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DESIGN IMPLICATIONS FROM AFTI/F-16 FLIGHT TEST

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Abstract

Advanced fighter technologies are evolving into highly complex systems. Flight controls are being integrated with advanced avionics to achieve a total system. The advanced fighter technology integration (AFTI) F-16 aircraft is an example of a highly complex digital flight control system integrated with advanced avionics and cockpit. The architecture of these new systems involves several general issues. The use of dissimilar backup modes if the primary system fails requires the designer to trade off system simplicity and capability. This tradeoff is evident in the AFTI/F-16 aircraft with its limited stability and fly-by-wire digital flight control systems. In case of a generic software failure, the backup or normal mode must provide equivalent envelope protection during the transition to degraded flight control. The complexity of systems like the AFTI/F-16 system defines a second design issue, which can be divided into two segments: the effect on testing, and the pilot's ability to act correctly in the limited time available for cockpit decisions. The large matrix of states possible with the AFTI/F-16 flight control system illustrates the difficulty of both testing the system and choosing real-time pilot actions. The third generic issue involves possible reductions in the users' reliability expectations where false single-channel information can be displayed at the pilot-vehicle interface while the redundant set remains functional.

Introduction

There are numerous design ramifications to the user of systems like the advanced fighter technology integration (AFTI) F-16 aircraft. Experience with the AFTI/F-16 aircraft has illuminated some generic requirements for degraded flight control modes, cockpit and system architectures. Three architectural characteristics are discussed in this paper. First, AFTI/F-16 flight test results suggest that it is important to provide flight-envelope protection while transitioning to degraded-mode flight control. A second broad implication of experience with the AFTI/F-16 architecture is that complex systems are difficult to test before the first flight, and they are no less difficult to understand in real time. It is possible that cockpits based on expert systems may significantly improve real-time cockpit decisionmaking. Expert systems provide an interactive interface, with computers searching lists and pilots identifying situation features. The final ramification was exposed by having asynchronous architecture and redundant channels that could operate alone. Neither architectural characteristic, however, should allow single-channel interaction at the pilot-vehicle interface while redundant channels are still functional. These broad design implications are discussed in terms of delineating relevant system mechanization, observing more fundamental architectural characteristics, and suggesting design requirements.

AFTI/F-16 System

The AFTI/F-16 aircraft (Fig. 1) is a basic F-16 airframe with a dorsal fairing added to house instrumentation, and vertical canards added for flight control applications. The avionic and flight control systems have been modified extensively to meet program objectives.

The digital flight control system (DFCS) for the AFTI/F-16 aircraft (Fig. 2) consists of three flight control computers, an actuator interface unit, a flight control panel, and associated sensors, controllers, and pilot displays. The flight control computers contain the digital hardware required to implement the multimode flight control software, and a limited analog independent backup unit (IBU). The computers are identical and operate asynchronously in a frame time approximately 16 msec, with some functions operating at 32 Hz and 4 Hz.

The AFTI DFCS includes the standard F-16 sensors and controllers, as well as equipment specific to the AFTI/F-16 configuration. A throttle twist grip was added to provide decoupled pitch control. Pilot displays specific to the AFTI/F-16 aircraft were also added. Two multipurpose displays were included in the cockpit to provide dual-redundant pilot/vehicle interfacing for weapons management and DFCS mode control and status. Extensive flight

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control system fault information is displayed on the multipurpose displays by means of codes indicating the type and level of failure.

The software for the computer consists of seven computer program components that perform the basic software functions of redundancy management, control law calculation, and flight control system interfacing with the avionics multiplex bus and pilot displays. The redundancy management function uses three program components: The system monitor program module insures that the system is error-free before takeoff, and the selector/monitor and failure manager provide all in-flight detection, isolation, and reconfiguration for faults. The redundancy management function provides the dual-fail operate capability with the required fault detection, isolation, and reconfiguration for the sensors, controllers, actuators, and computers, which are all monitored in real time during flight. Ground built-in test is used by the redundancy management function to identify flight control hardware failure before flight.

The control law function consists of control law software, which interacts with the input sensors, controller, actuation system, and vehicle aerodynamics. The AFTI/F-16 is a fly-by-wire aircraft that is statically unstable in the pitch axis, necessitating a pitch feedback system to provide stability. The pitch feedback is an essential feature of all AFTI/F-16 modes — cruise conditions as well as takeoff and landing. The control laws provide eight modes of operation, as shown in Table 1. The standard normal mode is used for cruise conditions as well as takeoff and landing. The standard mode is implemented along with three standard task-tailored modes: air-to-air gun, air-to-surface gun, and air-to-surface bomb. Each of these modes also has a decoupled counterpart that can be selected using a switch on the side-stick controller. The controller and the command option implemented in each mode are given in Table 1. The decoupled modes provide independent control of specific aerodynamic parameters, as shown in Figure 3. This highly complex control function relies on the redundancy management function to provide valid input and output commands.

