

AFTI/F-16 DIGITAL FLIGHT CONTROL SYSTEM EXPERIENCE

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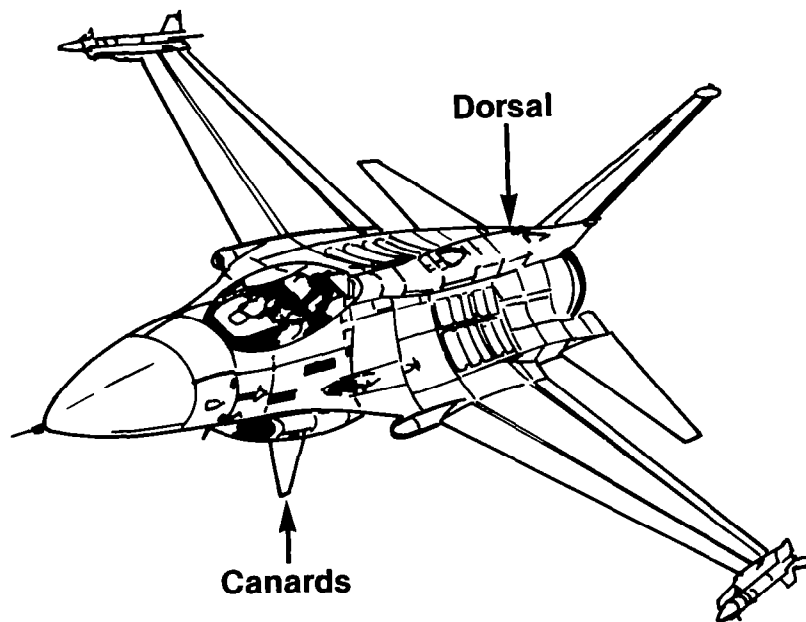
ABSTRACT

The Advanced Fighter Technology Integration (AFTI) F-16 program is investigating the integration of emerging technologies into an advanced fighter aircraft. The three major technologies involved are the (1) triplex digital flight control system; (2) decoupled aircraft flight control; and (3) integration of avionics, pilot displays, and flight control. In addition to investigating improvements in fighter performance, the AFTI/F-16 program provides a look at generic problems facing highly integrated, flight-crucial digital controls. An overview of the AFTI/F-16 systems is followed by a summary of flight test experience and recommendations.

AFTI/F-16

The Advanced Fighter Technology Integration, AFTI/F-16, is a joint Air Force, NASA, and Navy program. The Air Force's objective is the integration of emerging technologies into a single test bed fighter aircraft. The technologies include a triplex, dual fail/operate digital flight control system; decoupled flight control; and integration of the cockpit functions, avionics, and flight control system. NASA's primary goals for the program were to assure safety of flight of the vehicle and provide an independent assessment of these advanced technologies. The primary contractor is General Dynamics, Fort Worth, Texas.

The AFTI/F-16 is a modified full-scale-development (FSD) F-16. Most of the changes were made to the on-board electronic systems, flight control, and avionics. However, two external modifications were made. Vertical canards were installed below the engine inlet to support decoupled aircraft control. A dorsal fairing was added to house additional avionics and instrumentation.

