the pilot's initial control input, the function will cue the pilot to take control and maintain a safe or neutral state until the pilot has taken control.

LEVELS OF AUTOMATION

The levels of automation discussed below are generic and can be applied to any system. When applying the levels of automation to a fighter aircraft, the rules for automating a fighter aircraft must be applied to the implementation of the automation.

While automation may be total, most often, the operator and the automation share the performance of a complex function. The levels or degrees of automation refer to the degree of authority or action which is delegated to automation.

1Ø. Total automation - all of a function is automated so that its operation is transparent to the operator, that is, the function requires no direct monitoring of the process (although the results may be observable) nor does it require a response or action by the operator. As with all levels of automation, it may be disabled.

9. Monitored automation - automated function which allows the operator to monitor the sequence of operations in progress and override or disable the operation. The operator can stop and restart the function, but cannot change it.

8. Adjustable automation - an automated function which allows the operator to monitor the operation and adjust one or more parameters without interrupting the operation. The operator determines when and if to adjust.

7. Optional consent (or fixed delay) - automated function prompts the operator of a pending action, then delays the action for a fixed period of time to allow the operator the option to override the action. If the operator does not override the action during the delay period, the action will occur when the delay expires.

6. Consent automation - automated function displays pending action to operator then pauses indefinitely for operator consent. A "GO" input is required to continue the function.

5. Optional path automation - the automated function requires complex input (choice of two or more options). The automated function will prompt the operator with a list of options. The function will halt indefinitely until the operator enters a choice.

4. Informed automation - the automated function requires complex input (data or information) at one or more points. The automated function will halt indefinitely until the operator provides the input.

3. Reprogrammable automation - automated function which allows the operator to monitor the sequence of operations in progress and halt the operation, modify the operation, and restart the function. The automated function will continue without pause in the absence of an interrupt by the operator. When interrupted, the function automatically enters the re-program mode.

2. Operator aiding - the automation provides processed information to the operator, but takes no other action. The information may consist of suggestions for operator action, preview of anticipated events or situations, etc.

1. Operator amplification - the operators response may be enhanced or amplified by the system, as with a transfer function.

Ø. No automation. The function is continuously controlled by the operator.

The level of automation is determined by how the automated function interacts with the operator, not the internal operation of the automation itself. The higher level automation has more delegated authority and requires less effort by the operator. The lower level automation has less delegated authority and requires more effort by the operator. The levels of automation above have additional complexities which are not stated. The levels of automation allow flexibility in determining who (operator or automation) bounds the problem, makes some decisions, perceives the situation, analyzes the data, formulates a solution, or predicts the future situation (trends).

The functions being automated are usually complex. It is often the case where only certain subfunctions are automated, the remainder being performed by the operator. This condition may create an interactive scenario where both the operator and automated function have a predetermined sequence of actions to be performed to continue the function. When each performs according to the predetermined script, the function will continue. If either does not perform the expected action, or performs an action out of sequence, the function halts until restarted by the operator.

Where the system provides choices or information to the pilot for action (such as in Level 5, Optional Path Automation), it is not relevant to the degree of automation where the choices or information originate. For example, the automated function may offer the pilot a list of five choices. These choices could have been computed by artificial intelligence on board the aircraft, stored in the program itself by the designer, or entered by the pilot prior to takeoff. The level of automation is a function of how the pilot and automation interact, not how or when the information is generated.

RELIABILITY OF FUNCTIONS

The implementation of automation in fighter aircraft often involves computers. Computers do not perform reliably because of their complexity and because the input data may be imperfect or incomplete. Reliability here refers to the common definition, that is, something which can be relied upon, and implies both availability (the machine has not failed) and functionality (the machine does its job as intended). Future automated systems must help keep track of the degree of accuracy of data and help evaluate the alternatives as a function of the degree of uncertainty. The goal is to avoid presenting irrelevant or erroneous information to the pilot and avoid unnecessary responses by the pilot.