Design Implications

Degraded Flight Control

The AFTI/F-16 architecture reflects at least three design ramifications of general interest. Highly augmented aircraft such as the F-16 rely on flight control system "intelligence" to inhibit aircraft responses. Indeed, the flight envelopes of all recent fighters are limited by their flight control systems. Unstable aircraft obviously require closed-loop feedback control to provide conventional stability and control. Increasing dependence on the flight control system to provide aircraft performance and safety requires classical tradeoff decisions when the system is mechanized with digital computers.

Traditionally, software engineers have argued for simplicity in the generic software failure recovery mechanization. The IBU of the AFTI/F-16 aircraft generally follows guidelines for simplicity. In fact, the IBU was originally conceived with no pitch-rate feedback in the longitudinal axis. Even though the AFTI/F-16 aircraft is slightly unstable longitudinally, it was initially believed to be more important to keep the IBU simple than to minimize pilot control tasks. The emphasis on simplicity was generally motivated by the desire to maximize IBU reliability by minimizing complexity as well as the cost of covering a remote failure mode. The augmentation required by aircraft like the AFTI/F-16 encourages reexamination of the benefit of simple, degraded flight control modes such as the IBU.

The AFTI/F-16 aircraft requires angle-of-attack limiting to prevent post-departure deep stall. Simulation suggests that the IBU provides limited capability to recover from spins or deep stalls. The automatic yaw-rate limiting of the primary flight control system renders the AFTI/F-16 extremely spin resistant. In the IBU, however, the simulation indicates that stopping yaw rate requires considerable altitude, thus suggesting a smaller envelope may be necessary for safe aircraft operation should the aircraft degrade to IBU. A similar constraint has been encountered with the IBU at high airspeed. During aeroservoelastic testing, one pilot found the IBU sufficiently unstable laterally at Mach 1.2 that he reselected the standard normal mode and did not recommend flying faster. Even though the AFTI/F-16 aircraft is longitudinally stable supersonically, selecting a single fixed gain for fighter aircraft such as the AFTI/F-16 over their entire flight envelope may not be possible.

Analytically, there are at least two parts to the solution of optimum tradeoff between degraded-mode complexity and envelope-protection capability. First, consider transitioning from normal to degraded flight control. Transitions can be characterized by discontinuous step inputs or outputs, and failures that cause transition to degraded flight are usually assumed to be random. The second part of degraded-mode flight addresses whether the flight can be successfully continued or what constraints must be observed during abort and recovery.

The more difficult decisions occur with respect to transition flight. Degraded modes in the AFTI/F-16 aircraft accommodate discontinuous inputs or outputs satisfactorily, and the techniques are generally known. The assumption that one could "drop" into IBU at any time, however, presents the possibility of some adverse events. Transition to IBU while flying a maximum angle of attack implies an unfortunately high probability of departure. Similarly, degrading to IBU at high airspeed close to the ground suggests that the pilot must attempt to slow down while avoiding ground impact in an unstable airframe pilot system. Under such circumstances the costs of simplicity in modes like the IBU are very high during random transitions to degraded flight control. Highly augmented aircraft such as the AFTI/F-16 are penalized rather severely by simplicity in modes like the IBU during the relatively brief transition period. Development of the

IBU reflected several compromises between simplicity and adequate coverage; Fig. 4 illustrates the significant increase in complexity of the final design as compared with the initial design. Degraded-mode simplicity is not sufficient justification when it prevents flight-envelope protection during the transition to backup flight control. After reversion to a backup mode, however, the lack of envelope limiting during mission abort is much less costly, because the pilot can be asked to constrain the aircraft to more benign conditions.

For the case of AFTI/F-16 aircraft, angle-of-attack limiting would be beneficial, particularly during IBU transition. Similarly, if a single fixed gain is not sufficient to provide acceptable stability over the entire envelope, the backup systems should include additional gains. Morever, the primary system should automatically update the appropriate backup gains for the current dynamic pressure conditions of the airplane. This provision would solve stability problems associated with any fixed-gain system to which the aircraft can default at any time. It is not necessarily as important for the backup system to maintain equivalent envelope protection during mission abort and recovery. The pilot can be asked to constrain angle of attack to safe values during abort. Similarly, he can maintain airspeeds and altitudes appropriate to a fixed-gain control mode such as the IBU. It is feasible to postulate several gains that a pilot could select as he decelerated and descended to land. The only constraint to maximizing opportunities for simplifying backup systems during the recovery phase is that pilot workload or distraction may prematurely require a minimum level of augmentation during the abort/recovery phase. The IBU included pitch-rate feedback in partial response to cover pilot workload constraints.

