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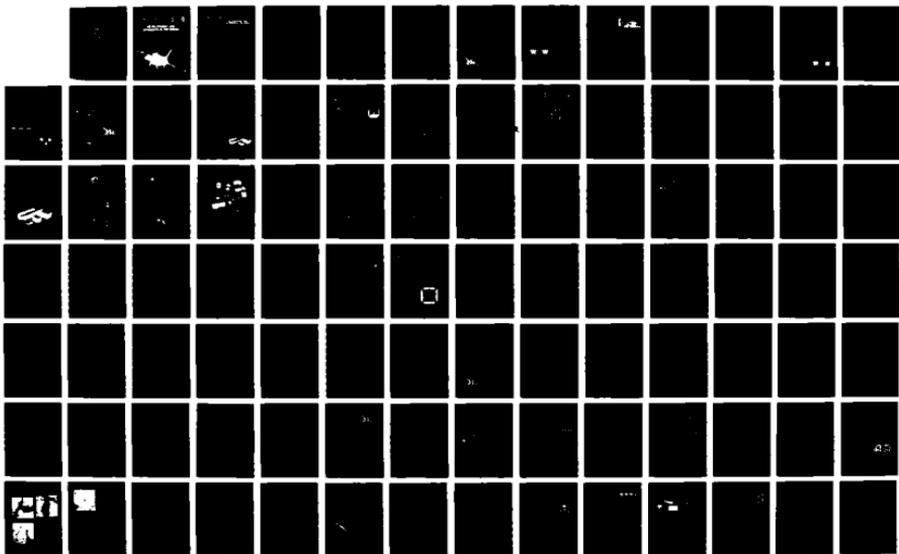
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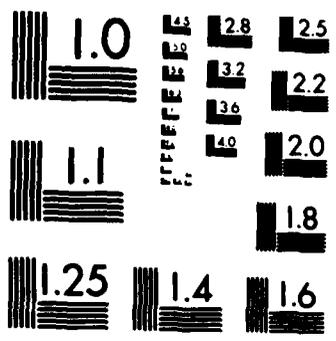
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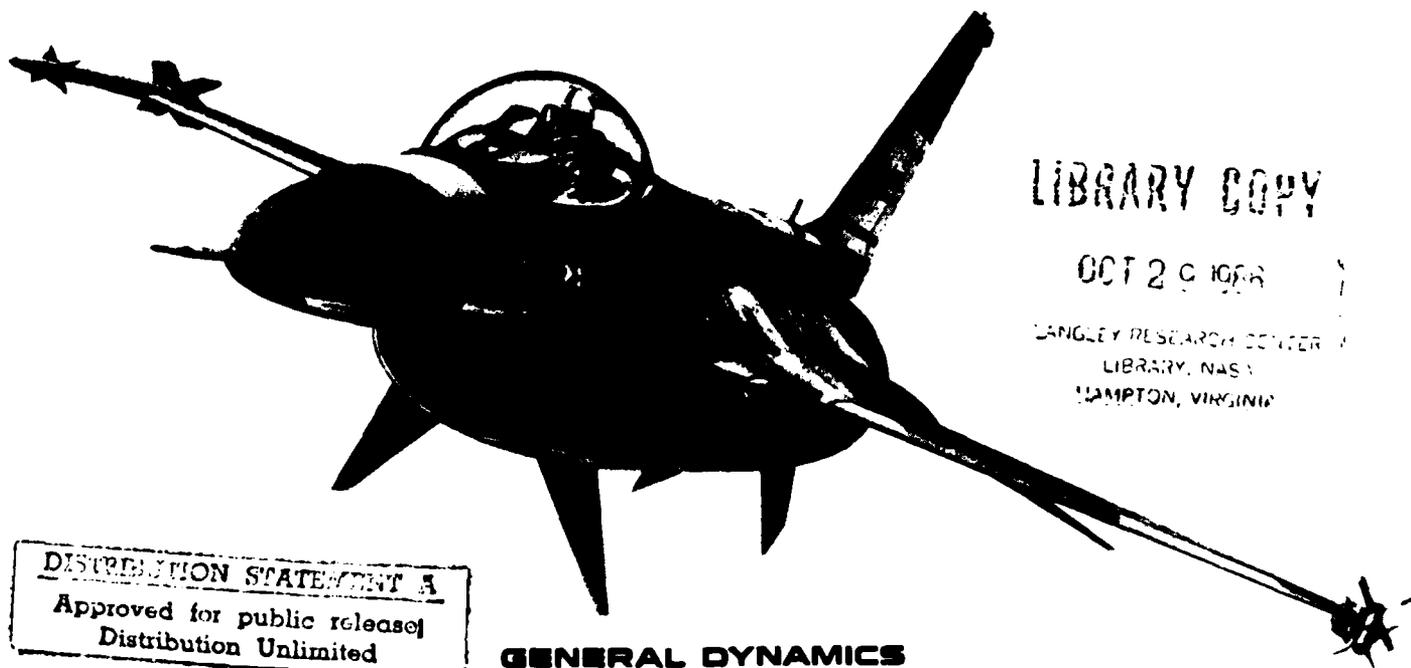
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DEVELOPMENT AND INTEGRATION PROGRAM

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11 JULY 1986

AFTI/F-16 AUTOMATED MANEUVERING ATTACK SYSTEM
TEST REPORTS/SPECIAL TECHNOLOGIES AND OUTLOOK

PRESENTED AT THE NAECON '86 CONFERENCE
DAYTON, OHIO
MAY 19 - 23, 1986

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FOREWORD

The National Aerospace & Electronics Conference (NAECON) provided a forum in which to report on the Automated Maneuvering Attack System (AMAS) Phase of the AFTI/F-16 Program. Three NAECON 86 sessions were organized to cover AMAS development, integration and interim flight test results. The three sessions, formed in the Flight Control Technology Area, were:

AFTI/F-16 Automated Maneuvering Attack System (AMAS)

AFTI/F-16 Automated Maneuvering Attack System Test Report

AFTI/F-16 Special Technologies and Outlook

The technical papers from these sessions were published in the NAECON 86 Conference Proceedings under the auspices of the Institute of Electrical and Electronics Engineers. The AFTI/F-16 Program Office, AFWAL/FII, has elected to republish the papers to provide a means of broader distribution to individuals and organizations with an interest in the AFTI/F-16 program. The IEEE grants the U. S. Government royalty-free permission to reproduce papers for U. S. Government purposes. This document is intended to serve as an interim AMAS Phase report until the formal, final report is completed in 1987.



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AFTI/F-16 Program Manager
Flight Dynamics Laboratory

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Per Mr. Dick Swartzel, AFWAL/FIGI

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**AFTI/F-16 Program - Phase II Overview Automated
Maneuvering Attack System**

Lt. Col. D. H. Ross

AFTI/F-16 PROGRAM - PHASE II OVERVIEW AUTOMATED MANEUVERING ATTACK SYSTEM

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ABSTRACT

This paper provides an overview of the second phase of the Advanced Fighter Technology Integration (AFTI/F-16 program, the Automated Maneuvering Attack System (AMAS) Phase. The AMAS development builds on the highly successful Digital Flight Control System (DFCS) Phase that was completed in 1983. In this follow-on phase, the fire control and avionics have been extensively integrated with the flight control system to demonstrate the advanced combat capabilities that a highly automated and integrated weapon system can provide. The AMAS phase is midway through its flight test program. This special NAECON session is organized to provide a report of the development, integration, and interim flight test results.

INTRODUCTION

The objectives of the AFTI/F-16 program are to develop, to integrate, and to flight validate advanced fighter technologies that will enhance the combat effectiveness and survivability of our future fighter aircraft. The program scope includes the four technology thrusts shown in Figure 1, with focus on the flexibility of the digital flight control system as a means of providing significant improvements to capabilities in a reliable and cost effective manner. The payoff of the program is the flight validation of technology alternatives for future fighter aircraft. The AFTI/F-16 program addresses both the air-to-air and the air-to-surface fighter roles, with emphasis on the weapon-delivery task.

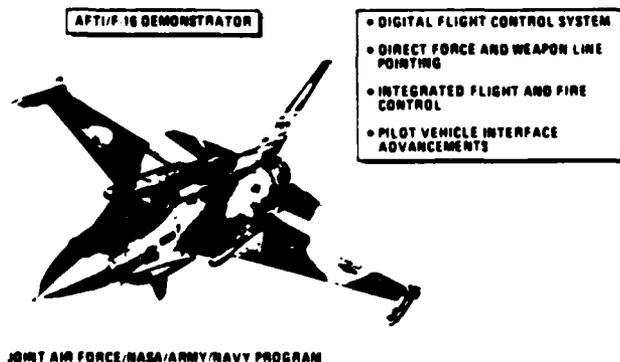


Figure 1 Advance Fighter Technology Integration (AFTI/F-16) Technology Thrusts

The approach followed in the two major phases of the AFTI/F-16 program is illustrated in Figure 2. The first phase, the Digital Flight Control System (DFCS) Phase, concentrated on the development of an advanced, multi-mode, flight control system. The flight research during that phase involved the investigation of advanced control laws and decoupled, flight-path control under pilot control. During the DFCS Phase, design hooks were provided to accommodate hardware and software growth to support the objectives of the follow-on phase, the Automated Maneuvering Attack System (AMAS) Phase. This phase explores combat automation and integration concepts that are enabled through extensive integration of the flight control system with the fire control and avionics systems.

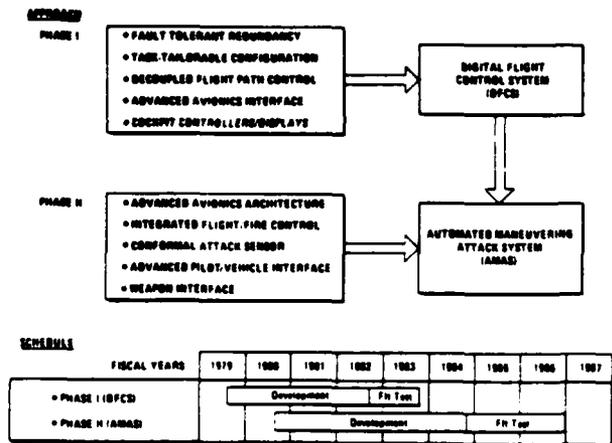


Figure 2 Program Approach and Schedule

The AFTI/F-16 program is managed by the Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio. The program is a joint program that has included the participation of the Air Force, Army, Navy, and NASA. The prime contractor for system development and integration is General Dynamics, Fort Worth Division. The flight tests are being conducted at the NASA Ames-Dryden Research Facility at Edwards AFB, California. The Joint Test Force is managed by the Air Force Flight Test Center, with participation of the NASA and contractor test teams.

This special AFTI/F-16 session at NAECON '86 has been organized to provide a report of the interim results of the AMAS Phase of the program. The AMAS devel-

opment has been underway since 1980, and the system development and software integration is now complete. The AMAS flight testing is in full swing with a scheduled completion date at the end of Fiscal Year 1986. This series of technical reports has been prepared to share with you our findings to date and our expectations for the remainder of the program. A final report will be published in 1987.

BACKGROUND OF AMAS DEVELOPMENT

The modern combat scenario is characterized by increased numbers of enemy targets, both on the ground and in the air, and by an increasingly hostile airspace surrounding these targets. This changing environment requires timely improvements to the lethality and survivability of our next-generation fighters. This places a high premium on achieving a first-pass kill while minimizing exposure to the threat. Also, because of the large inventory of unguided conventional munitions in our arsenal, our Tactical Air Forces must be able to accomplish their mission while using these low-cost weapons.

These considerations necessitate a high degree of maneuverability to quickly achieve an advantageous weapon-delivery position, precision control during final weapon aiming, and the development of weapon-delivery capabilities that take full advantage of the operational flight envelopes of our fighters (Figure 3). Any approach to attacking this problem must also prove operationally suitable in terms of pilot workload and system safety.

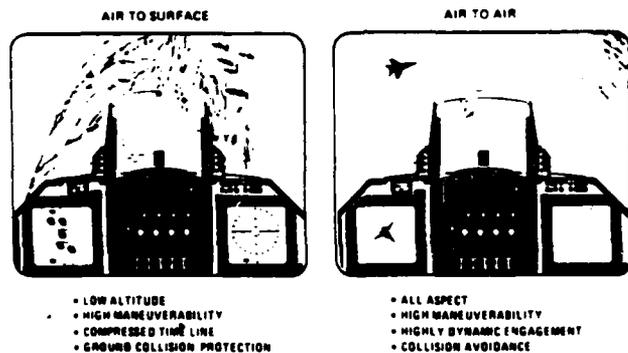


Figure 3 Combat Scenarios That Drive AMAS Design

The AMAS flight research objectives take aim at these fighter needs by demonstrating and validating several new combat automation concepts built around the integration of flight and fire control system functions. Through closed-loop coupling of the sensors to the flight controls, precision flight path control can be achieved under conditions outside the bandwidth of the human pilot. This allows for weapon delivery during dynamic maneuvering, and opening up new dimensions for working the fighter attack problem, as well as providing for workload relief in the fighter cockpit (Figure 4).

The forerunner of the AFTI/F-16 AMAS was the joint F-15 Integrated Flight/Fire Control (IFFC) and FIREFLY III program sponsored by the Air Force's Flight Dynamics Laboratory and Avionics Laboratory. This

- PRECISION ATTACK FROM HIGHLY SURVIVABLE MANEUVERING DELIVERIES WITH:
 - Fully Integrated Avionics/Flight Control/Cockpit
 - Minimum Performance Compromise
 - Acceptable Pilot Workload
- TECHNOLOGY OPTIONS FOR MULTIMISSILE CAPABILITY



Figure 4 Payoff of AFTI/F-16 Technology Integration

program demonstrated the feasibility of IFFC technology, highlighted by the shoot-down of a QPM-102 drone from a front-quarter gun attack. Also, in a limited flight test against inertial targets, the IFFC/F-15 demonstrated the feasibility of low-altitude bombing using turning, curvilinear, flight paths. The FIREFLY III director fire-control algorithms used in the IFFC/F-15 provide the baseline for the integrated AMAS design.

The AFTI/F-16 program builds on this IFFC technology by providing a critical evaluation of the technology in more combat-relevant scenarios and flight envelopes. A key difference between the IFFC/F-15 and the AFTI/F-16 flight demonstration is the low-altitude, operating requirement that has generated more emphasis on system safety design. This has presented a design challenge to simultaneously implement the IFFC algorithms, satisfy safety requirements, and maintain a practical, low-cost system configuration. Another key difference between the AFTI/F-16 AMAS and the IFFC/F-15 developments is the flight control system design. The AFTI/F-16 DFCS features a more generalized command structure that simplified the design of the couplers. Also, the IFFC/F-15 demonstration was limited by the command authority from an electronic Control Augmentation System (CAS); the AFTI/F-16 AMAS uses a full-authority DFCS that provides a large operational envelope.

AMAS OVERVIEW

The AMAS flight demonstration addresses two critical questions: (1) how far can platform performance be pushed in enhancing the delivery of ordnance, and (2) what degree of combat automation is needed to accomplish this objective, particularly for single-seat fighters? To answer these questions, the AMAS development encompasses a broad, extensively-integrated approach to providing combat automation (Figure 5). The cockpit features a voice system, helmet sight, and tactical situation display to help reduce the workload associated with operating modern avionics. A conformally-mounted sensor/tracker, optimized for multirole attack with minimum airframe-performance penalties, provides precision target information. This target-state information is further processed in the fire control computer which provides guidance commands based on ballistic computations and relative geometry to the target. At the weapon interface, the AMAS is

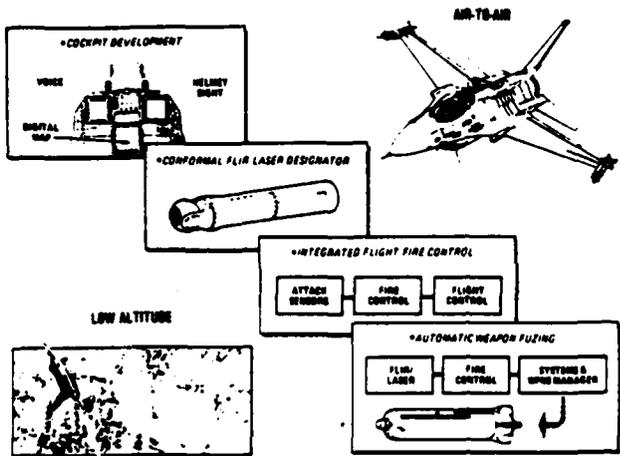


Figure 5 AMAS Combat Automation Flight Research Areas

demonstrating the use of a digital MIL-STD-1760 multiplex bus for real-time, automatic fuzing of weapons.

The AMAS flight demonstrations are pushing combat-automation technology to the practical flight envelopes that are necessary to successfully operate in the modern combat environment. The low-altitude, air-to-surface mission requires the ability to ingress at very low altitudes and deliver weapons using threat evasive maneuvers. As a program goal, the AMAS bombing system is designed to deliver weapons in a 4-5 g lateral toss maneuver as low as 200-ft AGL, with all-attitude ground collision avoidance protection (Figure 6). For the

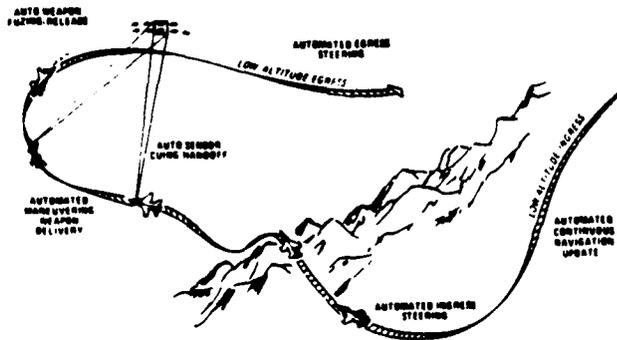


Figure 6 Air-to-Surface Automated Maneuvering Attack Demonstration

air-to-air encounter, a more versatile, gunnery system is needed to complement the air-to-air missile capabilities. The AFTI/F-16 gunnery system is designed to provide an all-aspect attack capability, to include a head-on, automatic attack and escape maneuver. This capability provides a lethal advantage that can be employed as a follow-up to a missile attack (Figure 7).

Associated with these general demonstration goals, the specific programmatic and technical objectives of the AMAS phase are as follows: (1) to define advanced integrated-flight/fire control system concepts for improving combat effectiveness and survivability of fighter aircraft, (2) to identify candidate system configurations

- 300° ASPECT GUNNERY/MISSILE ATTACK FOLLOW-UP
- CONFORMAL LOW DRAS FLIR/LASER SENSOR
- AUTOMATED RADAR/HELMET MOUNTED SIGHT/FLIR HANDOFFS
- RADAR FLIR/LASER SENSOR FUSION
- AUTOMATED GUNLINE CONTROL/TRIGGER/COLLISION AVOIDANCE
- GROWTH TO COVERT INST

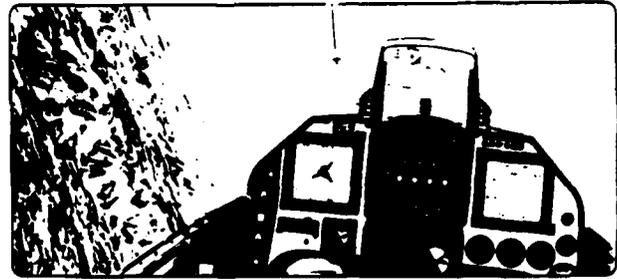


Figure 7 All-Aspect Aerial Gunnery Demonstration

for evaluation of performance and mission effectiveness, (3) to integrate a digital, multi-mode, flight control system, advanced controls and displays, and weapons for validation of system performance and mission effectiveness, (4) to quantify improvements in weapons delivery capabilities and accuracy achievable with AMAS system configurations, (5) to assess the survivability achievable as a result of evasive maneuvering profiles during the weapon-delivery phase, (6) to determine pilot acceptance, adaptability, and workload reduction associated with the AMAS modes in the weapon-delivery phase, and (7) to establish design criteria and recommendations for AMAS technology applications and integration of associated technologies. These objectives are listed here to provide the reader with a better understanding of the program. No attempt is made in this NAECON session to individually address each objective.