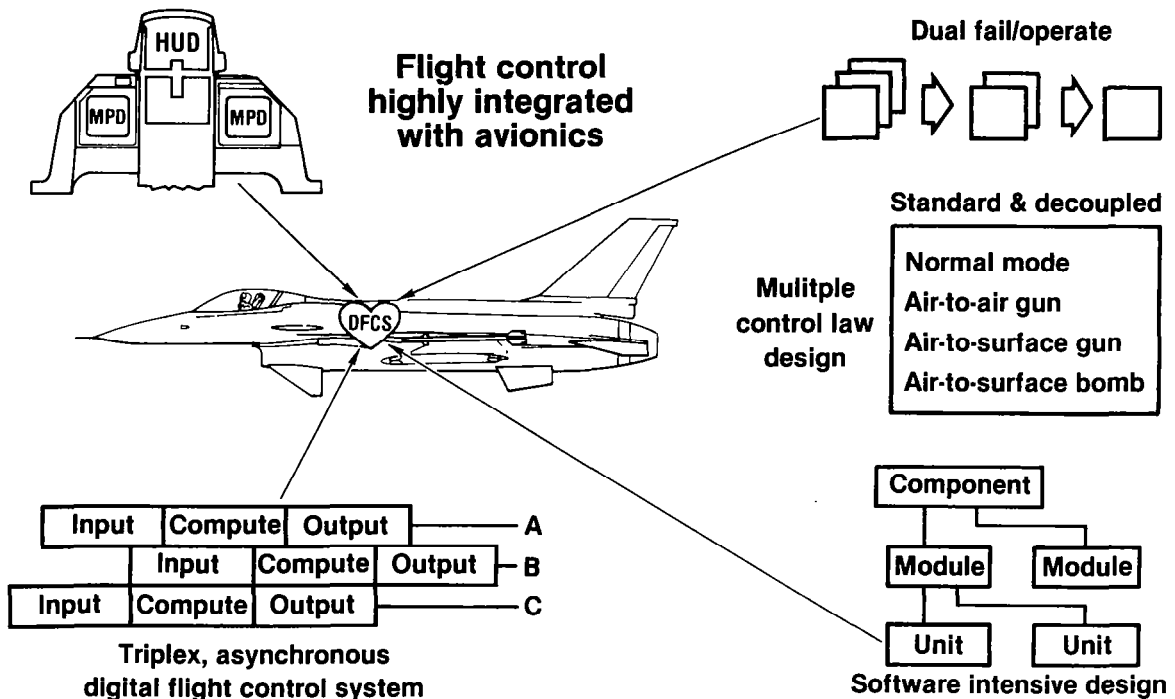


AFTI'S INTEGRATED TECHNOLOGIES

The digital flight control system is the heart of the technologies integrated into the AFTI. In the area of fault tolerance, the dual fail/operate system provides dual fail/operate capability 95% of the time for computer CPU faults. Dual fail/operate was a goal in addressing dual failures of sensors and discrete inputs for the AFTI program. The control law design includes mission-specific and decoupled-control modes. The primary goal is to improve aircraft survivability in an attack.

Another goal to reduce pilot workload is approached by integrating avionics and flight control functions with cockpit displays. One selection of a mission phase switch configures avionics, weapons, and flight control to a specific mode. The multipurpose displays allow for a centralized information display for all systems.

These main technologies resulted in two spinoff technology goals for the flight control system, asynchronous computer operation, and a software-intensive design. Asynchronous operation is a major design characteristic which affects the dual fail/operate capability, decoupled control law design, and the pilot's display of flight control status. The primary purpose of software-intensive design is to avoid additional unique hardware in accomplishing the dual fail/operate requirement.



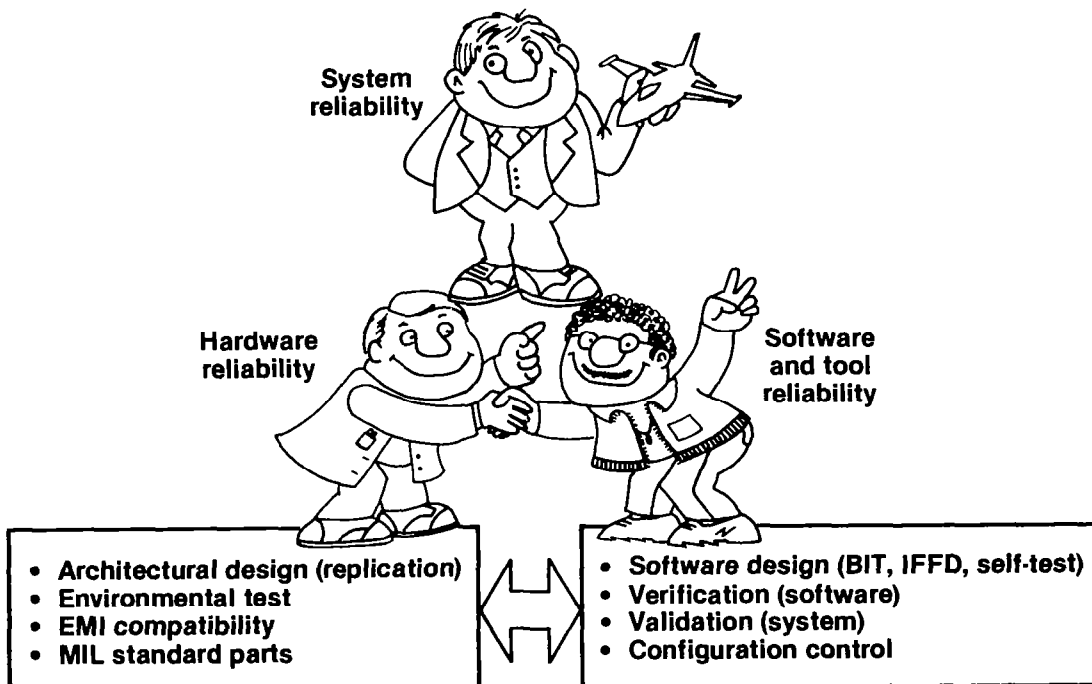
RELIABILITY AND FAULT TOLERANCE

Experience with the AFTI F-16 digital flight control system has highlighted the relationship of fault tolerance and reliability. The software-intensive design of AFTI for aircraft control and fault detection emphasizes the role software plays in overall system reliability. Hardware reliability, based on the replication of hardware components, has been the only contributor to system reliability numbers and loss of control probabilities. The reliability of the software and the functions, such as fault detection algorithms, designed in software must be considered in overall system reliability.

Software reliability continues to be difficult to determine. Software reliability for AFTI was accomplished through test and configuration control. Adequate software reliability was determined indirectly after confidence in system operation was achieved by successful completion of verification and validation testing.

The relationship of fault tolerance to reliability comes through the software. The proper detection of hardware component failures by the software is essential to support the reliability figures for the hardware. If a single failure which caused loss of control went undetected, the reliability for the system would be greatly reduced. Reliability is a function of the fault detection software. Here again, reliability is assured through the testing process.