System Complexity

A second architectural characteristic that significantly affected our experiences reflected the integrated nature of the system. The AFTI/F-16 is complex in terms of the number of system components and the permutations on component configuration. The large number of system configurations and their extensive interaction produce rather subtle consequences. It is frequently very difficult to explicitly know or test all the system effects of pilot actions in the real-time cockpit environment. Although the AFTI/F-16 system is not stochastic, it is often no more clearly deterministic at the time one is trying to anticipate system response to pilot-controllable options. System complexity impacted both the testing and flying of the AFTI/F-16 aircraft.

The AFTI/F-16 flight control system was extremely difficult to test, both for preflight qualification and for flight test. This difficulty was caused by several factors: the complex system design, the asynchronous operation, and the dual-fail operate, fault-tolerant design goal. Each of these factors individually generates a large test matrix; together their interactions generated an extremely large test matrix.

The AFTI/F-16 system contained eight major flight control laws having three controller options for each control law set with ten reconfiguration modes and the ability to combine any of the controller options in four of the major modes. The testing required to assure that all the options were operating correctly was not accomplished in the limited time available; consequently, the controller mode combinations were fixed. Combining these control laws with the fault-tolerant design increased the test matrix. No dual failure was to impair mission effectiveness, and no single failure was to cause reversion to the independent backup mode. The time required to perform the failure-modes-and-effects testing necessary to assure the proper operation in all conditions again exceeded the time available, so it also was reduced to the basic requirements. Asynchronism added a third dimension to test matrices, because any skew condition between the three channels is possible. Unfortunately, this last matrix condition was not explicitly addressed during testing (Fig. 5).

The inability to completely test the system resulted in many unknowns during flight test. It was extremely difficult to reliably predict the total system response to a given condition. One major cause of the unpredictability was the different rates at which the flight control functions were processed in (64 Hz, 32 Hz, and 4 Hz). Each of these rates can have a worst-case skew condition which, when compounded with another rate's skew, can cause nuisance software failures that are difficult to predict.

The complex interactions between the control laws and asynchronous system operation caused further complications during flight test. To provide decoupled motion, the control laws provide submodes that switch on various input conditions, such as rudder pedal out of detent or flaps at their limit positions. These submodes were allowed to switch asynchronously. As a result, channels operated with different sets of control laws, causing surface failures, branch failures, or both. This switch interaction was not predicted or expected before flight test. Skew between channels was instrumental in determining whether a failure occurred. Because skew conditions are totally random and unpredictable, it was impossible to determine exactly when any failure condition would occur. The failure conditions caused a design change that forced the system to vote the submode switch conditions so that all three channels would operate in the same submode.

Because the matrix of possible conditions presents such a large and varied set of patterns, providing real-time monitoring capability of all possible effects is quite difficult. The real-time determination of what failure has occurred and its cause is an important task for the discipline engineers monitoring a flight. A given failure annunciation, both in the aircraft and in the control room, can have a variety of causes. During flight test, a software submode switch resulted in a system nuisance failure with conflicting information presented on system status. Each channel indicated the other two as failed, resulting in no communication between channels. At the same time, one channel was "talking" on the multiplex bus while another was listening, which resulted in a loss of the ability of the pilot to know what was occurring in the flight control system, as well as a loss of reset capability.

An automated testing system can provide assistance in testing complex systems. Many more test cases can be examined in the time available if the testing is performed using a "smart" test system. This "smart" test system can perform the specific tests and examine their results with much greater efficiency. The effort required before testing is well worth the cost. The greater the complexity of the system, the greater the requirement for an automated testing system.

The effects of system complexity on the real-time cockpit environment were similar to the difficulties experienced during preflight testing. A second dimension of AFTI/F-16 complexity often manifested itself in the cockpit: Several discretes were required to indicate a specific component problem, and several components drove the same discrete. The AFTI/F-16 employs an architecture in which a single discrete may indicate multiple system conditions and, conversely, several discretes are often required to indicate a single system configuration or degradation. The multipurpose displays (MPD) are frequently sequential interfaces with the flight control system, stores, or fire control computers where the pilot's eventual interaction with the system is a function of a series of key strokes whose system effects change based on the "page" displayed on the MPD at the time of option selection. Frequently, a time history of failure annunciations is required to accurately identify a specific failed component.