Reliability must also be considered in defining the need for redundancy. Functions which are more critical to survival and mission performance require more reliability (which may involve redundancy) than functions which are optional. A back-up flight control computer cannot be turned on and operate immediately following the failure of a primary computer, because it takes time to load and/or develop the data base which makes it aware of the situation, just as a pilot would. In NASA's Space Shuttle, for example, there are four primary flight control computers which operate simultaneously. The results of each is compared to the results of the other three. If one provides a different result, it is automatically ignored. This voting process is valid if three computers remain functional, but with only two, it is not possible to determine which is correct. If all four primary computers should fail, there is a back-up computer which was developed by a different contractor and programmed by different programmers. The assumption is that different developers would not create the same defect. Because the Space Shuttle is inherently unstable, pilots cannot fly it with a manual control system. Since a manual backup could not be provided for the critical flight control function, multiple levels of redundancy were required. This is an example of level one automation, operator enhancement. An autopilot is an example of level eight, adjustable automation.

In one aircraft, the manual backup control system which is so difficult to operate that some aircraft have been lost while practicing the use of the backup system. The system has a switching mechanism which is failure prone, so that upon selecting manual backup, only part of it may engage or upon returning to automated control, only part of it may engage, so that the resulting configuration is inoperable. In this case, the manual backup poses a greater risk than no manual backup. This serves to illustrate the criticality of proper design of automated systems.

INTEGRATION OF FUNCTIONS

Automation in a fighter aircraft does not involve one or two functions, but rather a large number. Because of the complexity of automation with which the pilot must interact, it must be an integral part of the system design, and implemented with a plan for integration and rules for consistency. Otherwise, errors will increase as the system becomes more complex.

The automation integration plan should follow an aircraft throughout its life cycle. Aircraft design is an evolutionary process occurring over many years, during which requirements and technologies change. After the aircraft is in production, design changes continue to be made. After initial production, different models of the aircraft are designed and produced. The rationale for earlier design decisions must be reconsidered and revalidated at each new design variation.

Inadequately designed automation interfaces have already caused several catastrophic accidents because pilots assumed that a function was being performed automatically, when in fact, the manual override was engaged. As the systems get more complex and automation proliferates, the pilot must be provided a means of managing automated functions, that is, a means to keep track of which functions are currently his and which are the aircraft's. For example, a B-1A bomber was destroyed in a crash that killed one crewmember and injured another. The pilot forgot (and was not adequately informed) that the system for automatically transferring fuel to maintain center of gravity had been switched to manual mode. When the wings were moved to the forward position, the center of gravity was too far behind the center of lift, resulting in stall and crash. The automated stability augmentation system masked the degrading handling qualities until the situation became unrecoverable (Smith, 1984).

CRITICALITY OF FUNCTIONS

It is natural for pilots to want to retain control of function which are essential for their survival and that of their aircraft, and for the successful performance of their mission. In cases where critical functions must be delegated to automation, the pilot wants to monitor the process closely so that he can intervene immediately if a malfunction or unexpected event occurs. For example, flying at high speed and low altitude is currently possible with automated terrain following/terrain avoidance technology. However, this automation is useful only during clear, daytime conditions because the pilot must still do the obstacle avoidance function (refers to towers, wires, etc. too small for the terrain avoidance radar to detect).

If the automation of a critical function is not perfectly reliable, the pilot will need to monitor it in order to intervene quickly should a malfunction occur. If the pilot continuously monitors the automation, he can intervene in about one second. If he is attending to another task when a malfunction occurs, the reaction time will be several seconds because the he must also refresh his awareness of the situation as well as detect that a malfunction has occurred, what has malfunctioned, and decide what to do about it. In many situations, the malfunctioning aircraft cannot survive even those few seconds. As a result, a pilot dares not perform a second non-critical task rather than monitor the automated critical task. So, while this type of automation permits a useful task to be accomplished, it does nothing to free the pilot's attention resources for other tasks.

TECHNOLOGY PUSH

Although many feel it should not be so, the design of modern fighter aircraft is technology driven. Independent programs develop new capabilities for fighter aircraft. As these mature, they are promoted as candidates for modifications to existing aircraft or inclusion on future aircraft. In striving to enhance the mission performance of any aircraft, designers cannot ignore new technologies which promise to provide enhanced performance. Sometimes, however, the promise is premature, resulting in a failure to meet objectives, increased development costs, and inefficient cockpits. Sometimes the reliability of new technologies may not be as good as expected, resulting in the additional burden of pilot procedures to exploit the utility which is available.