Total system reliability must consider the basic hardware architecture, the software testing process, and the fault detection algorithms which reside in the software. It is these last two considerations which will determine the validity of loss of control probabilities such as $1 \times 10^{-7}/\text{hr}$.

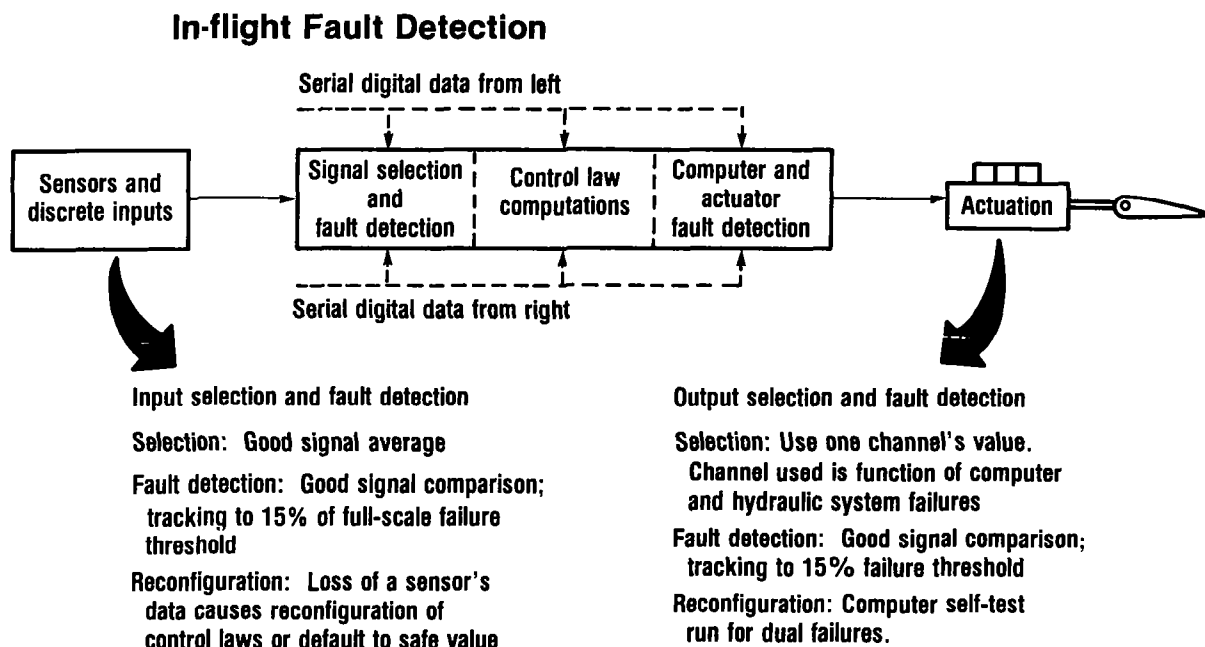


FAULT-TOLERANT DESIGN

The AFTI F-16 fault-tolerant design consists of two separate sets of checks to increase fault tolerance and provide the dual fail/operate capability. The first set of checks consists of selection and fault detection on input signals. The second set of checks selects values and provides fault detection on the computers and actuators.

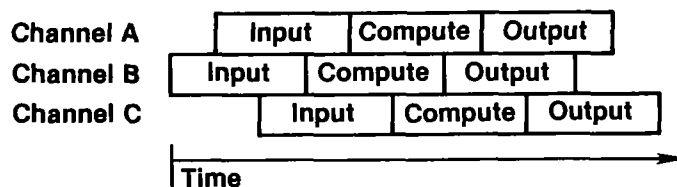
The purpose of the input signal selection and fault detection is to increase the system's ability to tolerate failures through cross-channel monitoring of the redundant hardware. Unique characteristics of the AFTI design include: signal selection based on the failure status of higher level devices, such as the inverter; an averaging selection routine; a 15% failure threshold allowance; and reconfiguration of control laws for unresolved dual-sensor failure.

Computer and actuator fault detection work together to provide the highest probability for valid aircraft command in the face of single and multiple failures. The primary aspect is to accomplish the dual fail/operate capability centered on self-test computer coverage. The self-test feature is responsible for identifying the last good computing channel when only two channels remain and their commands are not tracking. A unique characteristic of the output selector and fault detection design is the choosing of one computer's command, with a 15% failure threshold allowance, to control the actuators. This design choice resulted from asynchronous computer operation and interfacing constraints with the actuators.



ASYNCHRONOUS COMPUTER OPERATION

Although not intended to be a primary objective of the AFTI program, the investigation of the asynchronous computer operation became a major activity. The asynchronous architectural concept started with the intent to increase EMI immunity and overall system fault tolerance. It was believed that concerns about asynchronous operation (testability, data congruency, and nondeterministic operation) would be alleviated as the design matured. Considerable engineering effort went into designing and qualifying the DFCS with much being learned about asynchronous computer operation. Despite considerable effort and improvements in the qualification process, concerns for testability remained because anomalies related to asynchronous operation occurred in flight testing. Asynchronous operation, coupled with the complexities of decoupled control and dual fail/operate capability, resulted in an increased design task, extended qualification period, and marginal testability. After envelope expansion, flight test evaluation of the DFCS for mission performance did not identify any new anomalies related to asynchronous operation.