Such a cockpit differs subtly from more traditional pilot-vehicle interfaces where system discretes are largely dedicated to single, fixed functions. For example, failure annunciator lights are usually dedicated to single component condition in more conventional cockpits. In the AFTI/F-16 cockpit, those same lights may be used in combination with five-digit numerical fields on the MPD to indicate a specific flight control system failure or configuration. The salient characteristic of a system with such configurational flexibility is that cause and effect is deduced from a set of multivalued system displays that both pass information to the pilot and represent pilot commands to the system.

In the real-time cockpit environment where decisions are frequently required within a few minutes, it is often problematical whether the pilot has the information, total system knowledge, or time to analyze and consciously acknowledge all ramifications of his interaction with the operating system. The real-time decisionmaking constraints of systems such as the AFTI/F-16 can be addressed by increasthe dimensions of the pilot-vehicle interface with color presentations, audible tones, and voice actuation of system discretes. However, the systems still rely on the pilot to organize the system information, recognize inductive patterns in the system status, and deduce logical cause and effect relationships. The AFTI/F-16 may provide an early opportunity to evaluate "expert systems" in the real-time cockpit environment. A pilot-vehicle interface constructed around an expert-system architecture avails itself of a fundamental symbiosis. Human beings are unmatched pattern recognizers. Computers, their information structures, and certain mathematical algorithms have demonstrated equally peerless capability to search extensive graphs, trees, and other prestored lists. An expert system in the real-time cockpit of an aircraft like the AFTI/F-16 promises to use the strength of both pilot and computer. Not the least advantage of such a system would be its capability to partition decisions and system information into equivalent sets. Such partitioning would allow bounded decisions to be made without knowledge of the total system's response at the time of decision. Thus, expert systems may be powerful aids in solving the type of problems faced in the AFTI/F-16 real-time cockpit.

Simplex Information in Redundant Systems

A final ramification of system design that has proved interesting is the user's percepton of system reliability. The design goal of the AFTI/F-16 triple-redundant dual-fail-operate system required extraordinarily autonomous channels and a very powerful interchannel switching protocol to allow degradation to the last good channel. When the consequences of asynchronism are summed with this intrasystem autonomy, the operating flight control system often appears as a series of partially autonomous components that compete for aircraft control. Much of the interchannel independence arises from both unsynchronized interchannel skew and the requisite intrasystem autonomy of a triplex dual-fail-operate system.

It is important to distinguish the effects of asynchronism from last-good-channel operation. The AFTI F-16's asynchronous interchannel protocol created system states where single channels drove discretes and displays at the pilot-vehicle interface. Such simplex information is most important when it issues from the last good channel. Asynchronism, however, caused the display of false simplex channel information while the redundant set was still functional. Such annunciations diminish the perception that the system is highly reliable because it is composed of multiple identical channels – all doing the same "thing" – at least as long as there are no "real" faults in the system.

Unfortunately, the disagreeable impact of this architecture on perceptions of reliability causes difficulty in measuring the advantages of the capability to degrade to the last good channel and to operate asynchronously. Interchannel comparison varies between the extremes of bit-by-bit comparison and force summing across the power ram of an actuator. Even though AFTI/F-16 computers do not explicitly ascertain whether the other members of the operating set are performing the same operation, program development, nonetheless, shows continued localized synchronization. AFTI/F-16 channels do not employ dedicated hardware or software to communicate states to redundant channels and wait for acknowledgment; they "synchronize" by increasing interaction rates, or voting system states, or both. Interchannel differences are reduced by voting control law switch states, which control integrators and gains by interacting sufficiently fast or by exchanging status information in a timely fashion. As long as no errors exist, redundant systems cannot function reliably unless the implicit interchannel comparisons are sufficiently small to enable the system to behave as identical command paths. This requirement is independent of which synchronizing algorithms are used to achieve sufficient interchannel tracking. Furthermore, those same algorithms should not enable simplex information at the pilot-vehicle interface while a redundant set remains.

A graphic example of how dramatically the perception of reliability can suffer from permitting simplex information at the pilot-vehicle interface while reundant channels remain occurred during flight test. Although no failure has occurred, the pilot received messages that two of the channels had detected each other failed. With each channel in a different state, the actuators eventually selected a command. The pilot was unable to ascertain system configuration. It is important to recognize that the problem is not that the system failed to provide sufficient aircraft control. Such inconsistent simplex information erodes users' perceptions that the redundant system is operating reliably and will continue to do so in future confusing failures.