An important theme to keep in mind during this review of the AMAS development is that the system integration is a technology entity of its own rights. The AFTI/F-16 AMAS development, which departs from traditional integration approaches, in many ways demonstrates that significant capabilities can be achieved through the software integration of existing technologies. The capabilities may be provided en masse, or as a preplanned, product improvement that builds on several critical technologies and integration concepts. These fundamental building blocks include a multi-mode, digital flight control system; a multiplexed, digital-avionics architecture; an integrated sensor suite; fault-tolerant interfaces; a distributed approach to processing, and a supporting pilot/vehicle interface.

SESSION OUTLINE

It is the intent of these NAECON sessions to share with you our results and the lessons learned, so that our research will benefit the designs of our nation's future fighters. Because of security and technology export restrictions, the description of the development and the results will be sparse in several areas. However, we hope to provide a comprehensive overview of our accomplishments in terms that will benefit the acquisition planners of government and industry. In this first AFTI/

F-16 session we will be reviewing these AMAS development topics:

AMAS Configuration Development and Integration

AFTI/F-16 Sensor/Tracker Set

Guidance and Control

System-Safety Design

These four papers will cover the technical approach in detail, emphasizing the engineering and operational factors that have driven the design to the present configuration. Of particular interest in this session is not just the effort involved in putting the weapons on target with regard to sensors, target-state estimation, and guidance and control, but how to accomplish this task with safety and confidence.

The second session will cover our interim test results in these four areas:

Test Summary

Software Development, Integration, and Test

Flight Test Results

Pilot/Vehicle Interface

In these papers, we have captured the key results of the program to date and future plans for the remaining flight tests. This session will also provide a look at the challenges and frustrations that accompany the testing of such a highly integrated system.

Our final session will present a review of special technologies that are associated with the AMAS program:

Standardized Avionics Integrated Fuzing (SAIF)

Voice Interactive Avionics

Digital Terrain Management and Display System

These flight research experiments are being flown on the AFTI/F-16 testbed through external sponsorship of other government agencies. This set of technologies has been instrumental in providing an end-to-end look at combat automation, from the cockpit to the weapon interface.

This final session will be closed with a paper that presents our interpretation of the operational and technological impacts that the AFTI/F-16 program results might have. In particular, this paper will present a roadmap as to how we feel the integration concepts and individual technologies can logically evolve into operational systems that can provide very high payoffs to our future fighter capabilities.

We are very pleased to present these special AFTI/F-16 sessions and to be able to share with you our experiences in developing, integrating, and flight testing the AFTI/F-16 Automated Maneuvering Attack System.

OVERVIEW CLOSURE

The charter of the AFTI/F-16 Program has been to move technology from the laboratory to the operational Air Force. An important step in that process is the communication of results, and we are pleased to have this chance at NAECON '86 to share our experiences with you.

At the conclusion of the last AFTI/F-16 session, a final wrap-up paper will present our results in terms of the operational and technological implications they might have. In particular, this paper will present a roadmap of the direction, we feel, that the AFTI/F-16 integration concepts and contributing technologies could take.

The AFTI/F-16 Automated Maneuvering Attack System Phase has provided the opportunity to evolve and to validate some very exciting and promising combat automation concepts. With pride, we present to NAECON '86 the culmination of our research that is pioneering new ways to fly and to fight.

AFTI/F-16 Automated Maneuvering Attack System
Configuration Development and Integration

J. K. Ramage
W. S. Bennett

AFTI/F-16 AUTOMATED MANEUVERING ATTACK SYSTEM CONFIGURATION DEVELOPMENT AND INTEGRATION

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Air Force Wright Aeronautical Laboratories
Wright-Patterson AFB, Ohio

Willie S. Bennett
General Dynamics, Fort Worth, Texas

ABSTRACT

The AFTI/F-16 Advanced Development Program is developing and integrating advanced technologies, that will improve fighter lethality and survivability. Improved mission capabilities are achieved through integration of task-tailored, digital flight controls, fire control, attack sensors weapon interfaces, mission avionics and associated controls and displays into an Automated Maneuvering Attack System (AMAS). The core building block was achieved in the Phase I - Digital Flight Control System (DFCS) development, which emphasized fault-tolerant, inner-loop flight path control, avionics integration and cockpit interfaces. Phase II - Automated Maneuvering Attack System development expands the baseline systems in conjunction with a new FLIR-LASER Sensor/Tracker to demonstrate significant advancements in combat automation technology. This paper summarizes the Phase II AMAS configuration development and integration with emphasis on mechanization concepts, design rationale, and critical system-integration considerations.

ACRONYMS AND ABBREVIATIONS

A-A	Air-To-Air
A-S	Air-to-Surface
AFTI	Advanced Fighter Technology Integration
AGL	Above-Ground-Level
AMAS	Automated Maneuvering Attack System
AMUX	Avionics Multiplex Data Bus
BIT	Built-In-Test
db	Decibels
DCR	Design Change Request
DE/CIS	Data Entry/Cockpit Interface Set
DFCS	Digital Flight Control System
DMG	Digital Map Generator
DMUX	Display Multiplex Bus
DOF	Degree-Of-Freedom
DR	Deficiency Report
E-O	Electro-Optical
EMI	Electro-Magnetic Interfaces
EMOS	Electronic Mail/Office System
FCC	Fire Control Computer
FCS	Flight Control System
FLCC	Flight Control Computer
FLIR	Forward-Looking Infrared Radar
FOR	Field-Of-Regard
FOV	Field-Of-View
HMS	Helmet Mounted Sight
HUD	Head-up Display

ID	Identification
IFFC	Integrated Fire and Flight Control
IFIM	In-Flight Integrity Management
INS	Inertial Navigation System
IS	Ingress Steering
LAE	Lead Angle Error
LARAP	Low Altitude Radar Auto Pilot
LOS	Line of Sight
LRU	Line Replaceable Unit
MFDS	Multifunction Display Set
MSIP	Multinational Staged Improvement Program
NWL	Non-Wings Level
OFF	Operational Flight Program
OMB	Operational Mission Requirements
PK	Probability of Kill
PVI	Pilot/Vehicle Interface
RALT	Radar Altimeter
SAIF	Standardized Avionics Integrated Fuzing
SITAN	Sandia Inertial Terrain-Aided Navigation
STS	Sensor/Tracker Set
SWIM	System-Wide Integrity Management
TMD	Tactical Munition Dispenser
TSE	Target State Estimate
VFR	Visual Flight Rules
WL	Wings Level
WMUX	Weapons Multiplex Data Bus

SYSTEM DESIGN

Design requirements for the AFTI/F-16 are driven by realistic air combat scenarios and are shown in Figure 1. The threat environment of the 1990's is projected to become increasingly difficult and complex. In the case of air-to-surface attack, survivability is a dominant factor.

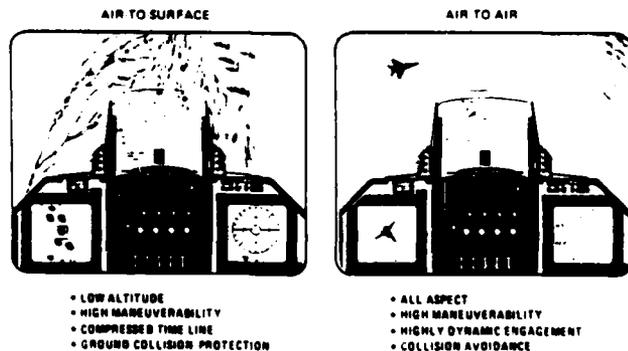


Figure 1 AMAS Combat Scenarios

* Portions of the material contained within this paper are funded under USAF Contract F33615-78-C-3022, with Air Force Wright Aeronautical Laboratories, AFWAL/F11, WPAFB.

High-speed maneuvering flight at very low altitude is an effective tactic for enhancing survivability. However, higher levels of technology integration and combat automation are progressively becoming required to enable the pilot to accomplish the critical functions of flight path control, threat management, navigation, attack engagement and weapon system management.

The AFTI/F-16 AMAS is truly an experiment in system automation and integration. As depicted in Figure 2, automation is the key to accomplishing the coupled AMAS weapon delivery profiles in a single-seat fighter. Pilot task saturation is inevitable if this is not accomplished to almost the maximum extent possible. Figure 2 illustrates the functions in the AMAS that have been automated. In each mission, air-to-air and air-to-ground, tasks requiring pilot actions that were definable and state-driven were automated. The other important development was the integration of the subsystems into a congruent system with proper functional partitioning and well-defined interfaces (Figure 3).

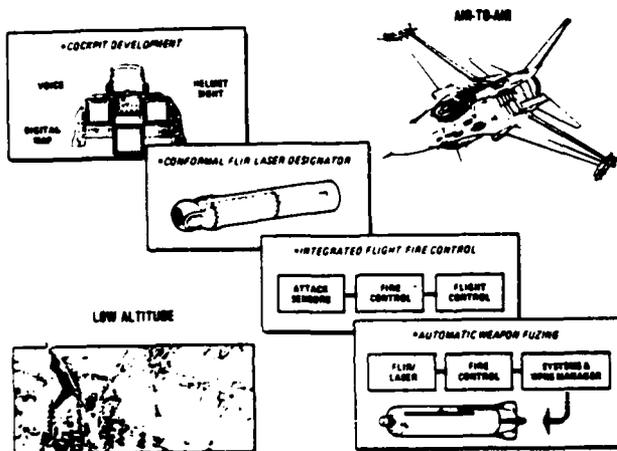


Figure 2 AFTI/F-16 Combat Automation

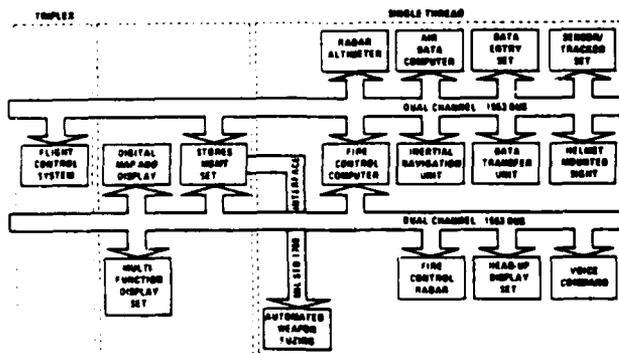


Figure 3 Fully-Integrated Systems

One of the key characteristics of the AMAS is that it extends the integration process into closed-loop control function. This brings many single-thread elements and avionics functions into the closed-loop control of the aircraft. Considerations of flight safety and system-wide integrity must be addressed and satisfied. Figure 4 illustrates the closed-loop structure of the AMAS.

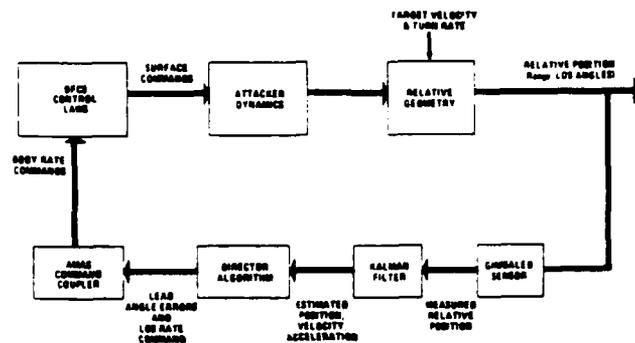


Figure 4 AMAS Closed-Loop Control

The nature of the automated weapon delivery requires that an automated ground and target collision avoidance system be implemented. The ground collision avoidance system was developed around the concept of establishing a pilot selectable minimum descent altitude, i.e., a floor, that the aircraft would not be allowed to penetrate. Should penetration be predicted, the automated fly-up maneuver is activated. In air combat, the automated breakaway maneuver is engaged when a minimum avoidance criteria is violated.

System-Wide Integrity Management (SWIM) also is a necessity for safe, reliable combat automation. Through the use of interactive built-in test, continuous inflight integrity testing, and automated enforcement of established operating restrictions, the system provides a measure of system operating integrity and safety against failures and improper operation.

The approach taken in implementing the AMAS system was to make it software intensive, hosting where possible in existing OFPs. Minimal additional equipment, and maximum integration of available subsystems were used to accomplish the automated air-to-air and air-to-ground weapon delivery.

Integrated Fire/Flight Control (IFFC)

The AFTI/F-16 AMAS can be characterized as a complex, multirate closed-loop control problem as shown in Figure 4, where the key controlled parameters are relative target position and orientation.

The system must accommodate both highly dynamic aerial targets and relatively slow-moving or fixed ground targets. Inertial line-of-sight rates can exceed 50 to 75 degrees/sec. Accurate, low-noise target sensing/tracking at these high rates is essential. A 9-state Kalman filter using multiple, independent sensor inputs provided the data for the fire control algorithm to compute the weapon delivery solution, thereby generating the required lead-angle error and LOS commands to the primary flight control system. Accomplishing this task involves multiple coordinate transformations relative to ownship body coordinates, target earth axis and inertial coordinate systems. DPCS inner-loop surface commands provide the final response to null relative target position errors.

Achieving the required system accuracy, bandwidth and stability represents a significant control dynamics challenge. Successful combat automation is dependent on the integration of several key functions as described

above. The primary elements which provide this capability are delineated below.

- o Digital Flight Control System
- o Automatic Flight Path Guidance
- o E-O Sensor/Tracker Set
- o Integrated Avionics Architecture
- o System-Wide Integrity Management
- o Pilot/Vehicle Interface

The AFTI/F-16 AMAS embodies the IFFC concept to provide steering commands for satisfying the fire control weapon delivery solution. Figure 5 illustrates the functional partitioning and signal flow established to optimize system interfaces and achieve acceptable dynamic performance. The AMAS mechanization builds on the DFCS baseline configuration developed and flight tested in Phase I. The Sensor/Tracker Set is the only new hardware development required for closed-loop system operation. All other AMAS functions were implemented in software using existing hardware elements.

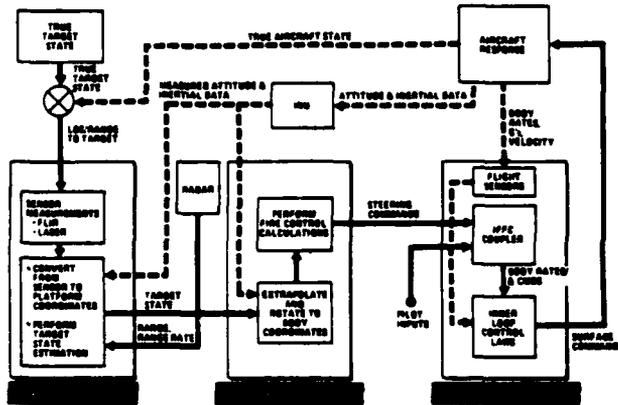


Figure 5 AMAS Signal Flow

AMAS Bombing

The AMAS bombing mission, Figure 6, was designed to provide increased survivability while maintaining weapon delivery accuracy. To maximize survivability through threat intervisibility considerations, the mission was driven to extremely low ground clearances. The impact of the low-altitude mission was reflected in several design features such as system-wide integrity management (SWIM), automated ground collision avoidance, the laser ranger, and a low-altitude radar autopilot (LARAP).

The automated phase of the mission includes ingress to the target, target attack, weapon delivery, and an egress maneuver. Figure 6 also illustrates the functions or actions performed during the bombing mission. The required pilot actions during the bomb delivery are system engagement, target designation or refinement, and consent for weapon release. The range to target at weapon release is pilot selectable and must be entered into the system prior to automated operation. Target

position or designation may be accomplished in a variety of ways, inertial coordinates, radar designate, helmet-mounted sight designate, and sensor/tracker designate and track. Utilizing the sensor/tracker and laser ranger removes the INU drift error in target location and provides good low-grazing angle range determination.

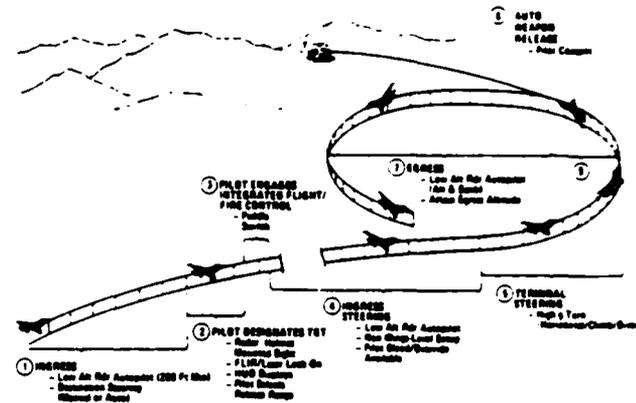


Figure 6 AMAS Bombing

The guidance laws are divided into three categories for the mission segment of (1) ingress, (2) attack and (3) egress. The ingress guidance is destination steering to the point where transition to the non-wings-level attack maneuver will occur. During this period the low-altitude radar autopilot provides a set ground clearance for essentially level terrain. The attack guidance performs a curvilinear non-wings-level turning profile to deliver the weapon at the preselected release range. This can be a climb, a dive, or a climb and then dive to the release point. The egress maneuver quickly returns the aircraft to the preselected egress altitude while maintaining a turning flight path.

The pilot is presented a variety of displays to improve his situation awareness. As shown in Figure 7 there are four major instrument panel displays and the helmet-mounted sight (HMS). Each display contains pertinent but dissimilar information that allows the pilot to evaluate system performance and determine any desired changes. The pilot has override control in all axes and several ways to disengage the system should he desire. The pilot also has hands-on control for all

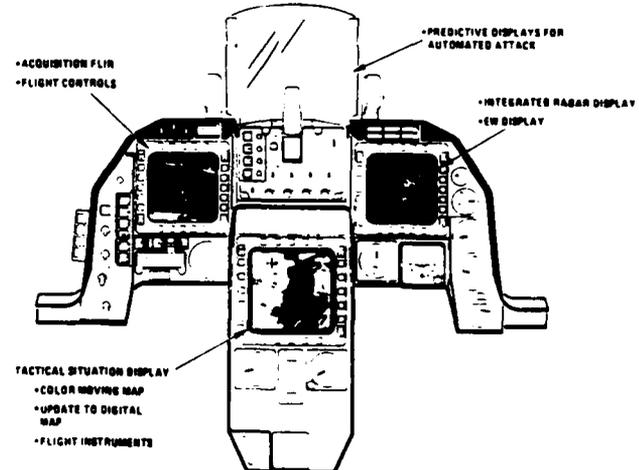


Figure 7 Optimized Pilot/Vehicle Interface

stores management computers are dual, and the displays contain redundant elements. The specific partitioning of AMAS functions is also illustrated in Figure 11.

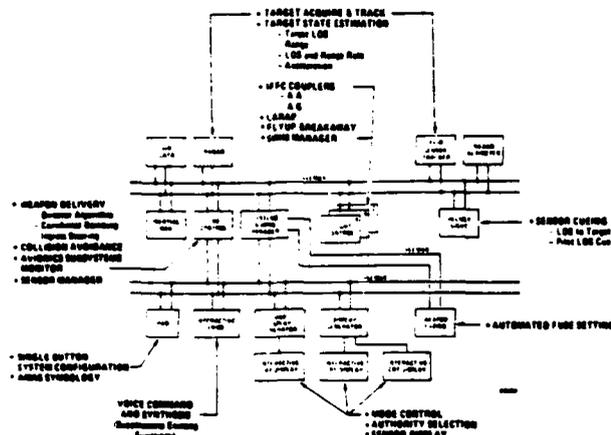


Figure 11 Functional Partitioning

One of the major challenges in airplane design is the trade-off between the benefits and penalties associated with each technology feature. The benefits always seem to bring with them penalties, in the form of complexity, expense, weight or drag. With AFTI/F-16 we have made a major effort to integrate the avionics into a digital architecture that simplifies and reduces the physical and algorithmic penalties to avoid overly complex systems. The architecture is a natural for autopilot functions, since the triplex flight control is integrated into its structure. Furthermore, the compact and efficient organization of the communications has allowed a major AFTI/F-16 thrust into SWIM. Although the bulk of the avionics systems are single-thread, much of the sensed data is inherently related. Therefore, by making comparisons of "massaged" data it is possible to achieve considerable "fail safe" coverage as will be discussed later.