Concept

- Increase immunity to EMI/lightning
- Increase computer channel independence
- Increase fault tolerance over synchronized system

Concerns

- Random computer relationship, non-deterministic
- Incongruent data sets due to sampling skew
- Testability; assuring reliable operation for all conditions

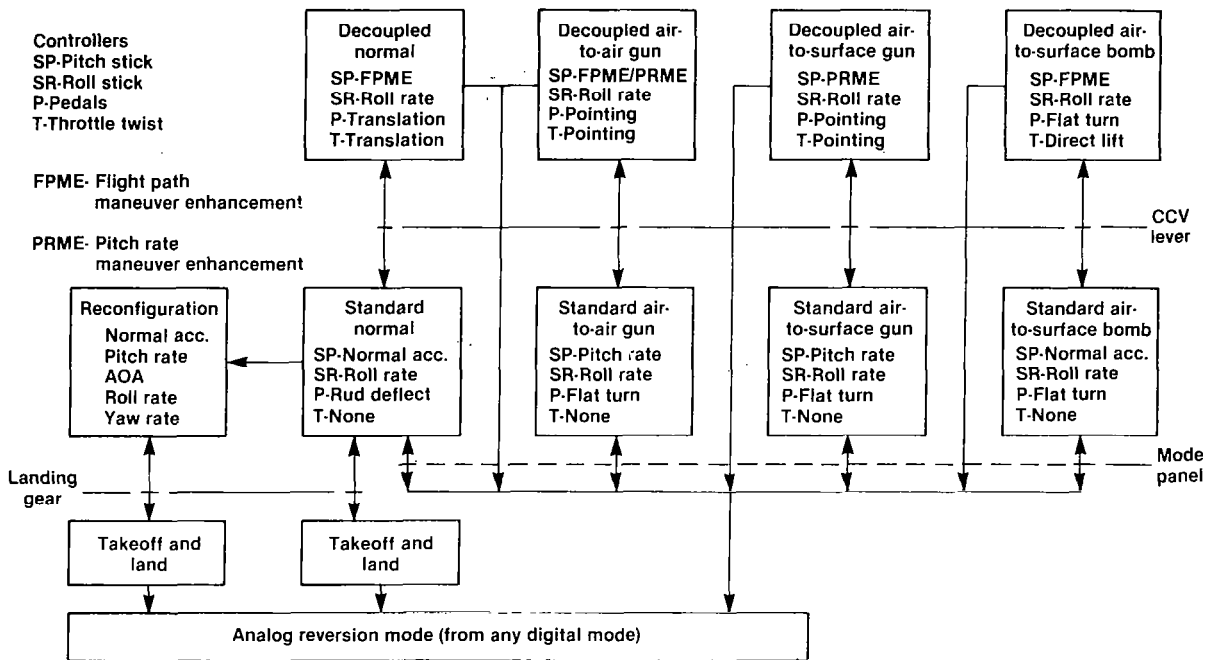
Results

- Design task complicated by asynchronism
- Qualification time extended, repeatability poor
- Complex interactions due to sampling skews
- Flight test operations affected due to marginal testability

FLIGHT CONTROL MODE STRUCTURE

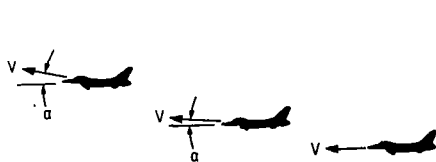
The AFTI digital flight control system consists of eight flight control modes, four standard and four decoupled options. The four mission-specific categories include normal, air-to-air gunnery, air-to-surface gunnery, and air-to-surface bomb modes. Mission-specific mode selection is accomplished through a mode panel or through hands-on selectors on the throttle. Mode selection configures both flight control and avionics. Decoupled mode options are selected through a CCV lever on the right-hand side stick controller. Decoupled options include pointing, translation, and direct force in both pitch and yaw axes. The decoupled options also include enhanced maneuvering modes utilizing the pitch stick. The decoupled air-to-air gun mode provides an adaptive mode for the pitch stick, changing control structure based on pitch rate errors. This allows for control optimization of gross acquisition and fine tracking in the air-to-air mission.

In addition to the advanced decoupled modes, reconfiguration modes are included to provide dual fail/operate capability for sensor failure; however, there is a loss of decoupled and mission-specific modes. A reconfiguration mode is derived from the standard normal mode for dual failures of all primary feedback sensors, both longitudinal and lateral-directional. Reconfiguration modes use either synthesized sensor information or zero values as required. The digital system is backed up with an independent analog reversion mode. This provides protection for common mode errors which could cause loss of the digital system.