The AFTI/F-16 incorporates very powerful simplex-channel capabilities to enable the system to degrade to the last good channel. Although the architecture retained this feature, reliability requirements forced additional localized interchannel tracking by voting system states and increasing interaction rates. Regardless of asynchronism, or last-good-channel capability, displaying single-channel information with no failures in the redundant system diminishes subjective estimates of total system reliability. Neither architectural characteristic should enable single-channel interaction at the pilot-vehicle interface during redundant channel operation.

Summary

Each of the three design ramifications discussed in this paper isolates an independent aspect of vehicles such as the AFTI/F-16. Our experiences have illustrated increasingly high penalties associated with failing to cover transitions to degraded-mode flight. The costs of simplicity for a highly augmented vehicle are outstripped by costs of aircraft requirements for envelope limiting during the transition than to degraded flight control. It is more important to provide envelope protection during transition than to constrain the backup system to be the simplest system that allows aircraft recovery. Aircraft control deteriorates so rapidly with unstable airframes that the advantages of backup simplicity are quickly overshadowed by risks of aircraft loss or severe operational constraints imposed to enable safe transition to backup.

System complexity caused a second set of design impacts during the testing and flying of the AFTI/F-16 aircraft. If a given input set does not always generate the same result, it becomes very difficult to test. The size of the matrix of tests required to fully understand system interactions, reconfigurations, and degradations dramatically increases with the complexity of the system. A system required for a critical task, such as fighter flight control, must be predictable and understood before it is useful.

Similarly, the complex nature of the AFTI/F-16 cockpit suggests rather fundamental constraints, which may imply architectures as radical as admitting expert systems to integrate the pilot-vehicle interface. Finally, the capability to degrade to the last good channel and asynchronous interchannel tracking suggest the advisability of suppressing simplex channel information while a redundant set remains functional. Just as the actual reliability of redundant set operation was improved by localized synchronization, the users' perception of system reliability is improved by preventing single-channel interaction at the pilot-vehicle interface during redundant set operation. Experience with the AFTI/F-16 system has indicated several interesting design ramifications and basic constraints that may be useful for future design efforts.

Reference

(1) Mackall, Dale A., Regenie, Victoria A., and Gordoa, Michael; "Qualification of the AFTI/F-16 Digital Flight Control System," NAECON Paper 324, May 1983.

Table 1. — AFTI/F-16 Controllers and Command Options

Mode	Controller			
	Pitch stick	Roll stick	Rudder pedal	Throttle twist
	Command option			
Standard normal (SNRM)	Normal acceleration	Roll rate	Rudder deflection	None
Standard air-to-surface bombing (SASB)	Normal acceleration	Roll rate	Flat turn	None
Standard air-to-surface gun (SASG)	Pitch rate	Roll rate	Flat turn	None
Standard air-to-air gun (SAAG)	Pitch rate	Roll rate	Flat turn	None
Decoupled normal (DNRM)	Flightpath maneuver enhancement	Roll rate	Translation	Translation
Decoupled air-to-surface bombing (DASB)	Flightpath maneuver enhancement	Roll rate	Flat turn	Direct lift
Decoupled air-to-surface gun (DASG)	Pitch rate maneuver enhancement	Roll rate	Pointing	Pointing
Decoupled air-to-air gun (DAAG)	Pitch rate maneuver enhancement + flightpath maneuver enhancement	Roll rate	Pointing	Pointing

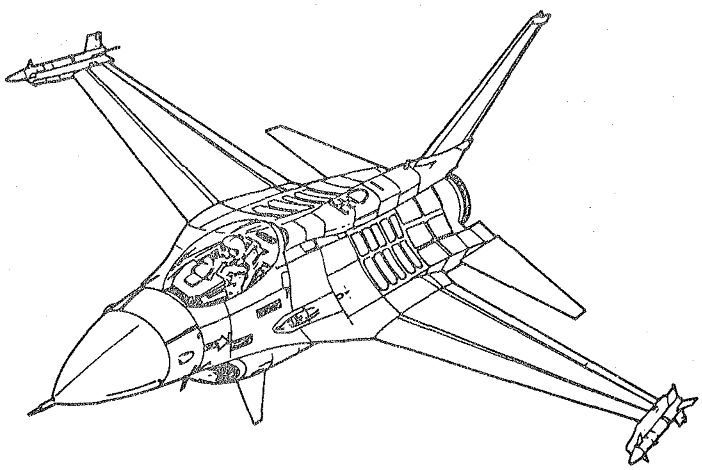


Fig. 1 AFTI/F-16 aircraft.