Data transport delay for the serial digital communication has been carefully studied. The effect on system accuracy can be shown to be quite small because the bus refresh time is small compared to other periods of uncertainty, for example, bullet flight time. Of more concern has been the delay on the closed "outer loop" stability. After making comparisons to delays, which would also exist in a realistic hybrid digital system, with analog signal paths we concluded that the real transport penalty for busing the command signals is less than 50 milliseconds. The analytically derived stability margins for the IFCC are excellent when compared with those normally required for flight control inner-loops.

Inner-loop flight-path control is accomplished through the triplex digital flight control system. The advanced highly reliable fault tolerant DFCS is the core building block for implementing AMAS capabilities in a safe and practical manner. Significant design features include: (1) task-tailored multimode control laws incorporating decoupled 6 DOF direct force and weapon-line pointing; (2) triply redundant flight control computer complex using advanced redundancy management techniques; (3) compatible interface for integration with other subsystems, such as fire control, mission avionics, and associated multipurpose displays; and (4) independent

back-up and sensor reconfiguration modes for added safety.

The manual DFCS is augmented to implement two AMAS functions which are logically partitioned to that subsystem. First, weapon aiming errors, which are computed in the FCC, must be coupled into body-rate and acceleration commands usable by the inner-loop flight control laws. This conversion is accomplished in the DFCS, because it involves signal blending with high-bandwidth aircraft state feedbacks and pilot commands for which transport delays must be minimized. Command couplers are implemented for automatic gunnery, non-wings-level bombing, wings-level bombing, and an altitude/roll-attitude hold autopilot. An alternate command algorithm is engaged to prevent unsafe air-to-surface operating conditions. In this function, a flyup command overrides or disengages the normal AMAS guidance when certain system failures are detected, or when a projected ground clearance is inadequate. The second AMAS function performed by the DFCS is the overall assurance of system integrity prior to and during system engagement. In this role, the DFCS makes use of the In-Flight Integrity Management (IFIM) tests performed by other avionics subsystems. It also performs independent tests to validate the key inputs from the FCC and INS. Finally, the DFCS maintains sufficient information to autonomously recover from a system malfunction.

System-Wide Integrity Management

The System-Wide Integrity Management (SWIM) function (Figure 12) provides the overall safety net for the complete AMAS design. The in-flight SWIM function consolidates the monitoring of critical flight safety parameters provided by the avionics subsystem IFIM and various flight control sensors. Additionally, along with the results of the IFIM monitors, Operational Mission Requirements (OMR) are independently monitored by the FCC to provide a continuous qualification of AMAS integrity. Also, the SWIM function provides for safe recovery and transition to manual flight control from automated modes.

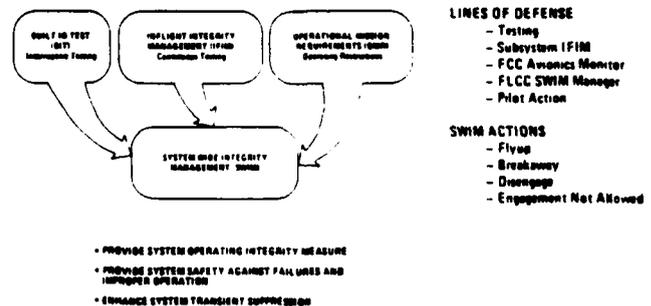


Figure 12 System-Wide Integrity Management

A sound design approach first begins with a clear identification of the central problem: automated maneuvering of a high performance fighter at close proximity to the ground demands a rapid assessment of systemic hazards resulting from malfunction or miscalculation. In addition, timely action must follow to provide (1) a safe recovery from the existing situation; (2) the detention of suspected controlling subsystems; (3) an orderly resumption of manual pilot control; and (4) the

proper identification and annunciation of faults. Operational considerations (e.g., mission requirements) preclude a simple response to every situation because many faults do not present a hazard while other faults are hazardous only under certain conditions. For example, the traditional "flyup" maneuver is not a warranted response when adequate altitude above ground level (AGL) exists; it could easily be ranked as a nuisance under such conditions. All these issues dictate thoughtful design consideration in proper identification and classification of hazards.

Potential hazards can be grouped into three major categories related to (1) the physical elements (e.g., hardware, pilot, vehicle); (2) the processing elements (e.g., algorithms, procedures, priorities); and (3) the information which defines the state of the system such as altitude, airspeed, pilot-stick force, etc.

There are five physical partitions to the overall AMAS System-Wide Integrity Management, one of which resides in the DFCS OFF. The other four partitions support the overall objectives of flight safety, some of which are procedural in nature. These partitions provide five lines of defense against hazards and are specifically:

1. Rigorous design testing
2. Subsystem BIT, self test and IFIM
3. FCC SWIM
4. FCS SWIM
5. Pilot actions.

Each level of defense provides compensation for the limited coverage by the preceding levels. To be truly effective in its implementation, the FCS SWIM function must be supported by other subsystem SWIM functions.

During in-flight operations, the FCC and FCS share the majority of automated management functions. The FCC functions as the communications monitor in that it maintains control of AMUX and DMUX traffic. In addition to its fire control function, the FCC also consolidates the avionics subsystem IFIM. This is a natural partitioning of SWIM in that data from many subsystem sensors are required for traditional FCC functions.

The FCS monitors AMAS flight control commands coming from the FCC. During surface mode operation these commands are tested for reasonable content consistent with flight safety. Commands which aggravate the level of risk either result in ultimate disengagement of AMAS operation or are limited to levels more appropriate to safe control of flight.

The FCC provides the FCS with a separate validity bit accounting for each flight-control command signal. This validity bit signifies that the FCC considers the related subsystems to be functional. The FCC is required to process a set of two problems, which are to be worked during alternate FCC computational frames, and the results are relayed to the FCS via the AMUX. The FCS, in turn, checks the results for validity and cycling. This assures the integrity of that specific FCC computational process and the active status of the FCC at that point.

Additional FCC processing checks are made with regard to a checksum calculation upon flight-critical command parameters relayed to the FCS via AMUX. These processing checks provide a measure of assurance that FCC processing and process control is taking place. It should be pointed out that the FCC itself contains a hardware timer trap device called COP which resembles the FCS watchdog timer. If the COP timer is not managed correctly by the FCC OFF, it will shut down FCC AMUX operation altogether. The FCS checks previously described are fashioned to act as a staged backup to the FCC self-test structure.

The communication media is being continuously monitored by the FCS in normal AMUX processing. Stale data encounters are noted and persistence counters maintained to determine FCS tolerance levels. Because the AMUX function is essential to normal AMAS operation, a disengagement results if the AMUX is judged to be unusable.

The DFCS SWIM is tasked with the monitoring of information related to operational mission requirements. Such information can be broad in scope, but each form has one thing in common; it originates outside the hardware system and must be construed from sensor functions. Examples include the use of maximum pilot stick force to disengage AMAS operation. This construct does not reflect a malfunction; it is devised solely to provide for an optional pilot action, possibly in response to a potential hazard. Another example is a stalled condition, i.e., angle of attack greater than 29 degrees. Such a condition is identified as outside the scope of AMAS operations. As such, it is imperative that AMAS operations be discontinued in recovery from a stall for reasons of safety. Additional conditions exist that define the acceptable state of AMAS operation. These conditions include Mach number, minimum altitude, protocol in mode selection, and so on. Because they usually involve the operational groundrules for safe AMAS operation, they need to be considered as a distinct category.

Sensor/Tracker Set

The STS, Figure 13 is the primary sensor for the AFTI/F-16 Automated Maneuvering Attack System (AMAS). The STS was developed for General Dynamics by Westinghouse Defense and Electronics Center, Baltimore, Maryland and provides the features shown in Figure 14.

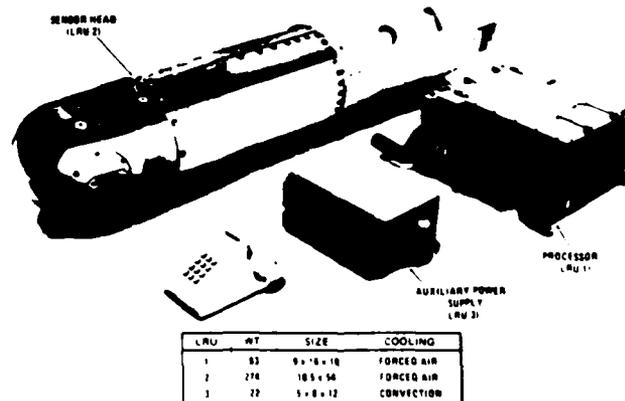


Figure 13 Sensor/Tracker LRUs

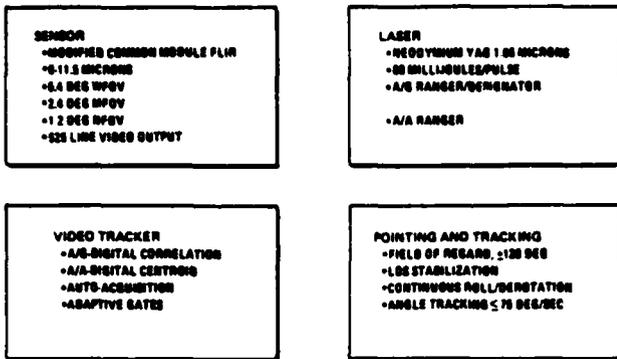


Figure 14 Key S/T Features

The desired small cross section and short length, required for installation at the strake location, was achieved by a combination of good partitioning, cooling, and package design. The STS was partitioned into three line-replaceable units (LRUs) as shown in Figure 13. The sensor head contains the sensors and gimbals. The processor contains the computer processing function and the signal interface with the AFTI avionics. The processor contains a 1750A general-purpose computer, an Intel 8086-based video tracker computer and a Motorola 68000-based video reformat.

Two of the three STS LRUs are installed in the AFTI/F-16 aircraft in the locations shown in Figure 10. The dummy head in the left strake location is provided for aerodynamic symmetry. The processor is mounted aft of the cockpit in the AFTI/F-16 peculiar dorsal bay. The auxiliary power supply is installed in the right inlet bay.

The strakes are among the best EO sensor installation locations on the F-16 aircraft for coverage capability (see Figure 15). Only the nose, occupied by the F-16 radar, provides clearer coverage. The strake and nose locations alone permit uplook and downlook sensor coverage without the necessity for handoff. Figure 16

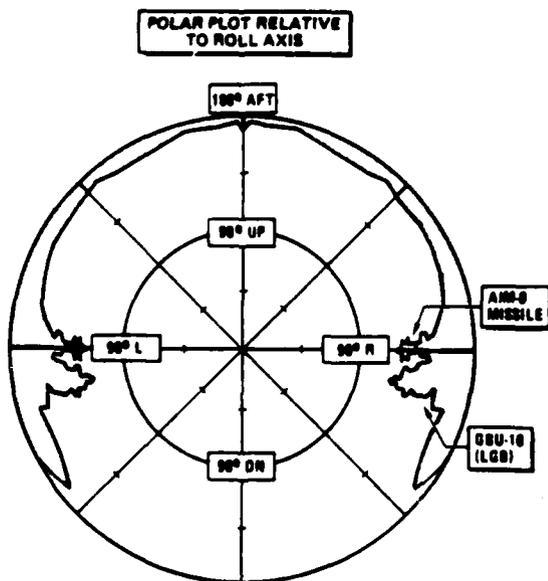


Figure 15 Dual-Head Obsecuration

presents the masking envelope for a right strake sensor head. Uplook and downlook coverage matches the AMAS requirement. Inboard masking occurs at approximately 12 degrees and prohibits wings-level, left-offset target acquisition. The decision to procure a single-head STS configuration was based on cost considerations only. Fortunately, the impact on system evaluation in the AMAS application has been slight.

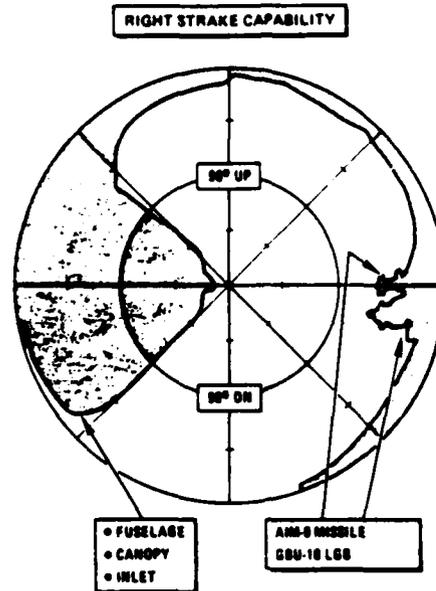


Figure 16 Single-Head Obsecuration

The STS includes a software-implemented 9-state Kalman filter derived from the APG-66 (F-16) radar Target State Estimator (TSE). The TSE fuses time-tagged radar range and range-rate data, if available, with laser range and sensor head line-of-sight angle measurements. The radar data also is used to preload the TSE matrix elements, in order to reduce settling time after track entry.

The TSE output is provided in platform coordinates to reduce ownship-induced output data variations. A stable TSE output is essential to the suppression of unwanted ownship oscillations in the flight control command loop. In A-A track TSE outputs include target relative position, inertial velocity, and acceleration. For A-S track, only position and velocity are provided.

The modes of operation of the STS are presented in Figure 17. All modes and control options are automated

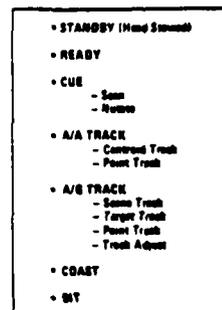


Figure 17 S/T Modes

through the fire control computer or by integral STS functions as illustrated in Figure 18. Also, the pilot has an override/selection capability on all usable control options.

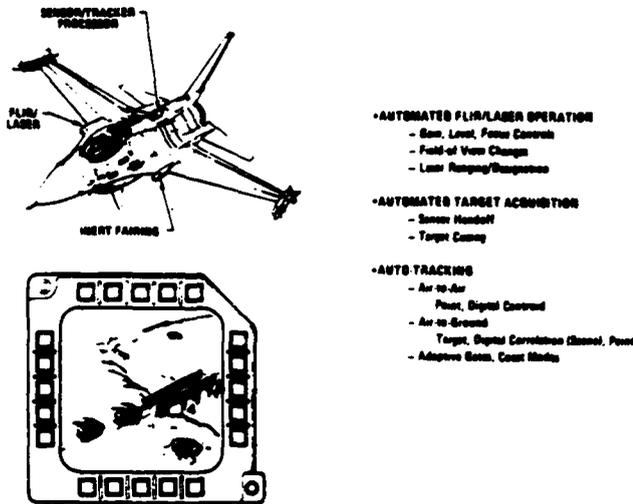


Figure 18 Automated Mode Control
Pilot/Vehicle Interface (PVI)

A very substantial development effort has been accorded to designing the pilot into, not out of, the system. Pilot acceptance of the integrated, automated systems is crucial. He must believe that the automatic flight path control is safe, and he must be given a satisfactory interface to the vehicle. Situational awareness is obtained through a combination of the head-up display that includes predictive information, multi-purpose displays, a color map display, helmet-mounted sight cues, and voice feedback. The controls and displays have been designed to provide acceptable pilot workload and efficiency during all of the mission phases. A significant portion of flight testing has been dedicated to evaluating the effectiveness of the pilot/vehicle interface features. The AFTI/F-16 cockpit is shown in Figure 7. Specific design features, rationale and projected, future emphasis are discussed in the following paragraphs.

Head-Up Display (HUD)

The HUD was developed for the AFTI/F-16 during the first program phase. This wide field of view (15 x 20 degrees instantaneous), conventional, optics HUD has since been transitioned to the F-16C/D production aircraft. Symbology is stroke-written with raster growth capability. The AFTI requirement for the wide FOV was to provide required flight data, including predictive weapon-delivery information, while maintaining high readability with low-clutter perception to the pilot.

In the low-altitude, automated maneuvering attack environment, the pilot must be given predictive information as to the aircraft trajectory and release conditions as well as the weapon aiming and delivery solution. Figure 19 shows HUD symbology for AMAS attack profiles. The predictive profile is displayed towards the left side of the HUD; the attack symbology is

displayed in the center. The predictive display shows the predicted flight trajectory (start, current position, apex, release) and weapon release conditions (dive angle, release, and recovery altitudes). The attack symbology displays the load factor and bank angle, both commanded and actual, to achieve the desired release conditions. The display allows manual steering, as well as automated, for the maneuvering weapon deliveries. Symbology is also presented to show impending, minimum-set altitude and auto fly-up (air-to-ground) or breakaway (air-to-air) maneuvers. The HUD symbology was developed with extensive pilot involvement and simulator evaluation. Display clutter and symbology stability are design problems requiring careful attention. Flight testing is validating the utility of the predictive displays.

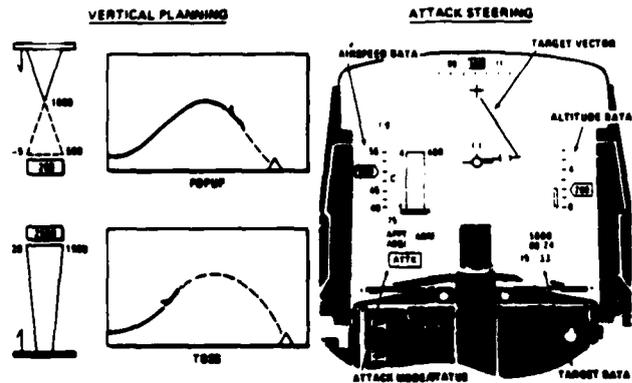


Figure 19 Predictive Display Symbology

Multifunction Display Set (MFDs)

The two monochrome MFDs which are common to the F-16C/D, but are raised high in the instrument panel to keep a minimum eye shift from "head-out" to "head in" the cockpit. They can be interchangeably used for radar, FLIR, threat warning, and digital map (monochrome) video as well as, for system status and control. Pilot interface is accomplished through the 20 bezel-mounted switches, hands-on-stick controller and throttle-controller switches, and voice command.

Color Display

The lower display serves as the Tactical Management Display and as a back-up to other primary displays. Situational awareness is a key design thrust for pilot assistance while operating in the low-altitude, high-speed, and high-workload environment. Although the film reader map was useful while operating on the restricted test ranges at Edwards AFB, the digital map offers new, revolutionary capabilities. It originally contained a film-reader, moving map and has been replaced by a digitally-generated map display. This five-inch color display will also be used for evaluation of raster and stroke-drawn, flight instruments. It should be noted that the AFTI/F-16 is currently configured only for day, VFR flight; significant changes and up-grade of flight instruments will be required for night/weather operations of the AMAS. This color display is also used as a back-up for clear-text, fault reporting of the digital flight control system. This was required for redundancy considerations because a single, programmable, display generator drives both monochrome MFDs.

Digital Terrain Management and Display System (DTMDS)

This system employs a third-generation, digital map generator developed by the Harris Corp. under U.S. Army (AVRADA) sponsorship. The objective is to evaluate the accuracy and usability of Digital Land Mass System (DLMS) data in a tactical-fighter, aircraft environment.