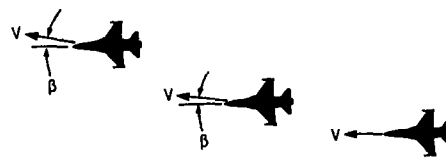


DECOUPLED CONTROL OPTIONS

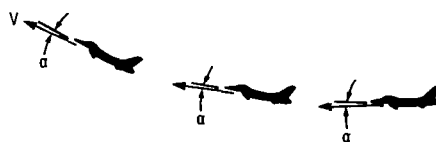
Decoupled control options consist of pointing, translation, and direct force for both pitch and yaw axes. Pitch axis modes use elevator and flap commands, and yaw axis modes use canards, rudder, differential elevator, and aileron commands. Pointing allows for changing aircraft attitude without affecting flight path. Pointing angles are equivalent to changes in angle of attack and sideslip for each axis. Translation commands a constant velocity without affecting aircraft attitude. Angle of attack and sideslip vary with the command. The direct-force modes command accelerations, affecting flight path, while keeping angle of attack and sideslip constant. The evaluation of decoupled options centered around weapon effectiveness while increasing aircraft survivability.



Vertical translation



Lateral translation



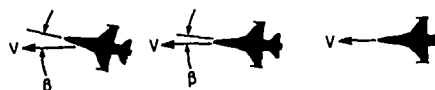
Direct lift



Direct sideforce



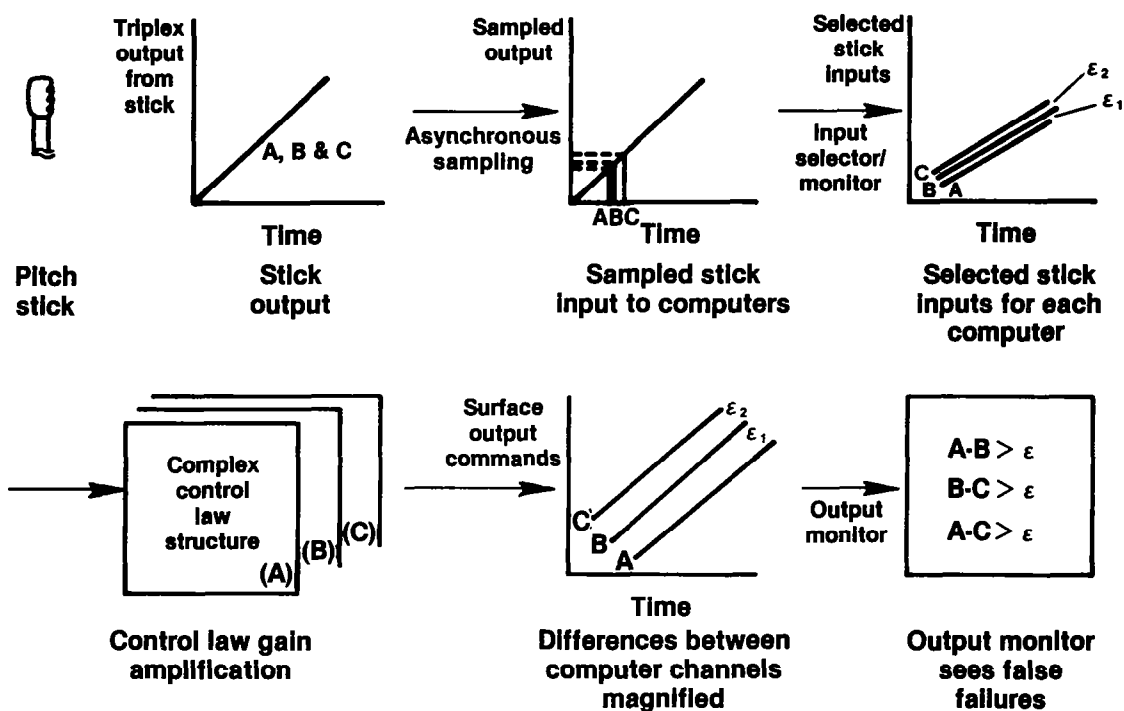
Pitch pointing



Yaw pointing

SYSTEM INTERACTIONS

An example of the interactions which occurred between the redundancy management functions and control law is illustrated below. Triple analog input sensors are sampled asynchronously and compared within each computer. If the inputs are within an established trip level, the control laws in each computer use an average value for the triplex inputs. Because the system is asynchronous, the average value used by the control laws is slightly different in each computer. The complex control law structure, with its high gains, amplifies the difference in generating an output command. The output command is monitored by each computer to assure that the differences between output commands are within a given difference (that is, trip level). The amplified differences generated by the high-gain control law function cause nuisance failures in the output command monitor. If three output surface commands fail within one computer, a channel is failed. This was particularly evident in the advanced and decoupled modes during ground qualification. The control gains were reduced to prevent nuisance failures as a consequence of the redundancy management/control law interactions.