For a system to be effective, the techniques for automation and backup systems must be consistent with the reliability of the automated function. If a function can be automated with great reliability, it can be automated to a greater degree, i.e., less monitoring by the pilot. If, on the other hand, a function is not reliable if automated, it should not be automated, or automated with redundancy and/or manual backup as well as provisions for continual monitoring. If a subsystem is new or has unproven reliability, it is best to assume a worse than predicted reliability.

CONCLUSIONS

The fighter crewsystem has unique characteristics which require the use of special design considerations. The system should not command the pilot. The aircraft should be viewed as a pilot's tool. While the pilot and aircraft together make up the weapon system, it is the pilot which has the responsibility and authority. The authority to use lethal weapons cannot be delegated to automation. Above all, the pilot must be able to disconnect an automated function.

The system should not withhold desired information from the pilot. The pilot must be provided relevant information in a timely manner. With multifunction displays, it is not possible to display all the information simultaneously, but all the information should be available. While there will always be situations which digital systems cannot handle (insufficient information, inaccurate information, erroneous input, etc.), the system cannot freeze up or cease to accept commands.

Failure of each automated function should be considered and explicitly provided for in the design. If a function is safety or mission critical, it must have a backup and/or redundancy. If the time required for the pilot to recover from a failure is too short to maintain safe flight, the system must automatically assume a safe state until the pilot can reconfigure and take control. More than anything else, the reliability of the implementation of automation and the criticality of the function should determine the degree or level of automation. If the implementation of an automated critical function cannot have a reliable backup or redundancy, then that function should not be automated.

RECOMMENDATIONS

Automation of the digital cockpit is the greatest challenge facing crewsystem designers. We have just begun to realize the magnitude of the issues involved and are faced with a great deal of work before a successful design methodology can be achieved. We need to study the relation between reliability, criticality and levels of automation. All failures are not of equal consequence. We have yet to gather the data to determine what level of automation is permissible for different reliabilities of the implementation.

There will always be situations where the rules for automation cannot be strictly applied. We need to develop acceptable trade-offs when application of rules is not technically feasible. As in the control system for the Space Shuttle where a manual backup was not possible, four levels of redundancy were provided.

We need to define measures of merit for cockpit automation. How do we know when the benefit automation is greater than the cost or problems it causes? How do we know that the pilot will be able to interact with the automated function effectively? How can the interface to automated functions be made consistent? How can the status of automated functions be consistently effectively displayed to the pilot?

We do not know the answers to all these automation questions, but perhaps we now know the questions. Until we know better, it may be wise to leave a function to the pilot than to automate it poorly.

REFERENCES

Air Force Studies Board - National Research Council, "Automation in Combat Aircraft", Washington, D.C., National Academy Press, 1982.

AW&ST "Airline Observer", Aviation Week & Space Technology, December 1, 1986, Page 49.

Eggleston, R. (editor) "Impact of Future Developments in Electronic Technology on Cockpit Engineering", Aerospace Medical Panel, Advisory Group for Aerospace Research and Development, NATO, AGAR-R-757, June 1987.

National Transportation Safety Board. "Eastern Airlines L-1011, Miami, Florida, 29 December 1972", Report No. NTSB-AAR-73-14). Washington, D.C. 1973.

National Transportation Safety Board. "Scandinavian Airlines System DC-10, John F. Kennedy International Airport, Jamaica, New York, February 28, 1984", Report No. NTSB-AAR-84-15). Washington, D.C. 1984.

National Transportation Safety Board. "China Airlines Boeing 747-SP, NN4522V, 300 nautical miles northwest of San Francisco, California, February 19, 1985", Report No. NTSB-AAR-86-03. Washington, D.C. 1986.

Russ, R. D., quoted in "Air Force to Reduce Tactical Forces, Trim Research and Development Base", Aviation Week & Space Technology, February 1, 1988, page 19.

Sheridan, T. B. "Computer Control and Human Alienation", MIT Technology Review. Cambridge, Massachusetts, 1979.

Smith, B. A. "USAF Cites Fuel Transfer Error in B-1 Aircraft Crash", Aviation Week & Space Technology, October 8, 1984.

Wiener, E. L. "Application of Vigilance Research: Rare, Medium, or Well Done?", Human Factors, 1987, 29(6), pages 725-736.

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