Internal to the digital map generator (DMG), multiple micro-processors operate on a parallel data bus with a common, shared memory. This architecture allows growth to support additional functions, such as terrain-following/avoidance. In the APTI/F-16 AMAS configuration, the Sandia Inertial Terrain-Aided Navigation (SITAN) algorithm is hosted within the DMG to provide auto-navigation capability. The stored terrain data provides elevation information for comparison with radar altimeter data that SITAN utilizes to precisely locate the aircraft within the map field. During the AMAS phase of the APTI/F-16 program, the digital map is being evaluated with respect to the use of color, elevation shading, cultural features, scales, automatic navigation accuracy and overall pilot interface.

Interactive Voice System

Another dimension to the pilot/vehicle interface is provided through interactive voice, i.e., voice command and voice synthesis (feedback) for communications with aircraft avionics systems. Careful attention was given in designing hands-on controllers for the APTI/F-16; however, the number of switches and functions (Figure 20) have reached the limit of reasonable operability. The interactive voice augments hands-on control, allows direct function selection without page scrolling and menu shopping from MFDs, and provides critical feedback information without bringing eyes into the cockpit. In the

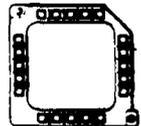
REQUIREMENTS: HANDS-ON/HEAD-UP CONTROL	
TODAY - Approaching Limits of Hands On Controllers	TOMORROW - Voice Interactive Control Augments Hands On Control
<p>• THROTTLE CONTROLLER</p>  <p>• 5 SWITCHES • 11 FUNCTIONS</p>	<p>SPEECH RECOGNITION & SYNTHESIS</p> <ul style="list-style-type: none"> - Display Status/Control - Mode Control - Data Entry - Status Query - Checklists - Advisories/Warnings
<p>• BISTABLE CONTROLLER</p>  <p>• 8 SWITCHES • 20 FUNCTIONS</p>	
<p>• MULTIFUNCTION DISPLAY</p>  <p>• 20 BUTTONS • 60+ FUNCTIONS</p>	<p>ENHANCES</p> <ul style="list-style-type: none"> - Single Step Operations - All Weather Missions - Night Attack Missions

Figure 20 Interactive Voice System

AMAS configuration voice command is used for: (1) radio channel and steerpoint selection, (2) MFD page select and control (radar, sensor/tracker, stores management functions), (3) data entry of radio frequency, destination coordinates and weapon release range (fire control system), (4) pilot selectable status queries (fuel, weapon, etc.), checklists, and event advisories (altitude, airspeed, time-to-go), and (5) system initiated warnings, cautions, and advisories, which are also synthesized.

The voice system interfaces with the avionics subsystems through the multiplex data bus structure. Vocabulary is very carefully chosen to be common to the subsystem and normal pilot operation. Manual control is available at all times for the voice-accessed functions.

Voice command was first flown on APTI/F-16 in the DFCS Phase. Here, the experiment's objective was to determine the feasibility of using voice in the high-noise (up to 112 dB) and g environments. This testing was very encouraging. While recognition rates needed to be greatly improved, feasibility was established. During AMAS flight testing, we expect to see recognition rates better than 95 percent, and with near-continuous speech operation (versus isolated word recognition). The systems are still speaker dependent and require a data cartridge to load individualized speech templates for the given vocabulary. The voice experiment on AMAS is structured to determine the utility of an interactive voice system in the cockpit. Real measures of workload reduction and performance enhancement are still being addressed.

STANDARDIZED AVIONICS INTEGRATED FUZING (SAIF)

The SAIF concept developed by the Air Force Armament Laboratory, Eglin AFB, Florida, allows optimization of the aircraft weapon interface by permitting real-time weapon fuzing based on actual release parameters and desired pattern size. On-board APTI/F-16 systems compute the necessary mission and avionic system parameters which are then communicated to the weapon through a MIL-STD 1760 interface to achieve optimum bomblet pattern size. This approach minimizes the pilot's weapon management task, while at the same time eliminating flight parameter restrictions associated with conventional, fixed, function-time fuze settings.

Figure 21 shows the sequence of events using the Tactical Munitions Dispenser (TMD). The pilot selects the target type on the display, and the fire control system then uses the optimum bomblet pattern density for that target. Based on aircraft flight conditions, the fuze function time is continuously computed and set in the fuze over the multiplex bus.

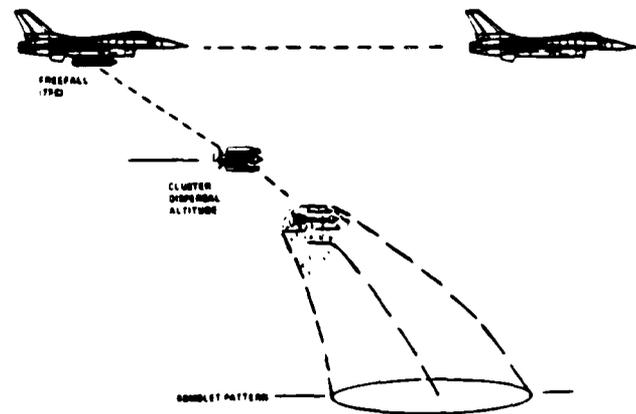


Figure 21 Standardized Avionics Integrated Fuzing (SAIF)

SYSTEM INTEGRATION

System integration is the key to effective and pilot-acceptable combat automation capabilities. From the beginning, the AFTI/F-16 development team stressed the importance of integration in the hopes of achieving a degree of synergism. The AFTI/F-16 program is deeply rooted in the philosophy of technology integration, in order to credibly demonstrate not only the projected improvements, but also to determine the practicality and the limitations of emerging fighter aircraft technologies. This integration philosophy is reflected in a formalized systems engineering approach, where top-level, mission, performance requirements affect the total design. System specifications were progressively allocated to lower levels in a traceable and controlled fashion. The design and integration process was dynamic and highly interactive during all stages of development. Design engineers, software engineers, programmers, test engineers, specialty engineers, and pilots participated fully in evolving overall design and integration concepts.

System developers were given considerable freedom and encouragement to explore innovative, and sometimes controversial, ideas in order to achieve the broad program objectives. Throughout the design process, major emphasis was focussed on end-item performance, safety, and pilot acceptance. Early involvement of the engineering and test communities proved invaluable.

Automated maneuvering attack encompasses several critical operational tasks ranging from target acquisition, target tracking, command guidance, and control steering through weapon delivery. Each of these tasks breaks down into subtasks, which are then translated into specific system design requirements. The challenge of system integration is to consider each of the unique task requirements in the context of a total system which can be realized in a practical mechanization. The AMAS integration effort is sharply focussed on control laws, pilot/vehicle interface, system architecture, sensor fusion, and safety. To further illustrate this point, the AMAS can be viewed as a classical, closed-loop, multivariable, control problem where relative target position is the controlled parameter (Figure 4). External disturbances including intentional pilot blending and sensor inputs must be accommodated. Implementing the AMAS control loop in real-time has significant implications on signal flow and system integrity. Practical considerations dictate a multibus architecture comprising many single-thread elements in conjunction with critical redundant functions. Automatic system-wide anomaly detection and recovery is essential, particularly in the low-altitude, maneuvering environment. Achieving acceptable stability and accuracy becomes a major challenge considering the inherent transport lags of multirate/multiprocessor architecture. For these reasons, system architecture, signal flow, and functional partitioning were major considerations in achieving required performance relative to throughput and system bandwidth.

The AMAS is a software-intensive design cutting across several existing and separately-developed baseline avionic systems. Achieving an integrated design required extensive development and modification of existing operational flight programs. The resulting mechanization maximizes the use of existing on-board computing resources, thereby alleviating the need for additional

specialized subsystem equipment. With the exception of the Sensor/Tracker, the AMAS design is literally embedded flight control and avionic systems to achieve fully-integrated mission capabilities.

The system was initially implemented in a software simulation to verify interface data and operating characteristics. As the design matured, the complexity and fidelity of the simulation modeling increased. Many times simulation efforts led to design development and definition from simulation software. An example is the AMAS modifications to the fire control computer operational flight program which were originally emulated in the software simulator and refined before the target computer was programmed. Extensive piloted simulations proved invaluable in evolving the AMAS design from concept definition through final, integrated, system validation.

The AFTI/F-16 Phase I DFCS operational flight program and the F-16 MSIP avionic operational flight programs were the baseline software for the AMAS development. To ensure a coordinated integration of the design, all system changes were defined and documented on a Design Change Request (DCR) and approved or rejected by the Design Change Review Board. Every DCR required the signature of each affected subsystem lead.

Approved design implementations then entered the test cycle illustrated in Figure 22. The hotbench simulation integration and checkout is the real test of whether the integration effort has been successfully accomplished. The hotbench is composed of a high fidelity aircraft simulation connected to avionics and flight control flight hardware and software as illustrated in Figure 23. The only equipments excluded from the simulation interface were the central air data computer and the inertial navigation unit. Engineering evaluation and checkout is accomplished utilizing the actual flight equipment. The hotbench simulation also provides full AFTI/F-16 mission capability with a large (60 degrees by 180 degrees) color, visual scene for pilot evaluation.

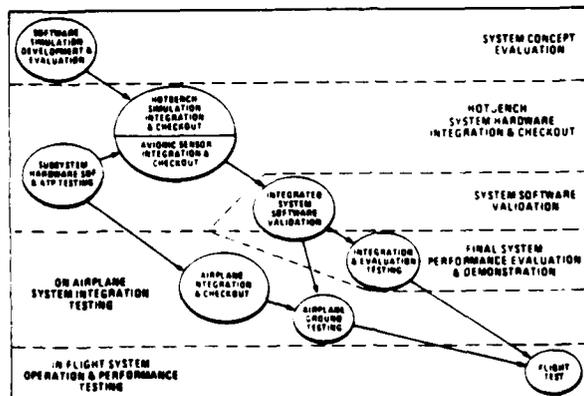


Figure 22 Multitiered Test Cycle

All system discrepancy reporting is accomplished by way of the Discrepancy Report Form (DR). The reports are logged into a computer, shared file available on the Electronic Mail and Office Systems (EMOS) for all parties to review and submit resolutions or changes. All system DRs are reviewed by the System DR Board and assigned

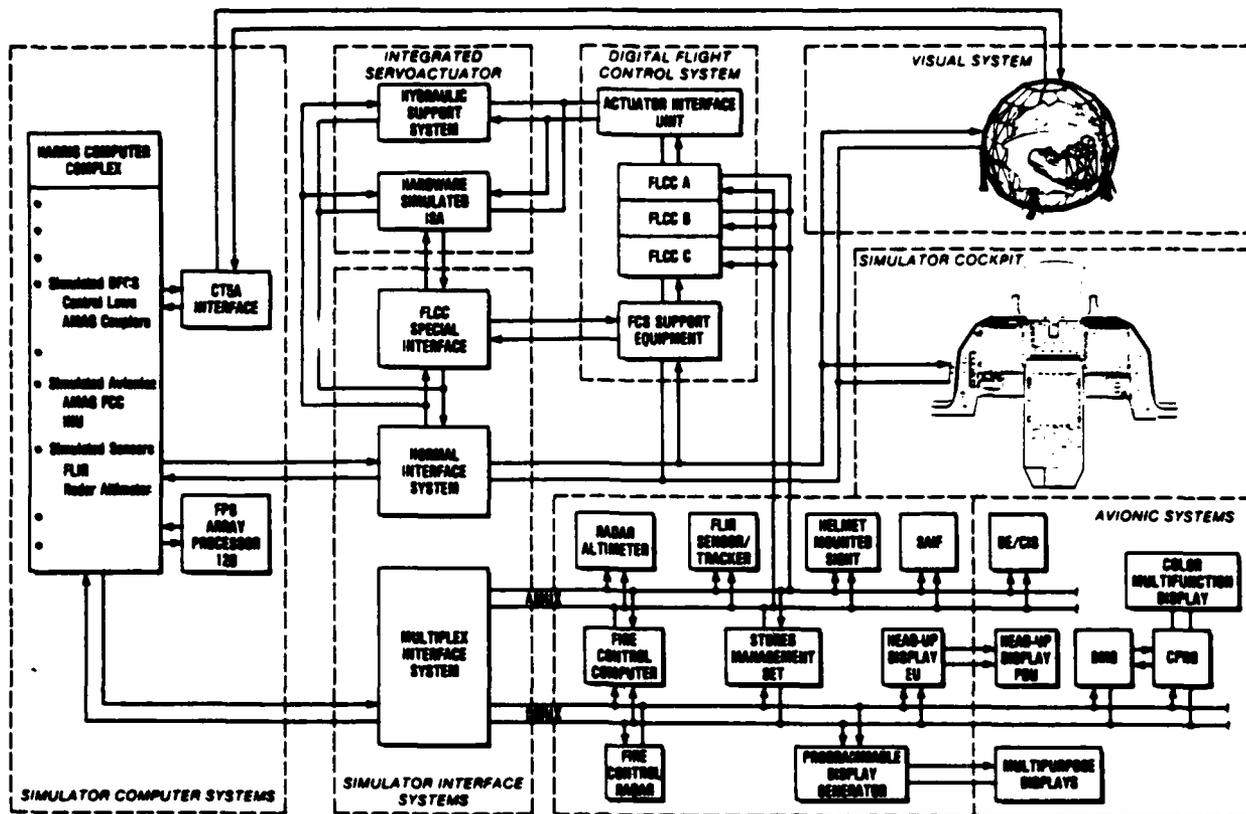


Figure 23 Hotbench Simulation Facility

to the subsystem if appropriate. Flight test and confidence test DRs are processed through the same system. This process has provided a mechanism to ensure that system integration considerations were given appropriate priorities and visibility.

The Integrated Verification and Validation Phase of testing is the formal, final step before releasing the OFFs to flight test. It serves to verify system interfaces, operation and integrity management. The integrated system testing encompasses the following major areas:

1. Built-in-Test (BIT)
2. Manual FCS Tests
3. Closed-Loop Response Tests
4. System-Wide Integrity Management Test
5. AMAS Operation and Mission Profiles Test

The on-aircraft integration began by conducting several verification tests to establish proper end-to-end continuity and electrical compatibility. The total closed-loop operation was investigated for sufficient structural gain margin by accomplishing a structural coupling test. Specific on-aircraft integration is performed with each new OFF, to assure proper operation of the integrated system.

CONCLUSIONS

The APTI/F-16 Automated Maneuvering Attack System has evolved through a disciplined, systems-engineering process, which emphasized realistic combat scenarios, technology integration, pilot utility and safety. Weapon delivery accuracy and survivability will likely diminish in a high-threat environment, without significant advances in the practical uses of combat automation and pilot situational awareness. The resulting AMAS design represents a crucial step towards the practical implementation of combat automation technology in modern, high-performance, fighter aircraft. Central issues addressed in the AMAS development include the pilot-vehicle interface, flight control and avionics integration, sensor fusion, system integrity and mission versatility. The AMAS design concept recognizes both the capabilities and limitations of the pilot to successfully engage and survive both air-to-air and air-to-surface combat. The system has the necessary provisions for blending manual and automated control features in a safe and effective manner. Additionally, the E-O Sensor/Tracker Set has been tailored for multirole-fighter Application. Pilot acceptance, effectiveness and practicality have been carefully considered. Through the process of flight test, APTI/F-16 is continuing to validate technology alternatives for improved mission effectiveness.

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AFTI/F-16 Sensor/Tracker System

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AFTI/F-16 SENSOR/TRACKER SYSTEM

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ABSTRACT

This paper describes a sensor/tracker system designed to support both air to air and air to ground automated weapon delivery at subsonic and supersonic speeds. The configuration, installation, operational application and test results are discussed. The 8-12 micron sensor, Nd:YAG laser, optics and gimbals located in the low drag conformal strake mounted head are described. A separate processor located in the aircraft hosting a 1750A computer, a video tracker and a digital scan converter signal processor and reformatter is discussed. Also discussed are the aircraft interfaces and the sensor/tracker operating modes. Pilot controls and displays are presented emphasizing interactions through the Multi-Function Display set.

INTRODUCTION

The AFTI/F-16 sensor/tracker is a small, high density, low drag coaxial FLIR/laser gimballed system with a sensor head that is conformally mounted in the strake of the AFTI/F-16 aircraft to provide accurate A/A and A/G target location information to an automated maneuvering attack system. It was developed using U.S. Air Force, General Dynamics and Westinghouse funds. Photographs of the three system Line Replaceable Units (LRUs) and a list of their physical characteristics are shown in Figure 1. Illustration of the conformally mounted sensor head and position of the processor and auxiliary power supply are shown in Figure 2.

The low drag was achieved primarily with a small cross-section and conformal mounting, both of which set demanding packaging requirements. Swept volume and the large field of regard were also packaging drivers. As a result, the sensor head, which rotates continuously with all of its components, houses only the gimbals, IR sensor, laser and essential electronics. Most of the processing is performed in the processor that contains a derivative of the AN/APG-68 radar 1750A

general purpose computer, a video tracker and a video signal processor/reformatter.

Wind tunnel drag data for a dual head installation is shown in Figure 3 and represents a 3x to 7x reduction in the drag increment typical of today's pylon mounted pods. Further, the conformal installation was found to have a negligible impact on aircraft lift and stability characteristics, and does not take up a store station.

In addition to low drag, the sensor head strake mount has proven to be good for boresight control and provides a broad field of regard including over/under fuselage capability essential for A/A combat as shown in Figure 4. Operationally conceived as a dual head system with hand over capability to overcome fuselage masking, a single head adequately covers the HUD field of view and was used during flight test for reasons of cost.

SYSTEM DESCRIPTION

The general partitioning of the sensor head is shown in Figure 5. The electronics, FLIR receiver pallet, and the laser modules are accessible as shown through covers. The FLIR receiver pallet and the laser separation provides good EMI shielding. The sensor head is supported by bearings at the mid and aft bulkheads and rotates with them. Not shown are the covers and the non-rotating roll can shown in the photograph in Figure 1. Installation and removal of the sensor head involves the entire assembly and is accomplished quickly.

FLIR Section

The 8-12 micron FLIR sensor design draws heavily upon the current and advanced common module FLIR components. It uses an electronically multiplexed Digital Scan Converter (DSC) in lieu of the conventional LED/TV camera method. Dual thermal references are used for automatic gain and level equalization. The FLIR also features Automatic Low Frequency Gain Limiting (ALFGL), Automatic Gain

Control (AGC), line/line interpolation capability, white/black hot display, electronic zoom and linearity correction using a scan position sensor. The detector array is read out vertically as the image is scanned across the array horizontally in 1/60 second. The second bar of the wig wag scan is used for interlace to form the 30 Hz frame rate. Each detector is displayed twice per frame.

The staggered 120 element HgCdTe detector array was supplied by New England Research Corporation. A specific cold shield design was used to increase the detector sensitivity.

The general layout of the FLIR optics chain is shown in Figure 6. It is composed of ZnSe, ZnS, Ge, and AMTIR elements. Thermal design in the optical areas was important to minimize transmission losses. The FLIR optical and laser areas, including the turret, are pressurized for reasons of cleanliness and cooling. Three fields of view of 5.4, 2.4 and 1.2 degrees diagonally operate through apertures of 1.3, 3.0 and 5.6 inches respectively. Automatic focusing is used to compensate for field of view changes, range and temperature. In-flight verification of FLIR/laser boresight is provided by a boresight projector. Optical alignment with the aircraft boresight is maintained by precision mechanical mounting. Boresight corrections are made via sensor/tracker software thus eliminating hardware preflight boresight operations.

Laser

The sensor/tracker uses a laser for accurate air to air and air to ground target ranging. A Mil-qualified 1.06 micron Neodymium YAG AN/AVQ-25 (PAVE SPIKE) laser designator transmitter is used unchanged. Its power supply has been repackaged to fit the allocated space. The laser energy out the window is a nominal 80 millijoules/pulse. An AN/GVS-5 silicon avalanche quad detector serves as the receiver. It operates on a first or last pulse logic.

A narrow divergence laser beam performs air to surface ranging while a wider divergence beam is used for air to air ranging. The laser operates at a 15 Hz pulse repetition frequency at a 15 nanosecond pulse width. Provisions are currently underway to incorporate laser coding for target designation.