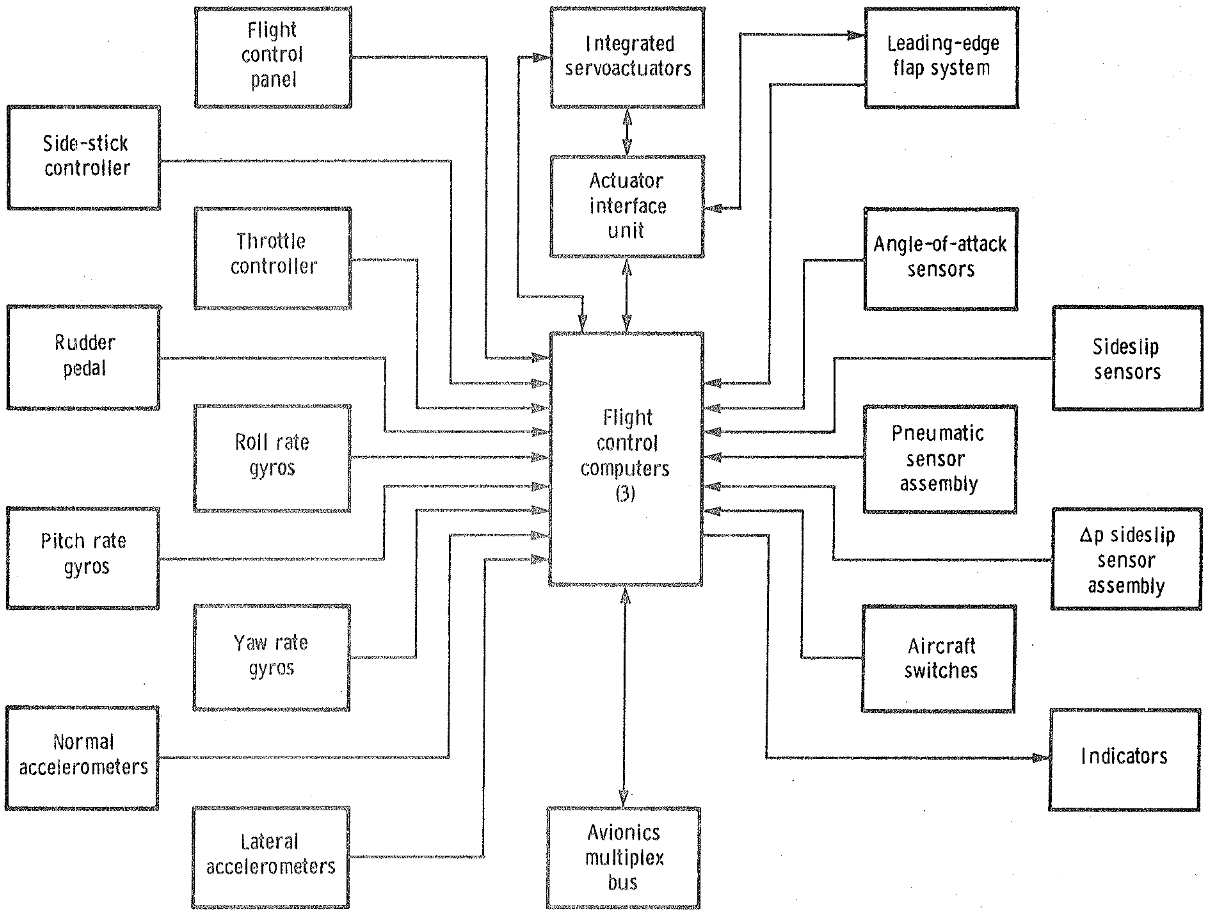
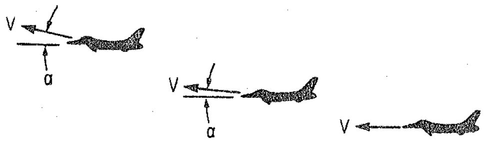
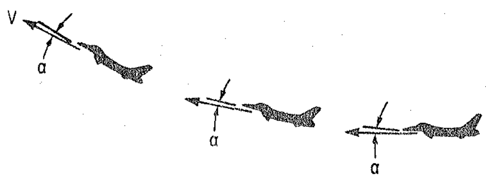


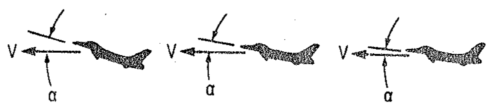
Fig. 2 Digital flight control system.



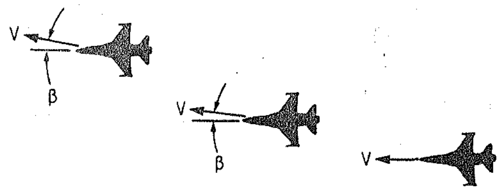
(a) Vertical translation: vertical velocity control at constant pitch attitude.