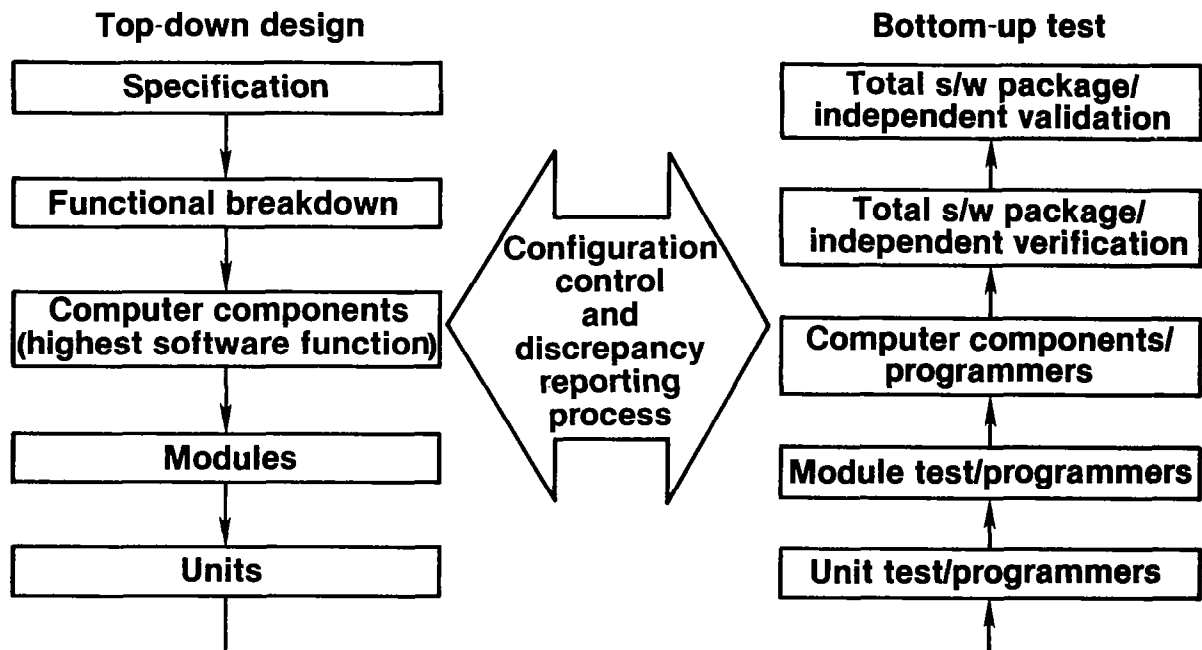


SOFTWARE DESIGN AND TEST APPROACH

The digital flight control software design and test activities are summarized as a top-down design with bottom-up testing. The design, test, and redesign cycle is accomplished through a configuration control/ discrepancy reporting process. Top-down design began with a function breakdown based on the design specification. The functional breakdown was carried directly into a structured software design. The lowest breakdown of the software is termed a unit and is required to have one exit and entry point and be less than 100 lines of code. Strict documentation, commenting, and software design reviews were essential to the software design process.

Software testing took a bottom-up approach, beginning with unit testing. The module and the component testing were accomplished as the necessary units were integrated. Testing to this level is done by the software design team, with a final integrated software package going to an independent test group. The independent test group performed verification (proper software implementation of the functions) and validation (proper system level operation testing of the flight control system). Detailed specification and design documents were used by the test team to assure proper testing of all flight control functions. Details of the qualification can be found in references 1, 2, and 3.

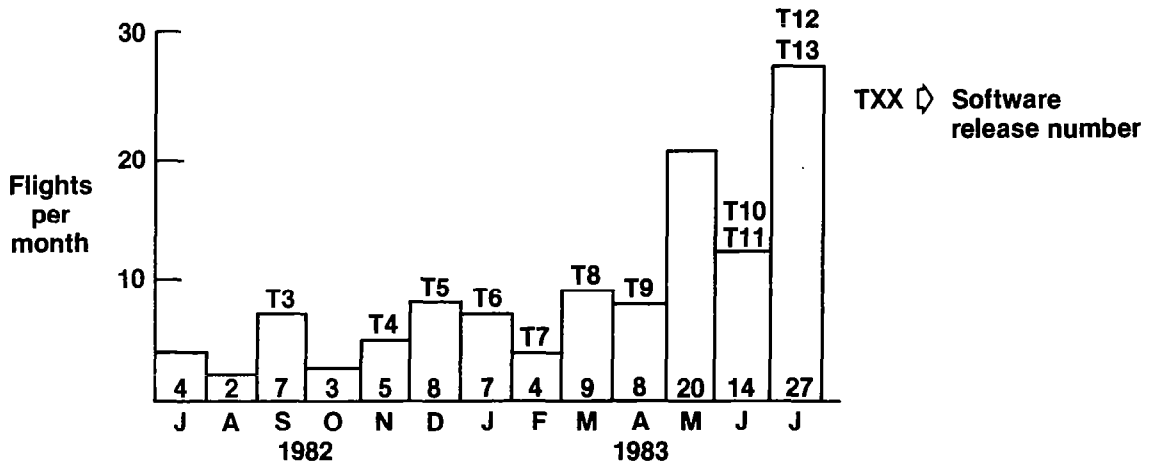
The configuration control process provided the means to document discrepancies found in test and to correct the discrepancies in the software or hardware as needed. The key to the process is a systems-wide approach covering control laws, fault tolerances, avionics, hardware, and software. Interdisciplinary knowledge and resolution of problems are essential in such heavily integrated systems.