Gimbal/Servo Characteristics

Gimbal rate commands are derived from pointing commands in the cue mode or from tracker error signals in the track modes. They are fed to the servo subsystem to direct the sensor/tracker line of sight (LOS) via the three axis gimbal set. The inner azimuth axis, stable body and gimballed mirror with feed-forward acceleration aiding, is carried on the elevation yoke. Az and El (and turret) gimbals, in turn, ride on the roll axis to yield the large angular field of regard. Azimuth travel of ± 8 degrees, elevation travel of ± 160 degrees and continuous roll capability produce the ± 120 degrees unvignetted field of regard. Together

the system provides the desired LOS isolation from flight-induced perturbations while allowing high-rate target tracking. Inputs from the Target State Estimator (TSE), aircraft inertial navigation system, and sensor/tracker gimbals are used to generate rate-aiding commands to ease the target tracking task. A continuous derotation loop is mechanized to provide either a "sky-up", "horizon natural" or "track-up" image orientation on the cockpit display.

Extensive rigid and flexible body model analyses and tests were performed to define and control gimbal resonances in order to achieve required LOS stabilization values. Also, the line of sight control laws were exercised via computer simulations to ensure optimal use of roll drive torque and smooth tracking through the gimbal pole.

Video Tracker

The multi-mode video tracker uses unformatted digital video for maximum sensitivity. Tracker signal flow for the various modes is depicted in Figure 7. Target detection and angle tracking logic was based on previous Westinghouse designs. Video tracker algorithms form a separate set of software resident in the Intel 8086 microprocessor contained within LRU 1. Because the detector array is contiguous, each video field used by the tracker contains a complete scene image so that a smooth tracking capability is maintained.

Air to surface tracking operations always begin by using a digital area correlation track technique. Attainment of this "scene track" state then permits automatic entry into a discrete target track submode with its greater accuracy and automatic target centering capability. This is the "target track" state of air to ground operations. If refinement of the track point is desired, inputs to the cursor control temporarily force the sensor/tracker into the "track adjust" mode. The track adjust mode may be either scene track adjust or target track adjust. In either case, it permits the target being tracked to move away from the center of the field of view so that a new target can be centered and locked on when leaving track adjust.

Air to air tracking uses a digital centroid track technique with automatic target detection and centering. A point track sub-mode permits acquisition and tracking of long range or small air to air targets.

Target State Estimator

The sensor/tracker includes a software-implemented Kalman filter resident in the 1750A general purpose computer within LRU 1. This Target State Estimator (TSE) is derived from the AN/APG-68 radar TSE. The sensor/tracker TSE runs at a 30 Hz rate.

The function of the TSE within the automated maneuvering attack system is depicted in Figure 8. The TSE fuses time tagged range and range rate data

with laser range and sensor head line of sight measurements. Estimated target position output of the TSE is provided to the AMAS director algorithms in platform coordinates to reduce ownership-induced output data variations entering the flight control command loop. In air to air operations, TSE outputs are target relative position, inertial velocity, and acceleration. For air to ground tracking, only position and velocity are provided.

INTERFACE AND OPERATIONS

The sensor/tracker is functionally integrated with the AFTII/F-16 mission avionics suite as shown in Figure 9. Communication between the sensor/tracker set and the aircraft avionics is achieved primarily over the MIL-STD 1553 (A Mux) bus. In addition to this bus interface, there are our discrete signals, three INU synchro signals, an RS-170 video coax and aircraft power lines.

The sensor/tracker's automated operations are initiated when the pilot selects his AFTII/F-16 weapons system mode. The Fire Control Computer (FCC) initiates the sensor/tracker, runs its built-in test, and sets its operational modes. As shown in Figure 10, the FCC cues the sensor/tracker to acquire and track a target using the appropriate MU, HUD, radar, or helmet mounted sight (HMS) command. Target acquisition and tracking is automated via the video tracker and automatic target centering features are available in either air to air or air to ground modes. Target hand-backs are also readily achievable between the sensor/tracker and the cueing sensors. Once tracking is established, the sensor/tracker delivers the Kalman filtered target state estimate to the FCC.

Figure 11 shows the operating modes of the sensor/tracker system. Correct mode selection depends primarily on the current FCC sensor manager state and involves a minimum of pilot switch actions. Automatic task-tailored mode selection was necessary to optimize one man weapon delivery. An additional sensor/tracker mode not listed on Figure 11 is a special simulation test mode for field or in-flight evaluation of the TSE. This mode permits operation of the TSE software with the head in the lowered position or even with the head LRU removed from the aircraft. In this mode, the processor responds to mode control and some sensor control commands even when the head LRU is absent.

Pilot interface to the sensor/tracker is designed so that the critical weapon delivery related functions are located on hands-on controllers to provide quick reaction inputs. The important task of slewing the sensor/tracker line of sight is accomplished using the cursor controller on the throttle. Target designation and return to search actions are controlled with the pilot's right thumb on a switch located on the sidestick controller. A display of interest switch is also located on the sidestick controller to allow selection of the desired sensor display. A "sinky" switch on the sidestick controller allows the pilot to manually change sensor/tracker fields

of view. Manual laser fire is accomplished by pulling the gun trigger on the control stick.

Less critical sensor/tracker control functions are located in the forward area of the cockpit, as are the primary sensor/tracker displays. The majority of the sensor/tracker controls and displays are provided to the pilot by means of either of the two 4-inch CRT multifunction displays (MFDs) located high on the forward instrument panel. There are two basic MFD formats for the sensor/tracker, the base page and the control page. The base page, shown in Figure 12, contains mode annunciation, image derotation scheme selection, field of view indication and back-up selection, video polarity selection, cursor zero indication, aimpoint indication, slant range indication, time to release readout, gain control, and laser arming status. The control page, shown in Figure 13, permits entry of engineering data words, video level control, focus trim and boresight corrections. Both MFD pages can display sensor/tracker video and symbology as well as the alphanumeric information discussed above. Certain sensor/tracker displays are also available through the HUD. During air to ground tracking operations, a crosshair is displayed over the target on the HUD. A small flashing "L" is displayed on the HUD when the laser is firing.

TEST RESULTS AND CONCLUSIONS

Westinghouse delivered the complete, flightworthy sensor/tracker equipment to General Dynamics in November 1984 for avionics system integration and ground testing. This activity was completed in early April 1985 and the system delivered to Edwards AFB for aircraft installation and checkout. The first sensor/tracker flight occurred on 24 April 1985. From first flight until the end of 1985, the sensor/tracker was available to support 34 of the 60 AFTII/F-16 flights. At the end of 1985, the sensor/tracker development had reached the point where the system could fully support coupled automated bombing deliveries. Air to air sensor/tracker capabilities have not yet been thoroughly tested as of this writing.

Delays in maturing the sensor/tracker system during this period to a fully operational state can be attributed to two broad classes of problems: (1) aircraft interface, and (2) sensor/tracker reliability and performance. Interface problems tended to cue the sensor/tracker to the wrong location or to prevent accurate control of the sensor/tracker line of sight. Fire control computer cueing logic errors, cursor control shortcomings, and boresight inaccuracies in the radar, HUD and helmet mounted sight are examples of the interface problems that had to be overcome.

Overall reliability of the sensor/tracker system has proved better than expected of a new FLIR design. However, because it is a one of a kind unit with a very limited spares pool, hardware failures inevitably resulted in some down time. The test history shows the Digital Scan Converter (DSC)

to have the lowest subsystem reliability caused mostly by mounting failures of the leadless chip carriers on the printed circuit boards. Several DSC component failures and a board loss have also been experienced. Additionally, the interface of the DSC and its supportability have either directly or indirectly accounted for a significant amount of down time. The DSC used is a modified preproduction unit built for the Army Helicopter Improvement Program. A recent acquisition of a similar set of boards, the growth of support capability and a reworking of the LCC mounting should significantly alleviate these problems.

Failures in the early part of the program also included significant detector artifact problems and detector cooling problems. Considerable downtime was experienced when engineering design changes were made to extend or improve performance. More recently, several power supplies had component failures.

The performance of the FLIR/laser system as originally delivered to the aircraft was barely adequate to support automated bombing at operationally relevant ranges. Performance improvements incorporated early in the course of flight testing have brought tracking performance up to design prediction levels. These improvements include a new thermal reference assembly, a revised target detection filtering technique, use of 8-bit histograms in the tracker versus the original 6-bit, and adjustment of tracking threshold settings. A laser receiver modification was also necessary to achieve acceptable laser range performance.

The flight test results are positive. Controlled tests revealed no adverse coupling effects. Dero servo elasticity tests were performed at maximum delivery airspeed without adverse effects. Most importantly, non wings level automated bomb deliveries with improved sensor/tracker tracking and laser ranging were successfully accomplished in late 1985.

To bring the system up to operational capability, the pilot workload needs to be decreased. This will be readily accomplished by eliminating aircraft range interface problems, improving cursor rates and incorporating sensor/tracker improvements. These improvements include adding adaptive gate sizing, and minimizing pitch coupling into the gimbals. With the operational workload reduced, a continued successful flight demonstration and development is indicated. This will provide the technical and operational design baseline needed to transition this or follow on sensor/tracker development efforts with maximum confidence and minimum technical risk.

In summary, the FLIR sensor/tracker program has been a successful sensor development and system integration effort. The equipment, with its early improvements, has fulfilled its air to surface test objectives and performed well in flight. It has also pointed the way to further refinements in the pilot-vehicle interface. The sensor/tracker's air to air testing, begun in late 1985 will be continuing throughout the remainder of FY 86.