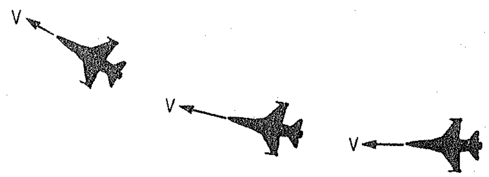
(b) Direct lift: vertical flightpath control at constant angle of attack.



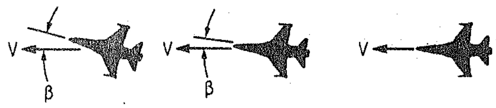
(c) Pitch pointing: pitch attitude control at constant flightpath angle.



(d) Lateral translation: lateral velocity control at constant yaw attitude.

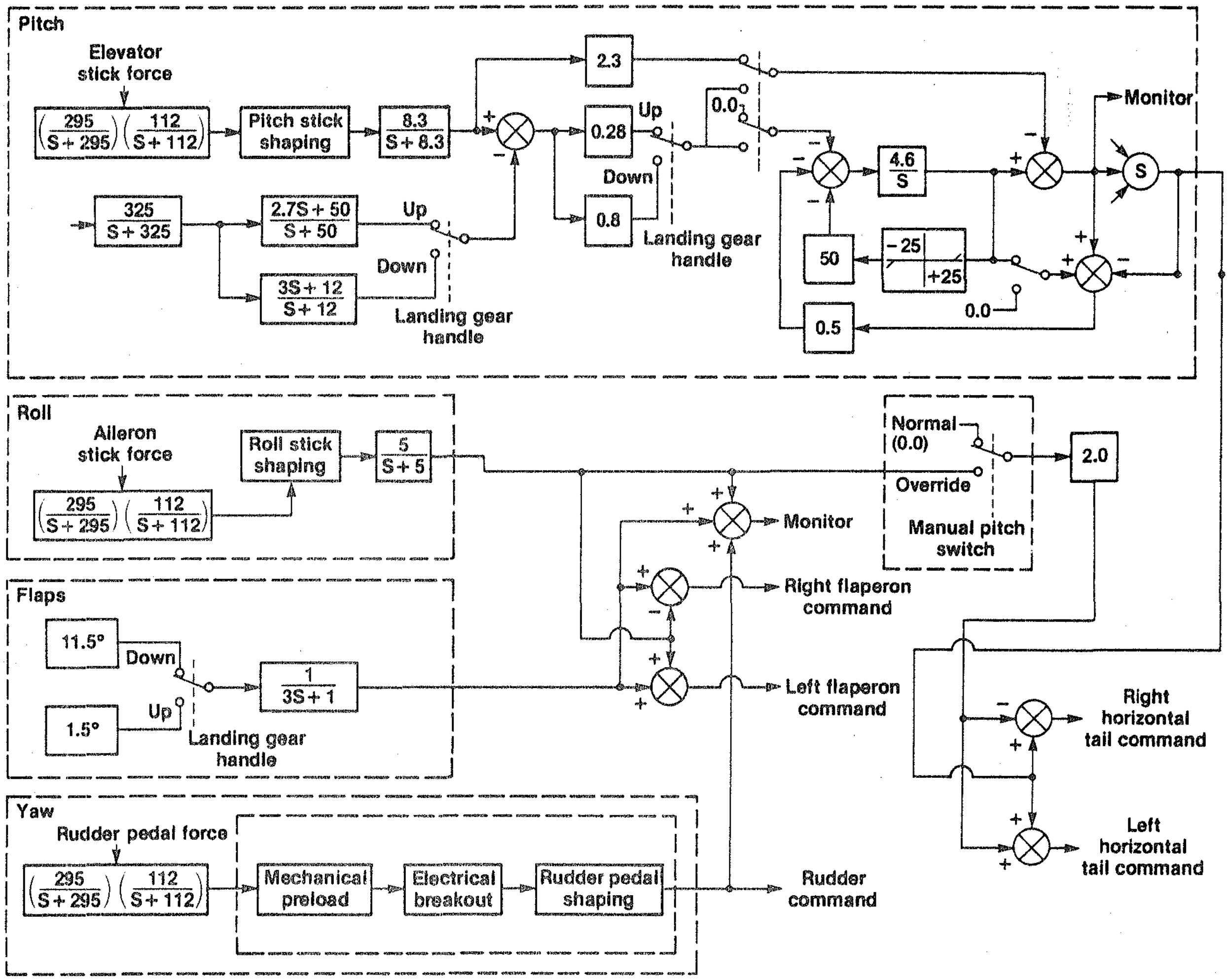


(e) Direct sideforce: directional flightpath control at zero sideslip angle.