FLIGHT TEST RESULTS: GENERAL

Flight testing of the AFTI F-16 was successfully accomplished over a 13-month period in 1982 and 1983. A total of 118 flights were flown by pilots from four organizations: Air Force, NASA, Navy, and General Dynamics. All major objectives were completed, including envelope expansion for high angles of attack and Mach numbers up to 1.2, combat mission evaluations of decoupled control, and structural load clearance for the decoupled motions. Low flight rates early in the program were due to anomalies of the basic aircraft as well as to the AFTI unique systems.

Thirteen software releases were made during flight test to the digital flight control system. Software changes were made to correct discrepancies and provide improvements in flying qualities, fault-tolerant operation, and structural-load-limit items. An efficient software change process is required to provide safe, timely changes needed to accomplish flight test objectives.



- 118 total flights by Air Force, NASA, Navy, and General Dynamics pilots
- Thirteen releases of flight control software
- Full envelope expansion of three separate flight control modes
- Air-to-air and air-to-ground mission evaluations of decoupled control options

FAULT TOLERANCE

Built-in test (BIT) is a highly automated test sequence that assures the digital flight control system (DFCS) is free of hardware failures prior to takeoff. BIT is run prior to each flight and takes approximately 2.5 min. Two failures of the hardware were detected by BIT during flight testing. The first was a failure of the flap actuator, the second involved memory chips which didn't meet timing specifications at cooler temperatures. Nuisance failures of BIT occurred a number of times. The cause is believed to be EMI.

In-flight fault detection is accomplished by comparing the three values for tracking among the different channels. The only real failure was an input signal which was traced to a pushed-back pin in the aircraft wiring. The 15 false failures were due to design deficiencies rather than actual hardware failures. The design deficiencies, which resulted in both temporary (resettable) and permanent loss of flight control redundancy, were corrected in subsequent software releases.

The asynchronous computer architecture affected a wide range of developmental activities including design, software/system qualification, and flight test operations. Initially DFCS qualification was not full proof because of the dependence of failure modes on computer skew. Testing at predetermined "worst case" computer skew improved testing results; however, some deficiencies still escaped detection. Ground operations during aircraft preflight were impacted by the asynchronous computer architecture. The most common problem resulted in DFCS failures, requiring reset by pilot or cycling of aircraft electrical power.

The false failures, not hardware induced, were the result of the design deficiencies associated with asynchronous computer operation. The design deficiencies resulted from the coupling of unique computer skews with characteristics of the flight environment, such as sensor noise. Undetected during qualification, these in-flight failures resulted in envelope and flight control mode limitations until they were corrected by software changes.

The software configuration control process details the procedures equivalent to the maintenance procedures for hardware, but in the software environment. Maintaining safe, operational software requires specification, design, test, and documentation for every change. Software change, specification, and time line for incorporation directly involved flight test planning. Testing and documentation provide details for operating characteristics and/or restrictions.

The 13 flight test software releases, in which design, coding, and test of the changes were performed at General Dynamics, Fort Worth, supported the needed changes for flight test. The first four releases provided full envelope capability for the AFTI vehicle in all flight control modes. The remaining nine releases modified the control system's control laws to improve flying qualities and the fault-detection function to improve reliability.

Software errors are software design or coding errors which escaped detection by the software verification and system validation testing. Two of the errors resulted from a loosening of the detailed established procedures. The third error was caused by a coding error involved in the correction of a previous false in-flight failure condition. The error was found when the in-flight failure condition recurred. It was found that the configuration control process provided excellent software operation in the face of constant change. The testing and documentation process, when strictly followed, will detect software design and coding errors.

Flight Test Results: Fault-Tolerant Design And Software Maintainability

Fault tolerance

- **Built-in test**
 - Comprehensive, automated 2-min preflight check
 - Some nuisance failures due to EMI
- **In-flight fault detection**
 - Fifteen false failures detected
 - Three failures, cause not known
 - One real failure detected
- **Asynchronous computer operation, problems**
 - Adversely affected DFCS qualification
 - Accomplice to in-flight failures

Software maintenance

- **Software configuration control process**
 - Details configuration/operating restrictions
 - Provides specification, design, test and documentation process
 - Interfaces to flight test planning
- **Software changes, always**
 - 129 total changes in 13 separate releases
 - Changes to both fault-tolerant/control-law designs
- **Software errors occurred**
 - Three errors found in flight releases
 - Process keeps serious errors from affecting flight operations

FLIGHT TEST RESULTS: CONTROL LAWS

A primary objective of the AFTI F-16 program was the evaluation of a multimode digital flight control system with decoupled aircraft control. The six different decoupled options and right-hand control options were evaluated with the decoupled feature best suited for a given task identified.

The adaptive control law, which uses pitch rate error to optimize performance in gross acquisition and fine tracking, was shown to be the best option for the air-to-air combat task. The adaptive gain control law was implemented using the right-hand controller; decoupled pointing with the pedals and twist grip showed no significant improvement for the air-to-air task.