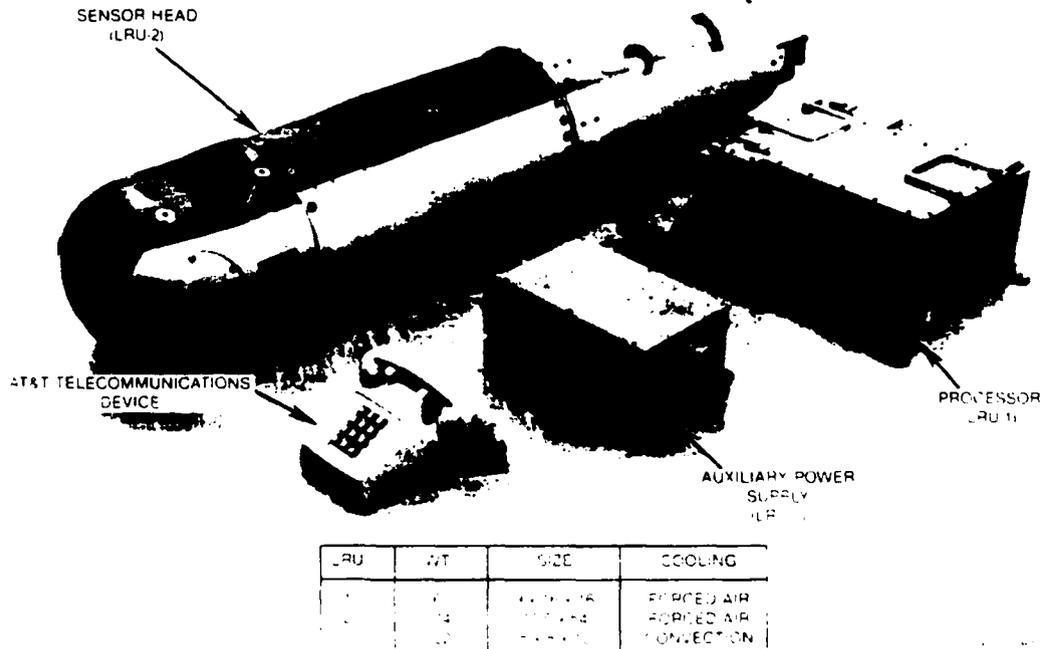


Fig 1. Sensor/Tracker Line Replaceable Units

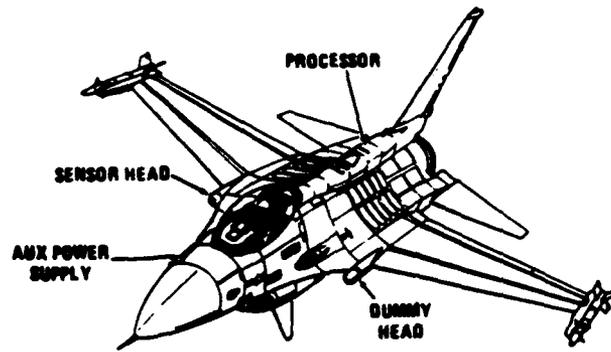


Fig 2. Sensor/Tracker Aircraft Installation

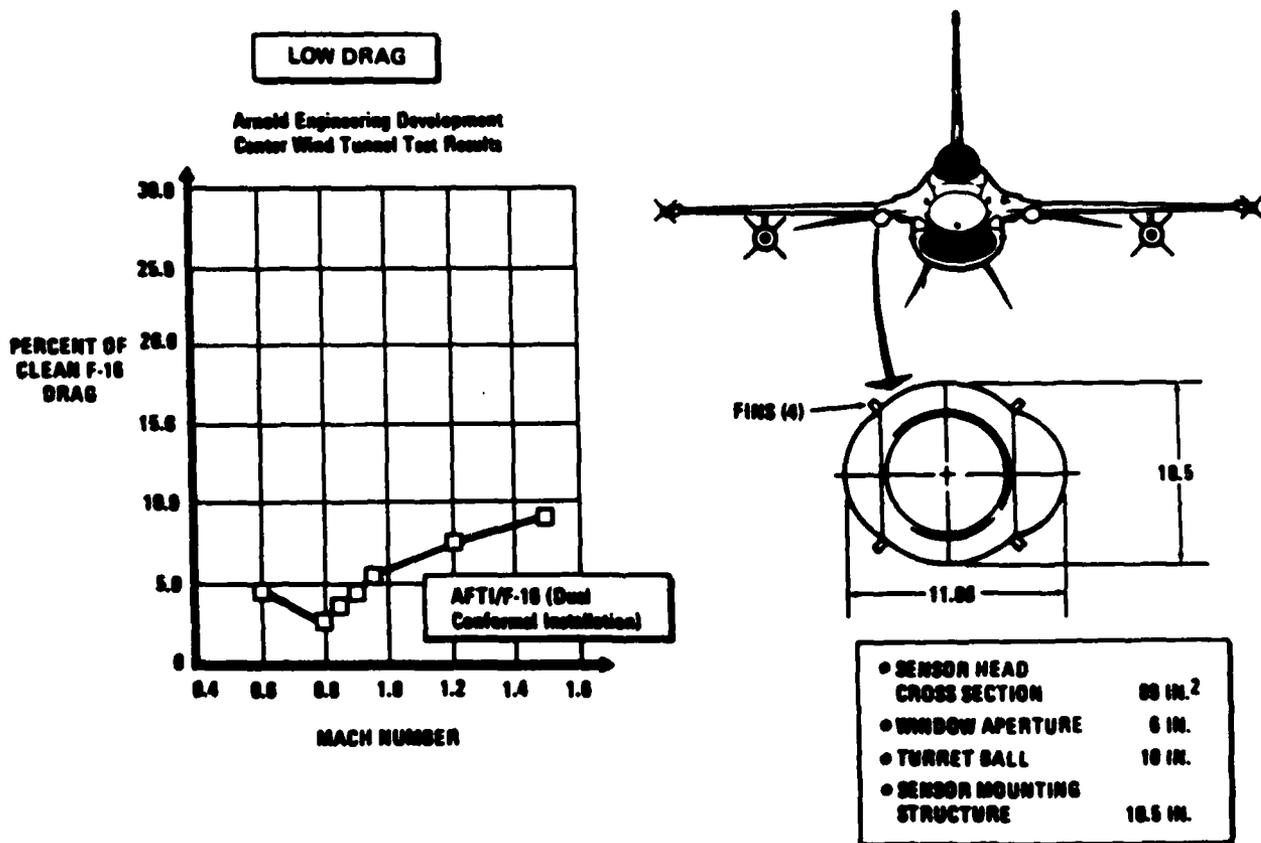


Fig 3. Low Drag Conformal Strake Installation

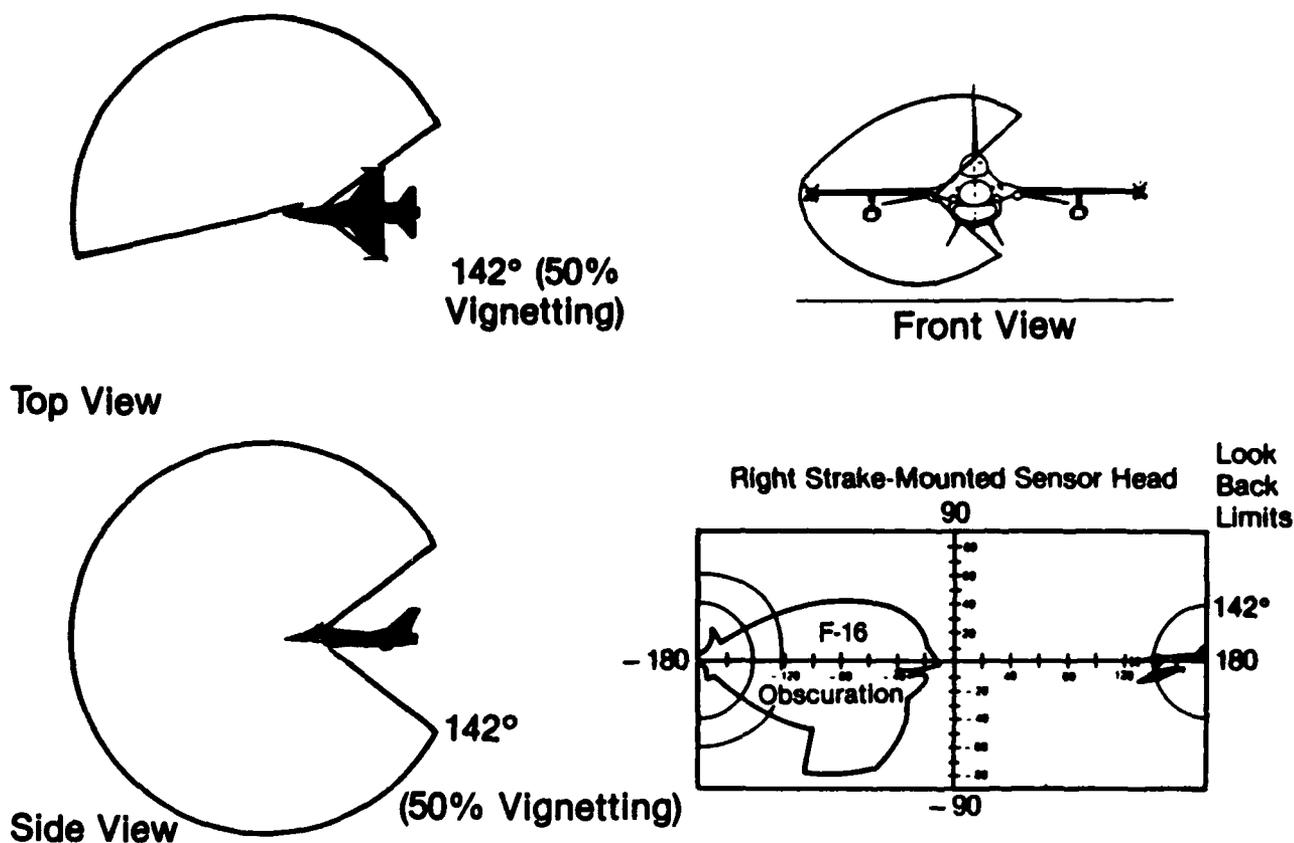


Fig 4. Sensor/Tracker Field of Regard

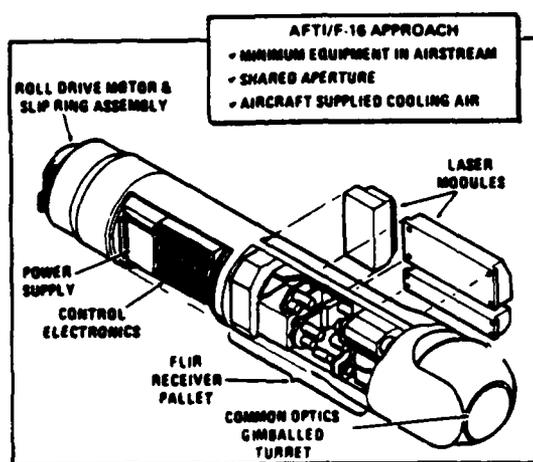


Fig 5. Sensor/Tracker Head Partitioning

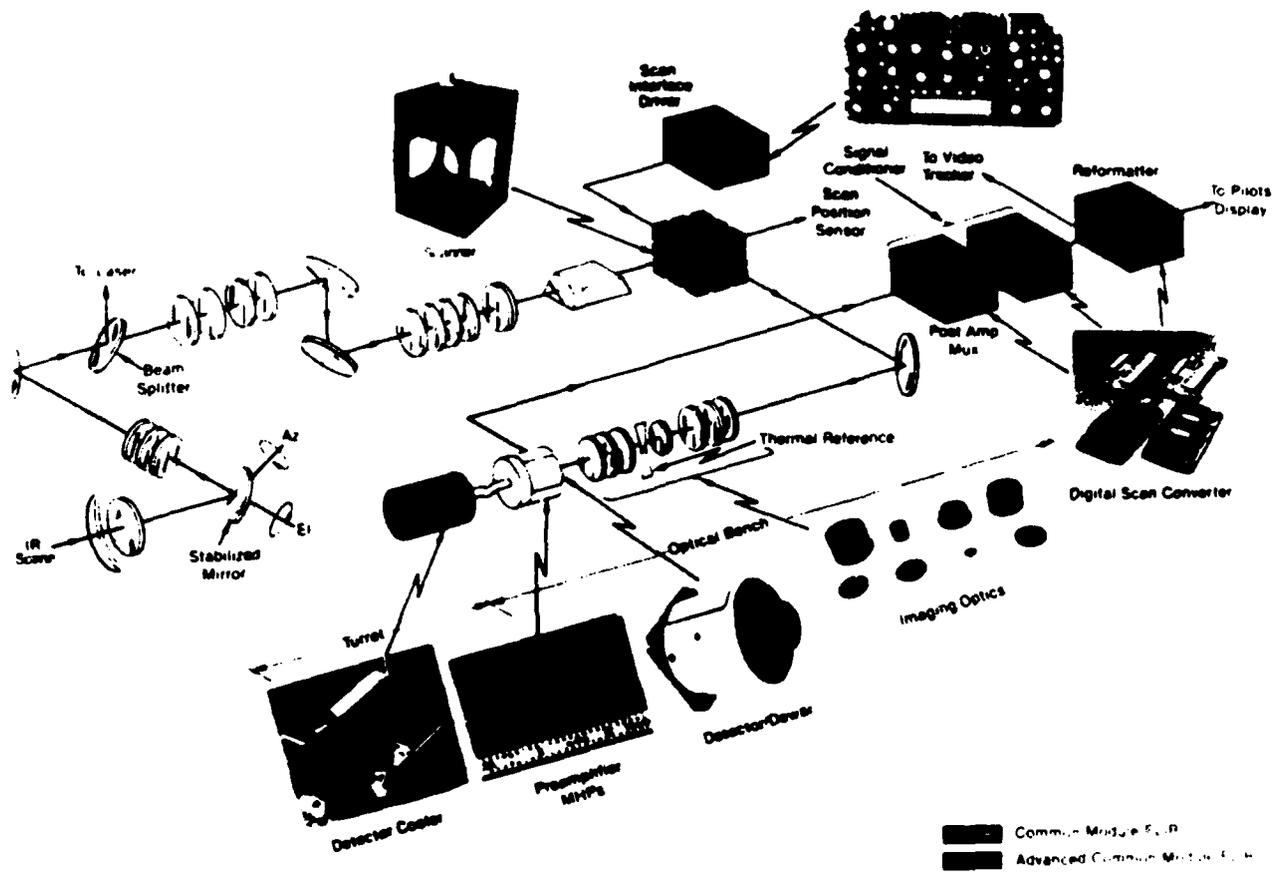


Fig 6. FLIR Section Components

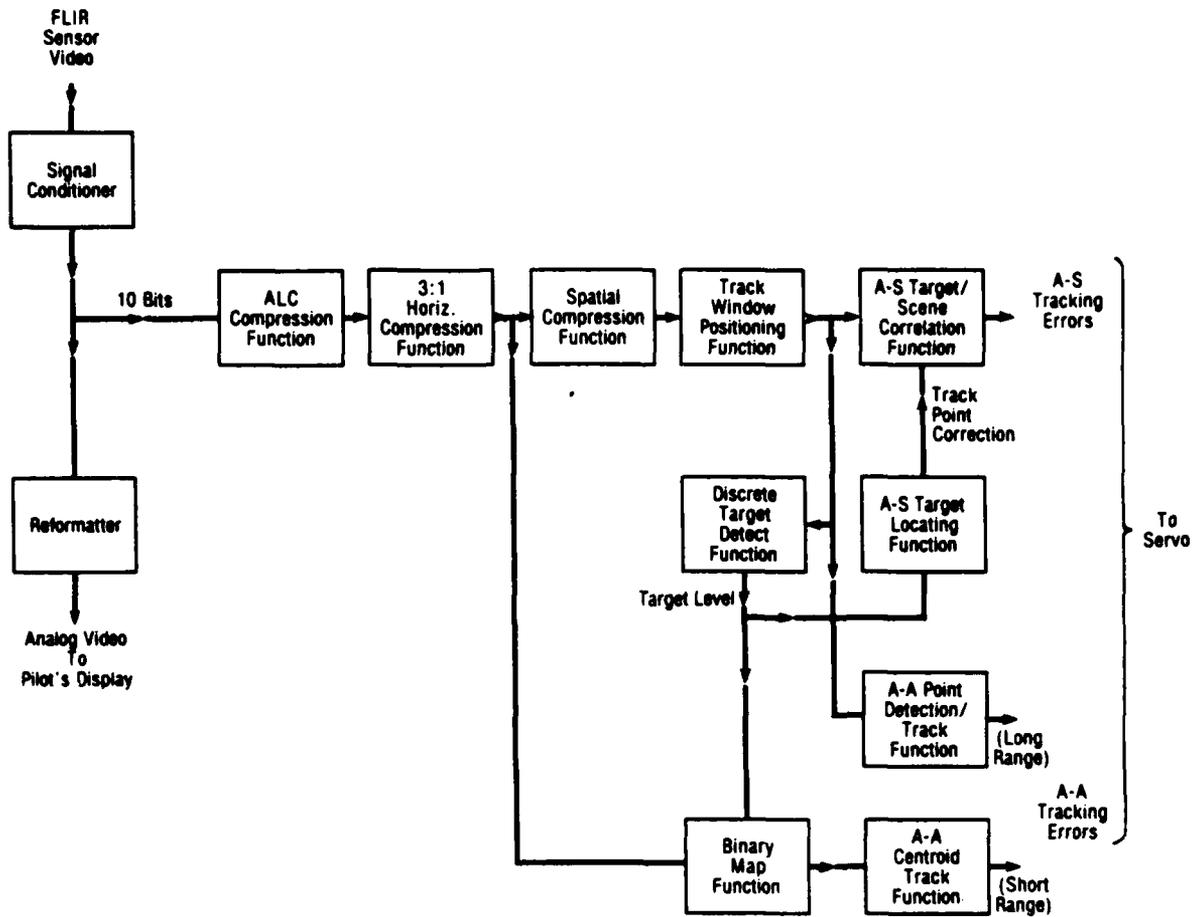


Fig 7. Video Tracker Signal Flow

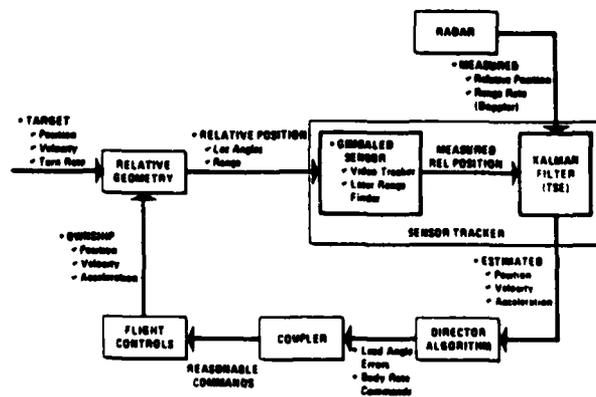


Fig 8. Kalman Filter Provides Target State Estimates

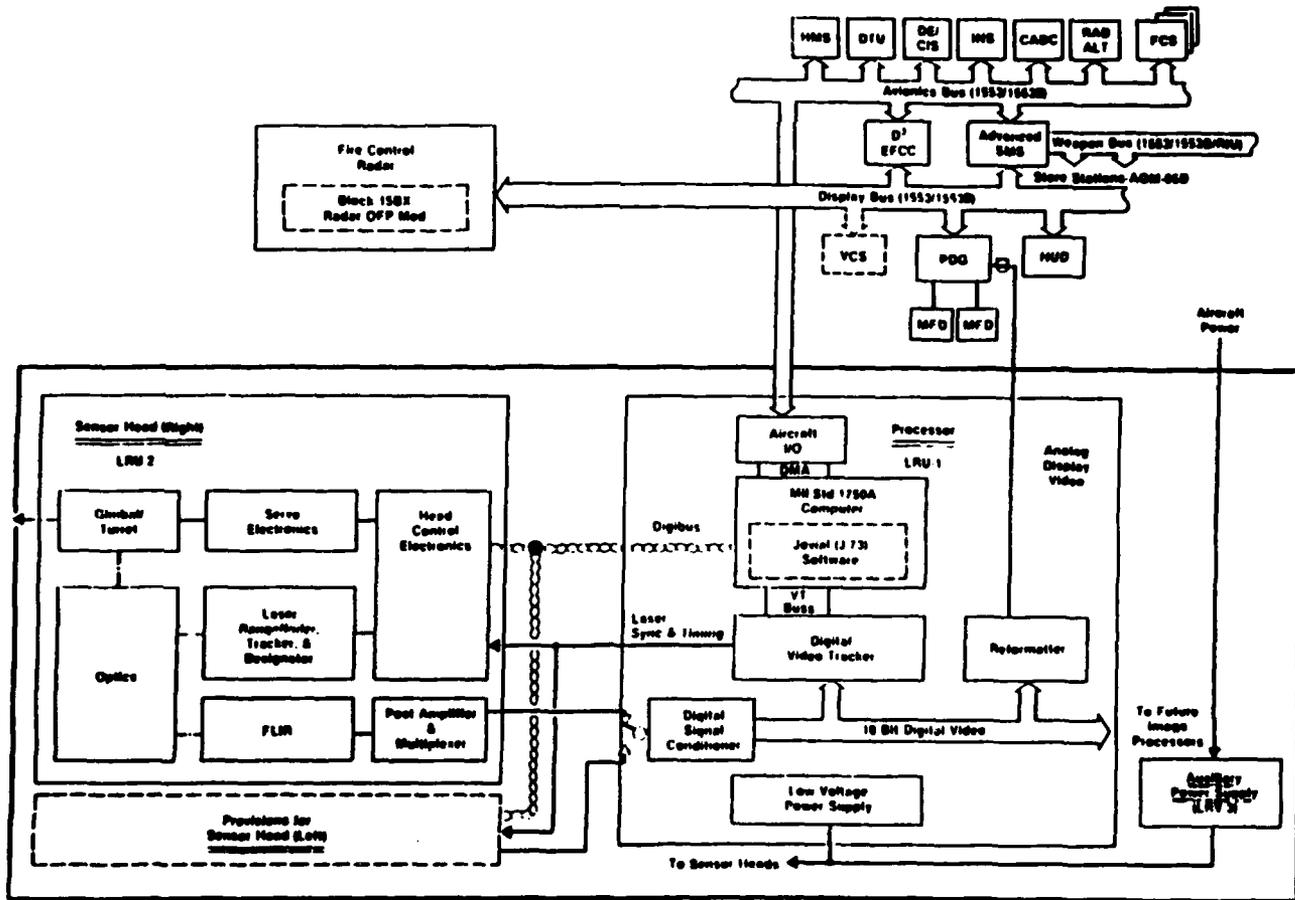


Fig 9. Sensor/Tracker Interfaces

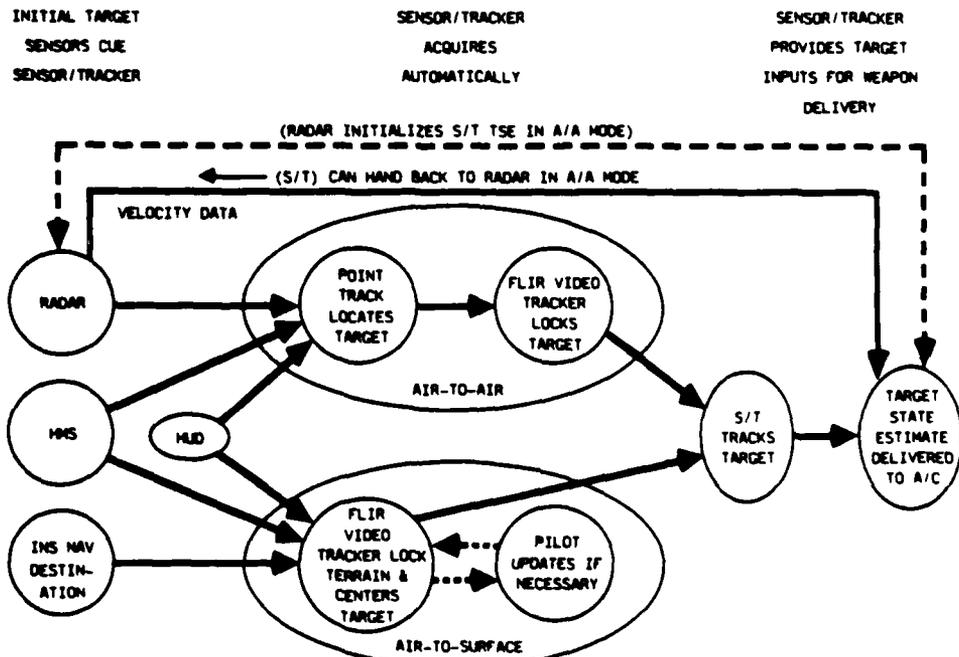


Fig 10. AFTI/F-16 Sensor Fusion

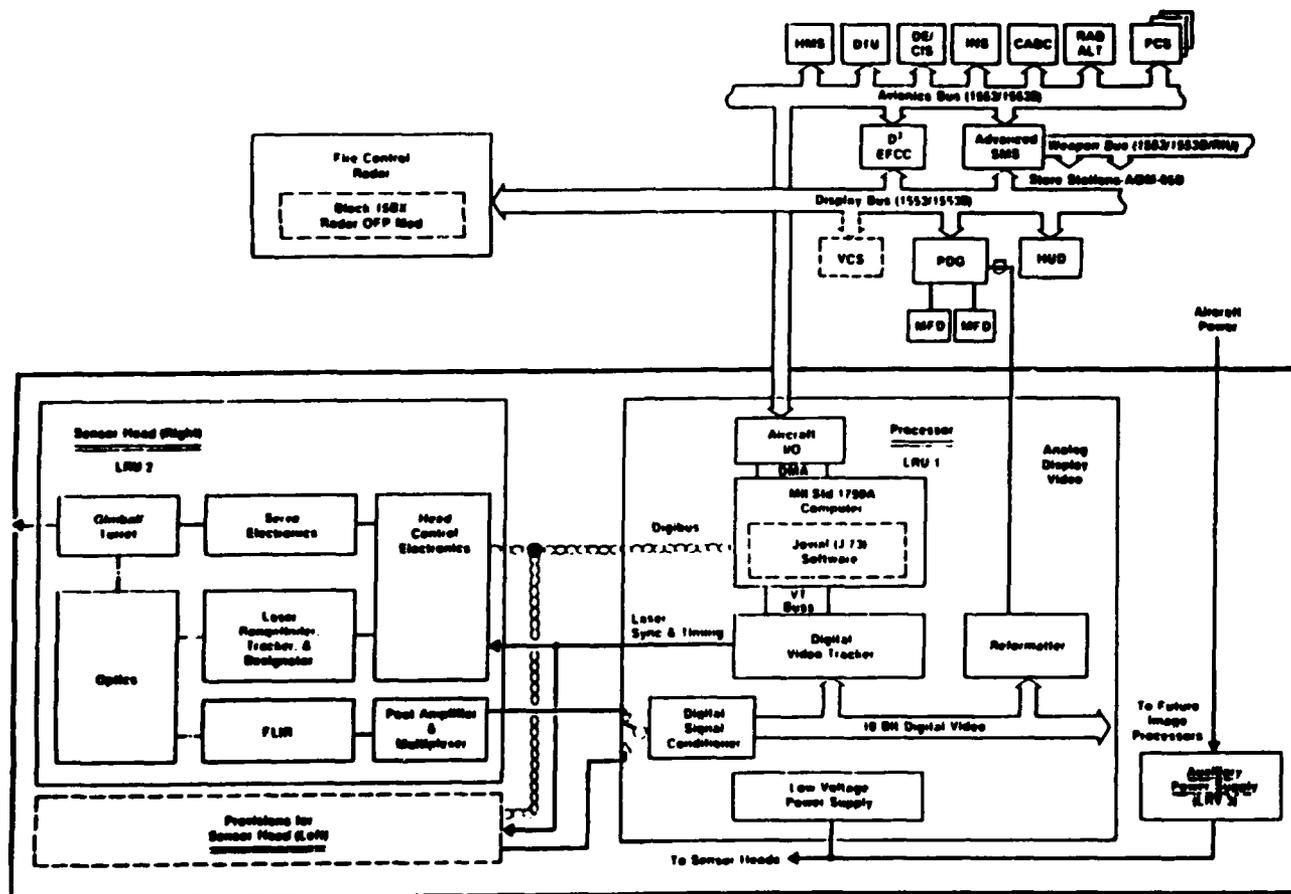


Fig 9. Sensor/Tracker Interfaces

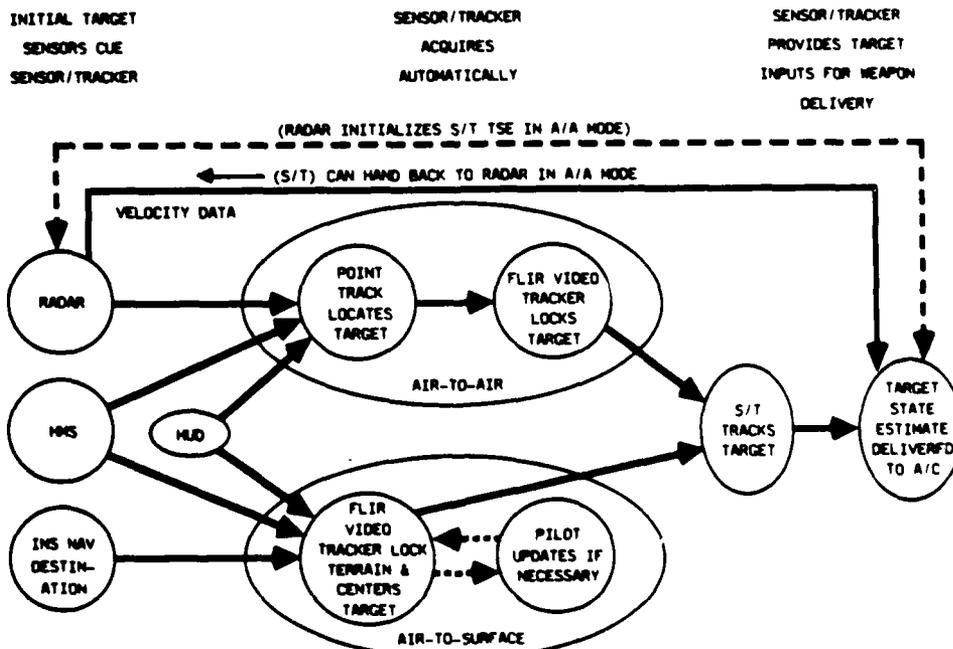


Fig 10. AFTI/F-16 Sensor Fusion

SENSOR TRACKER MODES	
• STANDBY (Head Stowed)	
• SLOW (Cue Not Attained)	
• CUE	
• Ready (Az = 0 - 0)	
• Dynamic (Body/Platform Coord)	
• Modulated (SCAN, ROTATE)	
• A/A TRACK	
• FLIR Passive Acquisition	
• POINT	
• CENTROID	
• A/S TRACK	
• SCENE (Correlation)	
• DISCRETE TARGET	
• TRACK ADJUST (Ground Stabilized)	
• COAST (A/A 5 Seconds, A/S 10 Seconds)	
• BIT	