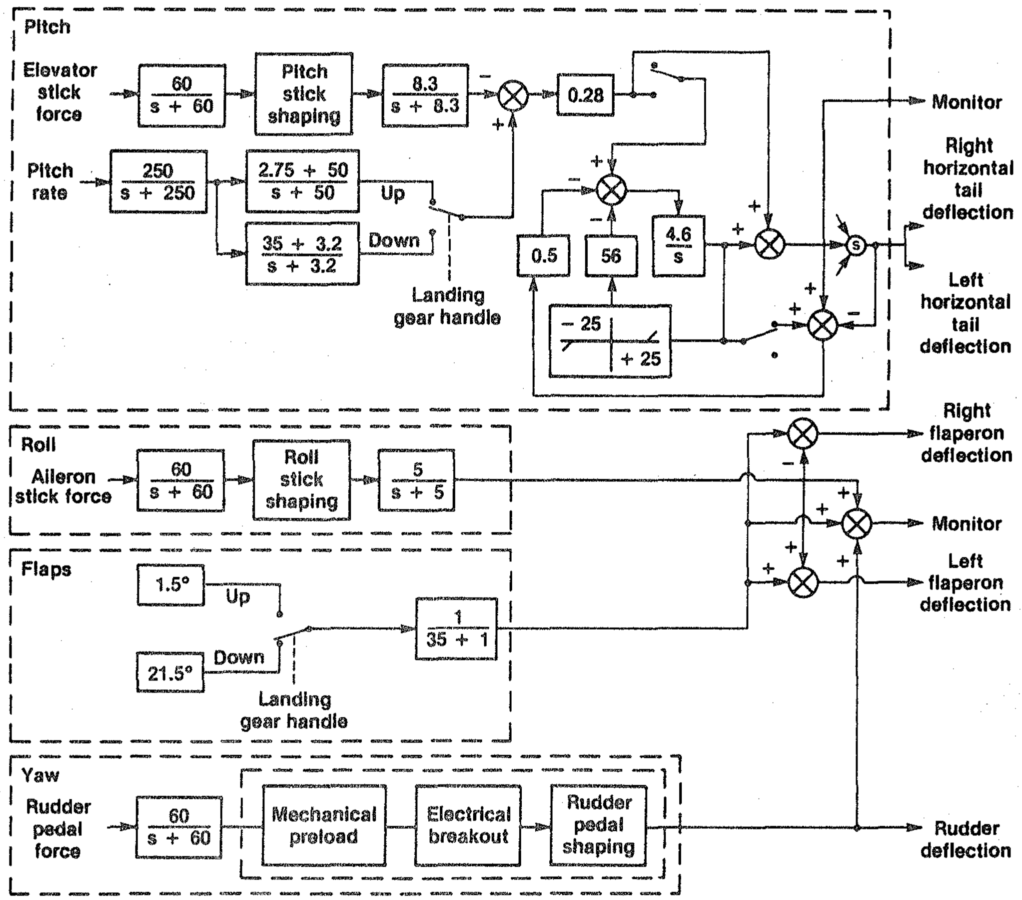
(f) Yaw pointing: directional attitude control at constant flightpath angle.

Fig. 3 Decoupled control.



(a) Original configuration.

Fig. 4 Independent backup unit.



(b) Final configuration.

Fig. 4 Concluded.

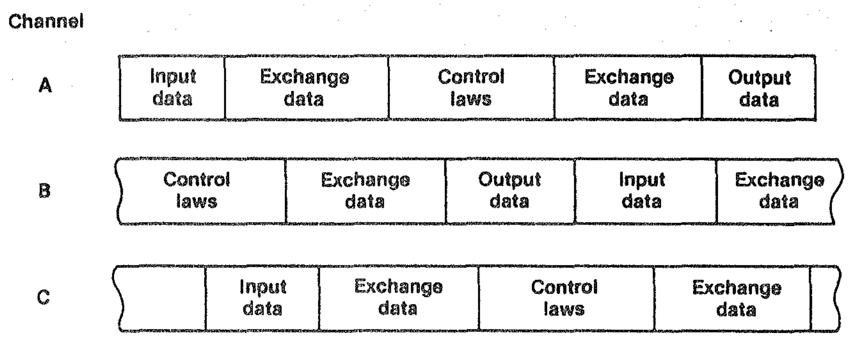


Fig. 5 Typical example of asynchronous operation.

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15. Supplementary Notes

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16. Abstract

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