The best feature for the air-to-ground task was again through the pitch stick with improved flight path stability and ride smoothness in turbulence. Direct side force or flat turn which is commanded through the rudder pedals improved the task by reducing pilot workload for obtaining lateral axis solutions. Problems with roll ratcheting affected all the advanced combat modes. Prefilter tuning was not sufficient to completely resolve the problem.

The standard normal mode, configured for gear-down, provided a greatly improved mode for power approach. Using more of a pitch-rate command system versus the normal acceleration command system on the F-16's, improvements in flight path and angle-of-attack stability were made.

The need for and design of the analog reversion mode to protect against common mode failures proved most interesting. Although the analog reversion mode (ARM) was never engaged because of digital system failure, flight test experience indicates ARMs are needed. Complexity of the ARM becomes a primary issue; a simple ARM cannot provide protection at envelope extremes which are possible with the digital systems. Furthermore, the relaxed static characteristic requires a certain level of augmentation. The simplified reversion mode used on AFTI provided get-home capability and level 2 flying qualities for landing as specified. However, simulation and flight test indicated a more capable ARM is needed to cover transitions from the envelope extremes possible with the digital control system (ref. 4).

Flight Test Results: Control Laws

- **Air-to-air combat task**
 - Longitudinal axis pitch stick control excellent based on adaptive, pitch rate error, gain system
 - Decoupled pointing showed no significant improvements for task completion
- **Air-to-ground task**
 - Longitudinal axis pitch stick control improved, better *flight path stability/ride quality*
 - Flat turn, direct side force useful, simplified task, reduced pilot workload
 - Roll ratcheting problem in all combat modes
- **Power-approach task**
 - Longitudinal axis control improvement over F-16, better flight path/angle-of-attack stability, precise attitude control
- **Analog reversion mode**
 - No automatic engagement of mode
 - Design of mode too simplified, reduced failure envelope, compromised flying qualities

FLIGHT TEST RESULTS: SUMMARY

Successful flight test accomplishments included envelope expansion for the primary flight control modes for stability and control and for structural loads. Envelope expansion included testing for low-speed, high-angle-of-attack, and high-speed-to-Mach-1.2 conditions. Evaluation of the advanced control modes, the final goal, was accomplished in the last 15 flights.

Advanced control options were evaluated in a variety of air-to-air and air-to-surface combat tasks. Advanced flight control modes for the right-hand controller gave the best performance of the decoupled control options; flat turn showed significant improvements over conventional control methods.

The asynchronous computer architecture proved to be one of the most interesting aspects of AFTI/F-16 because of its wide-ranging effects. The fact that a given architectural design feature can affect design, qualification, and flight test is noteworthy. Flight test was culminated with no fault-tolerant-type anomalies affecting flight test operations.

Representing a state-of-the-art, flight-crucial, highly integrated control system, AFTI provided the opportunity to find weaknesses in the developmental process resulting from the new technologies. Design and testing tools to support the development of increasing complex systems need to be developed. The goal is to develop tools which can support a generic set of digital control applications. Tools that assist in the design and testing of the fault-tolerant and software aspects of new highly integrated systems would prove beneficial.

- **Successful accomplishment of flight test goals**
- **Advanced control options improve aircraft performance**
- **Asynchronous computer architecture gave difficulties, costly**
- **Flight-crucial controls/integrated systems stress developmental process**

FUTURE CONSIDERATIONS

The AFTI F-16 program provided the engineering community another look at the development of a highly integrated flight-crucial system. Considerable knowledge was gained in the development and flight test of decoupled aircraft control, asynchronous computer operation, and flight-crucial software. As the dust settles and the results are reviewed, several areas for further consideration surface.

The time for a fault-tolerant system design tool has come. As any new technology begins to succeed and grow, design tools are needed to increase engineering productivity and provide better, safer product designs. Information exists to develop a design tool which documents fault-tolerant designs and allows for systematic test approaches that can increase operational reliability. The tool would allow for early integration of the fault-tolerant design with the control law functions to avoid costly downstream changes. The design tool would essentially be an expert system which would help guide the engineer in the specification, design, and qualification of a fault-tolerant design.

The development and the use of software and system-level testing tools also need to be applied to the development of flight-crucial controls. By increasing test coverage, automating the testing process, and providing integral configuration control, operational reliability and development time could both be improved.

Further consideration is also being given to the primary AFTI technologies. The use of AFTI flight control laws in an automated-flight fire control system is one example. Increasing weapon delivery accuracy while increasing aircraft survivability will be a primary emphasis of AFTI's second phase, Automated Maneuvering Attack System (AMAS).

- **Fault-tolerant design tool**
 - Design documentation
 - Systematic testing capability
 - Integration of control functions
 - Architectural studies
 - Expert system
- **Software/system testing tools**
 - Increase/measure test coverage
 - Automate testing process
 - Provide configuration control
- **Decoupled control in automated attack**
 - Increase survivability
 - Weapon accuracy

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