Fig 11. Sensor/Tracker Modes

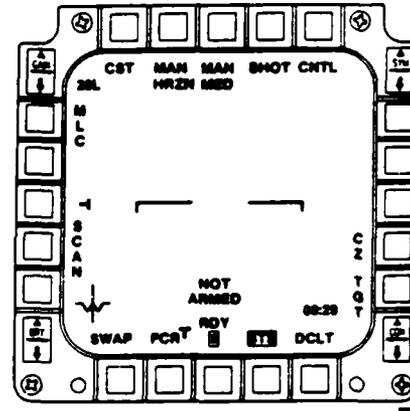


Fig 12. Base Page

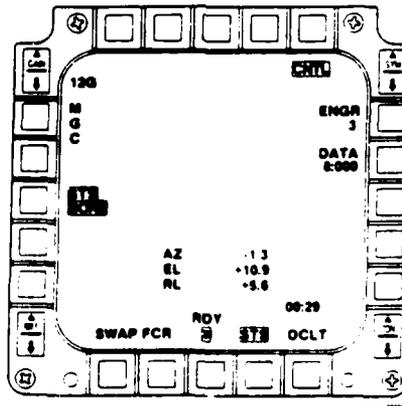


Fig 13. Control Page

AFTI/F-16 Automated Maneuvering Attack System AMAS

Guidance and Control

M. R. Griswold

AFTI/F-16 AUTOMATED MANEUVERING ATTACK SYSTEM

AMAS GUIDANCE AND CONTROL

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ABSTRACT

The guidance and control for the AFTI/F-16 Automated Maneuvering Attack System (AMAS) uses a multimode distributed processing network to perform the basic task of steering the aircraft to a continuously computed weapon delivery condition. The major functional elements of this system are target-state estimation, weapon-delivery solution computation, and light-path control. These elements form a closed-loop, dynamic system with the attendant issues of stability, accuracy and transient response. AMAS is a highly integrated, complex system and this is reflected in the guidance and control algorithms. Both aerial gunnery and bombing modes are supported by the use of various targeting options and full-pilot blending and override. In addition to the basic weapon delivery system, a radar-altimeter-driven autopilot mode is provided to allow the pilot more time for targeting and monitoring tasks.

SYSTEM OVERVIEW

The AFTI/F-16 Automated Maneuvering Attack System is a fully integrated, tactical, weapon delivery system that addresses all phases of the terminal attack mission. For bombing, this includes automated ingress steering, real-time target acquisition and tracking, weapon delivery and egress. For aerial gunnery, it covers target acquisition and tracking, terminal steering and breakaway. Comprehensive system health monitoring and collision avoidance is active at all times.

The closed-loop guidance and control system provides the necessary processing to accomplish target-state estimation, steering command generation and light-path control. These functions are partitioned into three major subsystems on the aircraft. Target tracking and target-state estimation is primarily performed by the advanced AFTI/F-16 Sensor/Tracker Set (STS). Steering commands are computed in the Fire Control Computer (FCC) based on STS data and ownship state data. Flight-path control is accomplished by the Flight Control System (FCS). All signals between subsystems are carried by a MIL-STD-1553 multiplexed data bus. Figure 1 depicts this arrangement. While the bombing and gunnery systems are conceptually similar, they are quite different in practice, and will therefore be described separately.

The AFTI/F-16 STS is a conformally-mounted, high-field-of-regard electro-optical (EO) sensor. This system employs an infrared detector for angular measurements, a closed-loop video autotracker and a laser ranger. Target-state estimation is performed by a 9-state

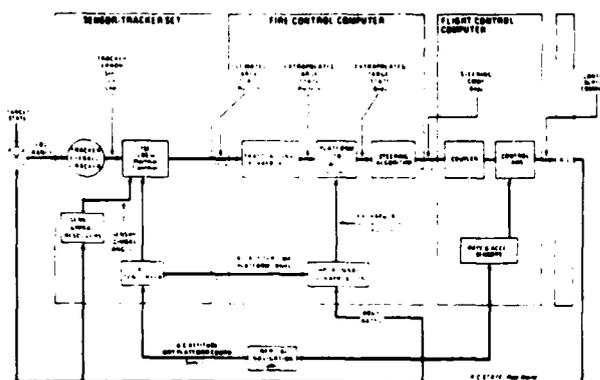


Figure 1 AMAS Outer Loop Signal Flow

Kalman filter, driven by video-tracker errors, and augmented by ownship velocity and acceleration terms. The range channel can be driven by the laser ranger, by the FCC (during acquisition), or by the fire control radar (FCR). Estimation is performed at a 30-Hertz rate utilizing an inertially stabilized reference frame.

The FCC is a general-purpose computer that performs the basic tasks associated with navigation, fixtaking, and weapon-delivery solution. The FCC accepts target-state data from the STS (and other sources during bombing) as the primary inputs to its AMAS steering computations. The FCC relates target state with ownship state to derive various steering commands depending upon the steering mode in effect. When the low-altitude radar autopilot (LARAP) is active, the FCC conditions above-ground-level (AGL) altitude data from the radar altimeter (RALT) and the forward-looking radar, performing source blending and antenna control.

Flight-path control is performed in the FCS by nulling the steering commands from the FCC. Conditioning of the various steering signals is accomplished prior to summing them into the basic stability and control augmentation control laws. Pilot blending and override is also accomplished by the FCS. In general, the automated system has the full-command authority in all axes. Structural limiting and anti-departure control is performed by the FCS.

AMAS BOMBING SYSTEM

AMAS can perform two basic types of bombing deliveries. The first is a constant-altitude, straight-in, wings-level (WL) delivery. In this mode, the automated

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system provides lateral steering to null bomb miss distance while maintaining aircraft altitude. Any vertical maneuvering is performed by the pilot. The second delivery option, and the one achieved by default, performs a high-G, non-wings-level (NWL) turning delivery as depicted in Figure 2.

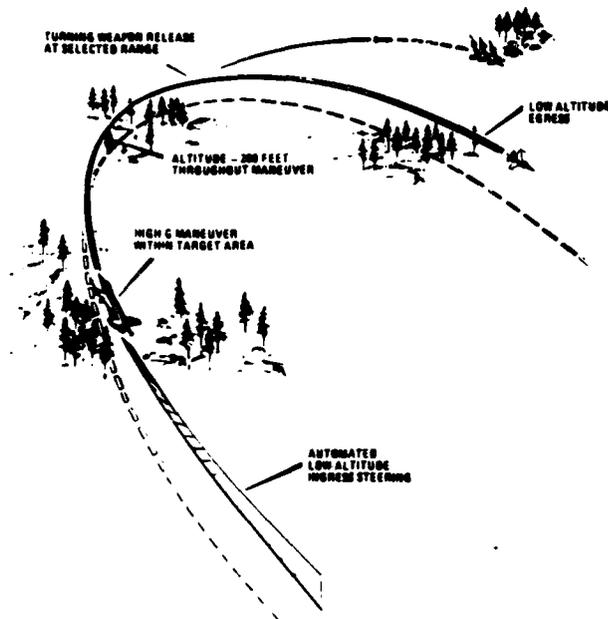
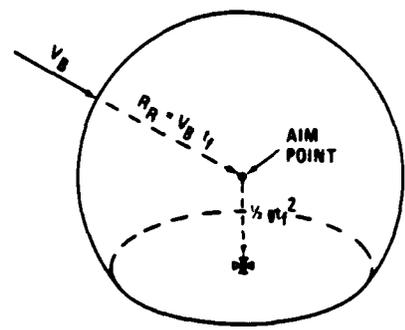


Figure 2 NWL Bombing Delivery

The AMAS bombing scenario can be considered in three parts. These parts correspond to three phases of the attack scenario, each of which requires a different steering algorithm. In the first mission phase, ingress, the system is steering toward a computed transition point at which terminal steering will be initiated. At the transition point, terminal steering is invoked to steer the aircraft to the weapon-release point. Following the delivery, the egress phase is entered; a graceful transition away from the target area is performed in this phase. During the terminal phase, the type of steering algorithm depends upon whether a WL or NWL delivery is being flown.

Targeting for AMAS bombing can be accomplished in two ways. To ensure highest accuracy, the STS should be locked onto the designated target. Initial cueing of the STS can be accomplished using preplanned inertial coordinates, the fire control radar, or the helmet-mounted sight. Once the target is locked up, the pilot can refine the track point by observing target video. In lieu of STS tracking, the bombing system will operate from inertial extrapolation of target position.

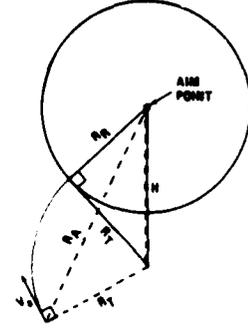
The characteristics of a NWL bombing solution allows two problem approaches. A spherical solution set exists (shown in Figure 3) around the aimpoint which is displaced from the target by approximately the bomb gravity drop during its time-of-fall. At release, the bomb velocity vector must be directed towards the aimpoint. This implies that the range to the aimpoint at release must be tangent to the aircraft flight path. Figure 4 depicts a two-dimensional view of the NWL bombing geometry. A unique solution exists for a given range,



- 1) AIM POINT DISPLACED FROM TARGET BY GRAVITY DROP
- 2) VELOCITY VECTOR IS DIRECTED TOWARDS AIM POINT AT RELEASE

Figure 3 Bombing Solution Set

A UNIQUE SOLUTION EXISTS FOR A GIVEN RANGE, VELOCITY, AND ASPECT ANGLE IF ONE UNKNOWN IS ASSUMED



P R O B L E M	ASSUME: V_A Constant
	KNOWN: R_A
	UNKNOWN: R_T, R_R, H
EQUATIONS: Solid Triangle Dashed Triangle	
S O L U T I O N	Assume R_T or R_R and Solve for Unknowns

- V_A - Aircraft Velocity
- R_A - Release Range
- R_T - Range to Aimpoint
- R_R - Turn Radius

Figure 4 NWL Bombing Solution Geometry

velocity, and target bearing if one unknown, either release range or turn radius, is assumed. The first solution of the NWL guidance problem assumes aircraft load factor (and therefore turn radius) as the independent variable. There is then only one tangent to the flight path containing the aimpoint and it defines the release range. In this approach, roll attitude is the only aircraft state requiring control in order to maintain the turning plane orientation. The second solution of the NWL guidance problem assumes release range as the independent variable. With this approach, there is only one turn radius (load factor) which intersects the release range with a tangent line drawn from the target. Both load factor and roll attitude must be controlled to maintain the proper turning plane. Both of these approaches were designed and simulated during AMAS development. The second method - predetermined release range, was selected for implementation.

The computation of the NWL steering algorithm is based on an iterative process. The basic geometry of the NWL guidance problem is shown in Figure 5. The inputs to the algorithm include the aircraft velocity vector, acceleration vector, target range vector, wind, and the preselected release range. An aimpoint is determined above the target and a vector (R_A) is defined from the aircraft to the aimpoint. This vector and the aircraft

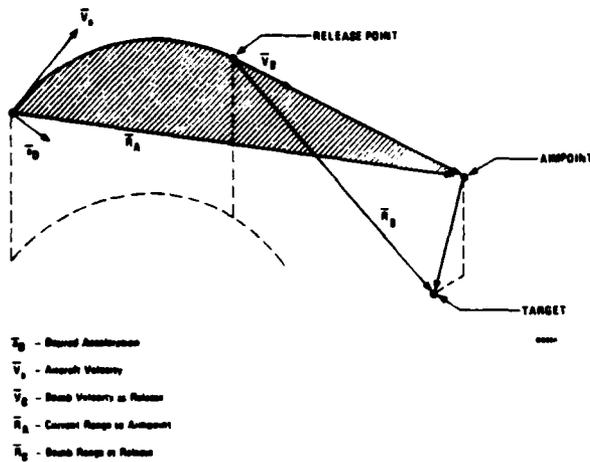


Figure 5 NWL Bombing Geometry

velocity vector define the turning plane. The point in this plane which meets the selected release range is the release point. A desired acceleration vector that will point the aircraft velocity directly at the aimpoint when the aircraft is at the release point is computed. The time-to-go to the release point is calculated and the aircraft flight path is projected over the time-to-go to the release point giving a release velocity vector and altitude above the target. A ballistic trajectory integration routine is then used to compute the ground impact point and the miss distance is determined. Based upon the miss distance, the aimpoint is adjusted through a rate-limited feedback path and the process is repeated as shown in Figure 6.

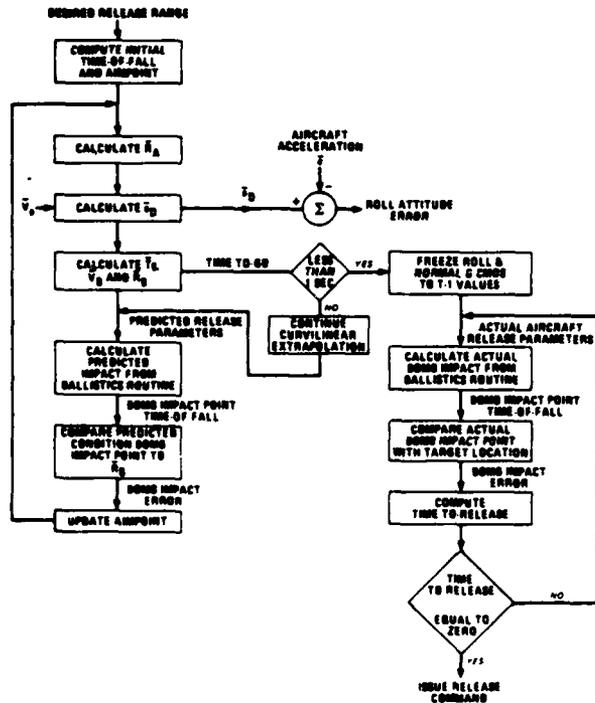


Figure 6 NWL System Equation Flow

Normally, extrapolated aircraft states are used as inputs to the ballistic trajectory computation. The solution converges quite quickly, however, and analysis has shown that further attempts to refine the steering commands during the last second of the delivery do not result in more accurate deliveries. At one second time-to-go, the steering commands are frozen and actual aircraft states are used as inputs to the ballistics calculations. Time-to-go is then computed using the rate of change of the predicted miss distance, and the weapon is dropped when the miss distance along the bomb track reaches zero.

The output of the iterative loop described above is the desired aircraft acceleration vector. This desired acceleration vector is matched with the actual acceleration vector by commanding bank angle and normal acceleration. The desired acceleration is used by the FCS directly to command normal acceleration. The bank angle error is determined by the cross product between the desired and actual acceleration vectors. Since the bombing geometry is continuously computed, the desired acceleration will decrease as the aircraft turns into the target. In order to maintain a high G delivery, the magnitude of the commanded acceleration is frozen when it is determined that the steering has converged (i.e., commanded acceleration close to actual acceleration).

The FCS interface for NWL bombing consists of roll attitude errors and normal acceleration commands. The roll attitude error is limited, blended with any manual pilot commands and fed into the roll rate feedback path of the inner-loop control laws. The normal acceleration command drives both the G and pitch rate command path in the longitudinal inner loop. To avoid excessive altitude variation during the NWL steering transition (due to rapid G onset), the acceleration command is conditioned as a function of roll-attitude error to provide a smoother transition (see Figure 7).

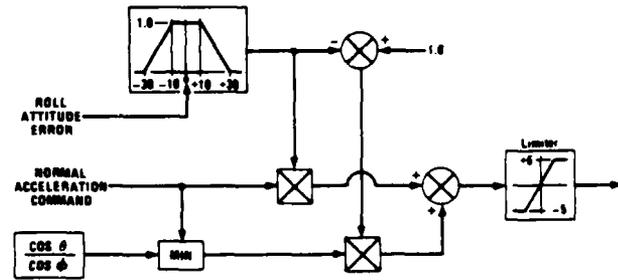


Figure 7 NWL G Command-Blending Logic

The tactical benefits derived from a NWL weapon delivery largely depend on maintaining a high turn rate throughout the delivery. Since the target range and bearing are important parameters in determining the turn rate required, careful setup is required for a successful NWL attack as shown in Figure 8. Since one of the major AMAS goals was to reduce pilot guidance workload, an automated ingress steering function was designed. This function provides azimuth steering commands to assure a successful high-G NWL attack from arbitrary initial geometries (including reattack steering following weapon delivery).

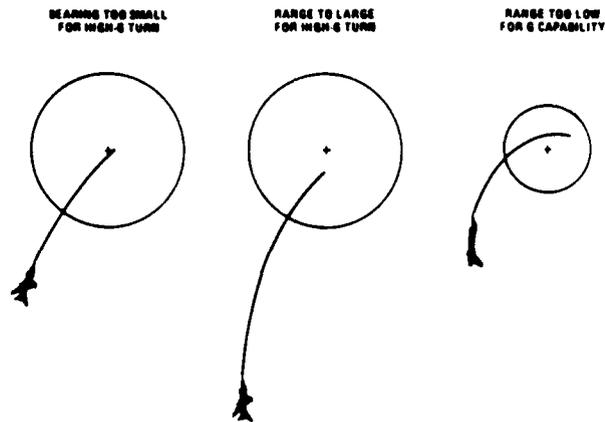


Figure 8 NWL Setup Problems

The operation of the ingress steering function depends upon the aircraft position relative to the target. The region around the target is divided into three zones, shown two-dimensionally in Figure 9. The sizing of these zones is determined by the preset release range and the minimum turn radius (a function of velocity and maximum G level). Within zone A the aircraft is clearly too close to the target. In this case, the ingress steering function performs a check turn to steer away from the target. The zone B-C boundary represents the transition point from ingress steering to NWL steering. If the aircraft intercepts zone B with a 90-degree bearing to the target, it can theoretically perform a max-G turn to the release point. Zone C steering then drives the aircraft toward this boundary. In reality, it is not practical to drive to a 90-degree bearing. Aircraft response time and variations in flight condition during the delivery require that the bearing be somewhat less than 90 degrees. The azimuth steering error is determined by

$$\epsilon = T_{BRG} \pm \sin^{-1} (.707R_B / |\bar{R}_A|)$$

T_{BRG} = Target Bearing.

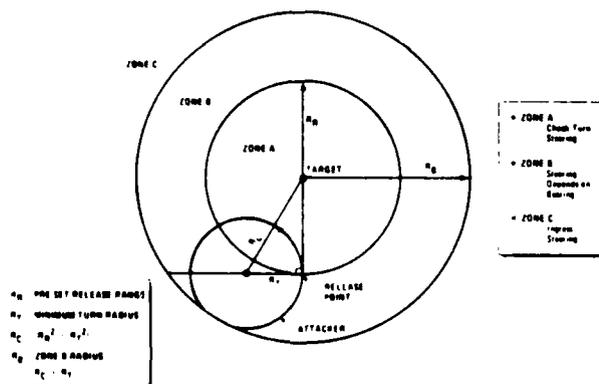


Figure 9 Steering Zone Geometry

Within zone B it may still be possible to transition to NWL steering if the target bearing is small enough.

The maximum target bearing for the current aircraft conditions is given as

$$\sin^{-1}((R_A^2 - R_R^2)/2R_A R_R).$$

If the actual bearing is less than the computed maximum, the system will transition to NWL steering. If the actual bearing is too large, the system will attempt to salvage the delivery by automatically decreasing the weapon release range until a delivery can be achieved or until the minimum release range (3000 ft) is reached. If no NWL delivery can be realized, a check turn is executed. The type of check turn performed depends on the target bearing when the check turn is initiated. Figure 10 shows the geometry of the check-turn options.

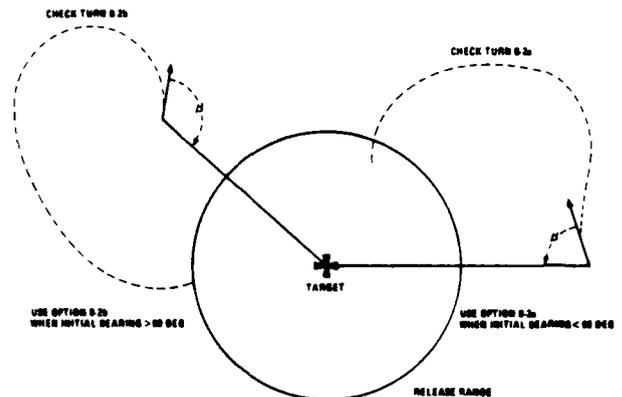


Figure 10 Ingress Steering Check Turn Options

Since the automated ingress-steering function only provides lateral guidance, a separate function is provided for altitude control. This system, referred to as the Low-Altitude Radar Autopilot (LARAP), provides a basic altitude hold function using AGL altitude and altitude-rate-data provided by either the radar altimeter or forward-looking radar. A simplified block diagram of the LARAP control law is shown in Figure 11. At engagement the current aircraft AGL altitude is sampled and used as the reference altitude until LARAP is reengaged. The altitude error along with altitude rate is summed with the steady state G's required for the current bank angle to form a G command. The minimum LARAP hold altitude is 200 feet, which is 50 feet above the minimum descent altitude (MDA).

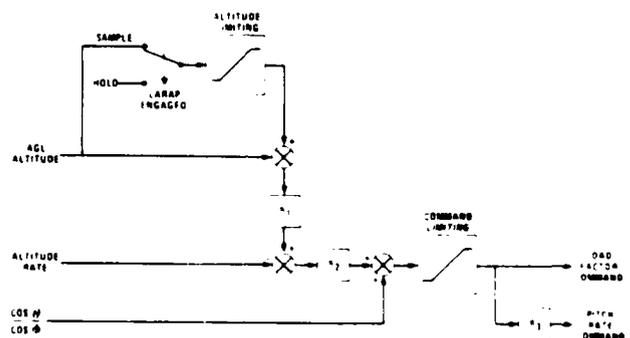


Figure 11 LARAP Block Diagram

LARAP is normally used in conjunction with the ingress steering function and during wings-level deliveries to maintain a selected altitude. LARAP can also be used as a stand-alone autopilot. In this mode, bank angle hold is also provided through a control-stick-steering type of mechanization shown in Figure 12. Prioritization between the pitch and roll channels is accomplished by the roll angle limiting function scheduled as a function of the G command required to null the proportional plus derivative altitude error. This causes the aircraft to roll towards wings level when additional G's are required to correct altitude errors.

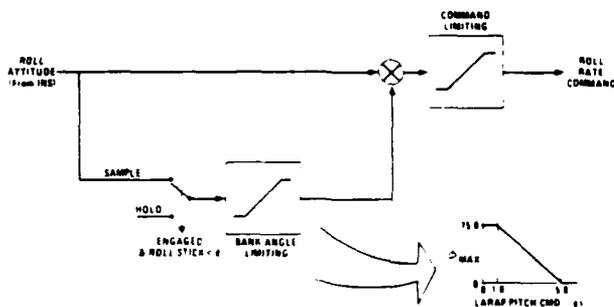


Figure 12 LARAP Bank Angle Channel

In addition to the NWL bombing system, AMAS can perform automated wings-level deliveries. This type of delivery is selected in one of two ways. The pilot can select a wings-level delivery during ingress steering, or the system may automatically switch to a wings-level delivery if it is initially engaged very close to the target with a small target bearing. The wings-level solution continuously computes a predicted bomb miss distance based upon actual aircraft states. The cross-track bomb miss distance is used to drive the lateral steering channel. When the along-track miss distance goes to zero, the bomb is released. In the wings-level mode only lateral steering commands are generated. To ensure altitude control, the LARAP system is utilized, or the pilot may manually control the pitch axis.

Lateral-steering commands are sent to the FCS in terms of steering (heading) error. This command is used to directly drive the APTI/F-16 flat-turn (direct side force), lateral-control mode. Since the turn rate provided by flat turn is fairly limited, a blending network is employed (see Figure 13) to command roll rate for large steering errors. This provides a quicker nulling of gross errors while retaining the superior fine tracking of flat turn for small corrections.

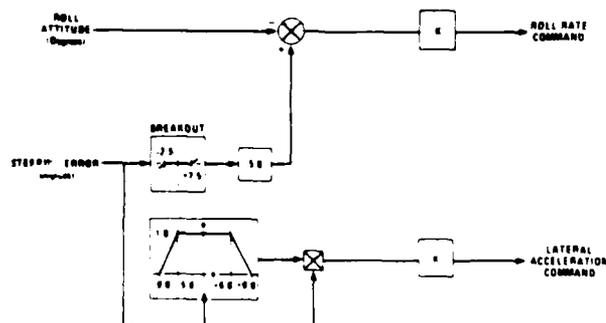
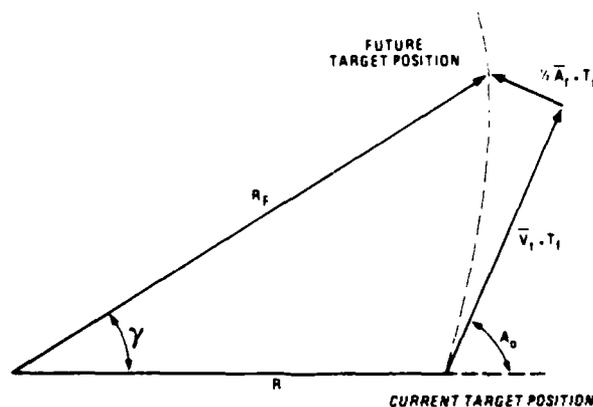


Figure 13 Ingress-Steering Command-Blending Function

Following weapon release, the automated egress steering function is activated to guide the aircraft to a preset egress altitude while maintaining a high turn rate. This is accomplished through a variation of the LARAP autopilot system. A predetermined egress altitude is set as the LARAP reference altitude for the sample and hold. To avoid pulling negative G's and still reach the egress altitude quickly, the aircraft bank angle is scheduled as a function of height above egress altitude. This results in a very aggressive, high-G slicing maneuver.

GUNNERY SYSTEM

The closed-loop air-to-air gunnery problem involves solving the lead-angle geometry problem, shown in Figure 14, and steering the aircraft to null the lead-angle error. In addition to nulling the lead-angle error, the inertial target rate must be matched for steady state tracking.



- R - Present Target Range
- R_f - Future Target Range
- V_t - Target Velocity
- A_t - Target Acceleration
- T_f - Bullet Time-of-Flight

Figure 14 Air-to-Air Gunnery Lead-Angle Geometry

Existing F-16 gunnery algorithms will not support closed-loop tracking, since they either do not compute lead terms (hot-line type), or they require the pilot to empirically determine inertial target rates by matching his aircraft rates with the target (LCOS). AMAS uses the director-type gun sight to compute lead angles by using measurements for both aircraft states and target states.

The AMAS gunnery system requires STS lockon for coupled operation. The STS may be cued by either the fire control radar or the pilot's helmet-mounted sight. Both the radar and STS are cued to a common line of sight. If either achieves a lockon, the other sensor will remain in a cue state until it also locks on.

The key to the director computation is the determination of bullet time of flight. Since the future bullet range is not known, it is not possible to solve for time of flight from the geometry alone. Two equations are therefore required, relating time of flight and bullet range. The first relationship is formed by considering the drag forces acting upon the bullet. For supersonic 20mm

bullets, the ballistic coefficient is inversely proportional to the square of the bullet velocity. Total drag, which acts on the bullet, can then be formulated and doubly integrated to determine the bullet range as a function of time of flight and initial bullet velocity (aircraft velocity plus muzzle velocity).

$$D_F = V_{BI} T_F - K_B \rho D_F \sqrt{V_{BI}} T_F$$

The next portion of the director time-of-flight calculation requires solving the basic geometry problem shown in Figure 14. This provides a relationship between bullet time of flight and future target range as a function of relative target states.

$$D_F = (R + V_t T_F \cos A_0 - .5 a_t T_F^2 \sin A_0) / \cos \gamma$$

Equating these two expressions yields a third-order, closed-form expression for bullet time of flight. The third-order term, not found in most gunnery solutions, arises from the target acceleration term. This target state is provided by the AFTI/F-16 sensor/tracker target-state estimator. For real-time considerations, the cubic equation is solved using an iterative (Newton's) method which yields

$$T_F = T_F - \epsilon / \left(\frac{\partial \epsilon}{\partial T_F} \right)$$

where (e) is the residual of the cubic equation solved at the current estimate of time of flight.

Instability in the time-of-flight solution can arise for certain geometries and flight conditions when the bullet cannot physically reach the target. Numerically, the solution will oscillate about a relative minimum or maximum. To prevent this, a dynamic limit on bullet range and time of flight is computed.

Given the bullet time of flight, target velocity, and acceleration, the target position can be predicted one time of flight into the future. The error between the current gun-lead angle and the required gun-lead angles can now be computed in azimuth and elevation (assuming the track is converging) as

$$A_{ZLAE} = \sin^{-1} (R_{RV} - R_{DV}) / R$$

$$E_{LLAE} = -\sin^{-1} (R_{RW} - R_{DW}) / R.$$

These parameters are coupled into the flight control system to be nulled. This mechanization provides a zero-order system which will develop steady state errors under accelerating conditions. In order to provide first-order control, rate-aiding terms must also be used. The required rate is essentially the derivative of the lead angle and is computed by dividing the future-target range rate by the future-target range (bullet range).

$$\dot{\omega} = \frac{\dot{V}(1 + \dot{T}_F) + A_t T_F (1 + \dot{T}_F) - \dot{V}_F}{R}$$

To provide a measure of compensation for the cross coupling between azimuth and elevation lead-angle error while rolling, the rate-aiding terms are modified as

$$\omega_{EL} = \omega_{EL} + P\omega_{AZ}$$

$$\omega_{AZ} = \omega_{AZ} - P\omega_{EL}$$

The basic, flight-control task is to null the lead-angle errors while matching the inertial target rates. Pilot command blending and structural limiting is also provided. The AFTI/F-16 air-to-air control laws provide dedicated feedback paths for all body rates as well as for lateral and normal acceleration. These same inner-loop control laws are used by conditioning the FCC-computed, lead-angle error commands, and lead-angle rate commands to provide body rate and acceleration commands. These signals are then summed into the inner-loop controls just as the manual pilot commands are summed.

The longitudinal command coupler is shown in Figure 15. The desired pitch-rate command is formed by the weighted sum of the elevation lead-angle error and lead-angle rate. After limiting, the rate signal is converted to an equivalent G command for pilot-command blending and structural limiting. The pilot-command blending function allows the pilot to bias the G command, as well as to completely override the command to the full opposite level. To add to the automated command, the pilot must first provide a manual input equal to the current automated command. Any additional manual command is then added to the automated command. Following structural limiting, the total-G command and the equivalent pitch-rate command is summed into the normal acceleration and pitch-rate command paths in the inner-loop control laws.

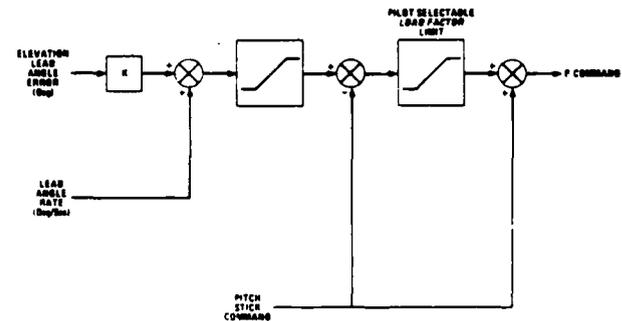


Figure 15 Longitudinal Command Coupler for Air-to-Air

The lateral-directional command coupler is somewhat more complex than its longitudinal counterpart (see Figure 16). For small tracking errors, the directional control axis can provide adequate performance. A weighted blend of lead-angle error and lead-angle rate is computed and converted into an equivalent G command. This command (after limiting) is summed into the inner-loop, lateral-acceleration command path. For large lead-angle errors, the best tracking performance is obtained by rolling the azimuth lead-angle error into elevation. It can then be nulled by the high-authority pitch channel. For this purpose, the lead-angle error is used to generate a roll-rate command. For low-turn-rate targets, it is also necessary to feed the azimuth lead-angle rate into the roll path to keep the target and ownship turning planes coincident. Since this path is destabilizing for moderate or high turn-rate targets, the gain in this path is scheduled as a function of aircraft normal acceleration.

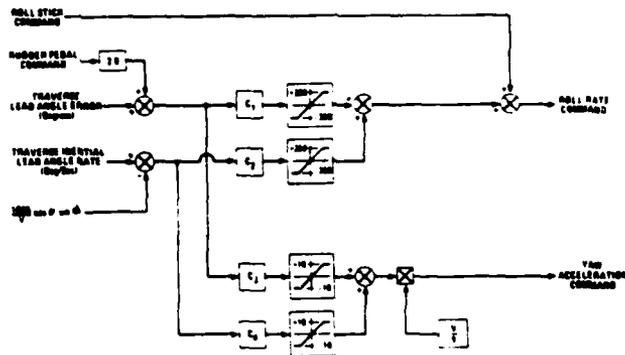


Figure 16 Lateral-Directional Command Coupler for Air-to-Air

Pilot-command blending is performed by summing the roll stick and rudder-pedal commands into the automated signals.

SUMMARY

The automated guidance and control of fighter aircraft in combat is a real technology. The development of the APTI/F-16 AMAS capability has yielded a system with high tactical applicability. The system is currently in the flight-test demonstration phase and is showing excellent results. On the basis of flight-test experience, additional changes are being made to the system to achieve maximum utility and effectiveness. The basic structure of the system is proving itself and points to the huge benefits that can be obtained from highly integrated systems.

Automated Maneuvering Attack System Safety Design

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A. M. Johnston
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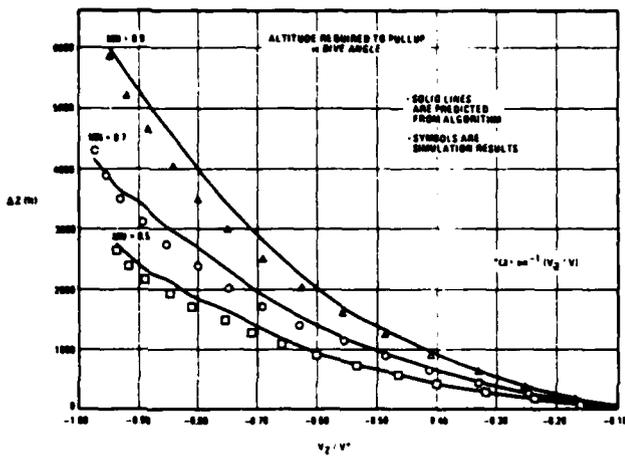


Figure 2 Wings Level Altitude Required to Flyup

A time-to-flyup is computed as follows,

$$t_{up} = \frac{AGL_{alt} - MDA - \Delta z}{-V_z}$$

- where: t_{up} = time-to-flyup
 AGL_{alt} = Above Ground Level altitude
 MDA = Minimum Descent Altitude
 Δz = GCAA predicted altitude required to flyup
 V_z = vertical velocity (positive in a climb)

The time-to-flyup is used to position a set of chevron symbols on the Head-Up Display (HUD). The chevrons are displayed on the HUD at five seconds to flyup and converge to an "x" as the time-to-flyup goes to zero (see Figure 3). The vertical bars on the chevrons denote, to the pilot, that the automated flyup is armed. In the AMAS modes, a flyup will automatically be initiated when the chevrons come together and touch. The

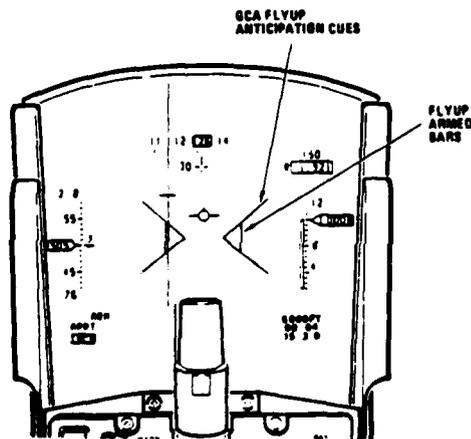


Figure 3 HUD Flyup Anticipation Cues

chevrons are also displayed (without the arming bars) during manual operation but then it is the pilot's responsibility to manually perform the flyup if required.

The second GCA function is the execution of the flyup maneuver itself which works as follows. A roll rate is commanded proportionally to the bank angle required to restore level flight. As soon as the bank angle is within the range + or - 90 degrees, a five-g pull-up is commanded. The flyup is terminated if the vertical flight path angle is greater than three degrees and the bank angle is within + or - 30 degrees. In any event, the flyup is terminated after ten seconds, if the first condition is not satisfied, as a safeguard in situations such as stalled or slow-speed flight.

The initial GCA design criteria was to recover as close to the MDA as possible (to allow the maximum AMAS maneuvering envelope) avoiding any MDA penetrations. But flight-test experience indicated that the pilots preferred an additional pad above the MDA. The pad chosen was to provide a one-second, time-of-flight, minimum-altitude recovery above the ground. For example, a flyup occurring with an initial sink rate of 500 feet-per-second should recover with a minimum AGL altitude of 500 feet. This modification was implemented with a simple coefficient modification of the GCAA polynomial.

Air-to-Air Collision Avoidance

The AMAS air-to-air collision avoidance (AACAA) is functionally similar to the GCA. The three main tasks for the AACAA are (1) the computation of when or if a breakaway is required, (2) the computation of which direction to breakaway, and (3) the execution of the breakaway maneuver itself. The determination of when to breakaway is complicated by the fact that the encounter geometries are complex and the target may maneuver unpredictably. Therefore, the AACAA design approach provides a minimum range-to-target to initiate the breakaway. The pilot is informed as to when and which way the breakaway will occur. Using this information and his tactical situation awareness, the pilot can either allow the auto breakaway to proceed, or he can manually override the automatic maneuver.

The first AACAA task is the determination of whether a breakaway is required. If either of the following two conditions,

$$R < 1000 \text{ ft} \quad \text{for } \dot{R} > -333 \text{ ft/sec}$$

OR

$$R + t_o \dot{R} < 500 \text{ ft} \quad \text{for } \dot{R} \leq -333 \text{ ft/sec}$$

where: R = range-to-target

\dot{R} = range rate-to-target

$$t_o = \begin{cases} 3.5 & \text{for } V_{ru}/\dot{R} > .95 \\ 10 (V_{ru}/\dot{R}) - 6 & \text{for } .75 \leq V_{ru}/\dot{R} \leq .95 \\ 1.5 & \text{for } V_{ru}/\dot{R} < .75 \end{cases}$$

V_{ru} = relative target body x-axis velocity

are satisfied, a breakaway is initiated. A time-to-breakaway is generated by dividing the range conditions above by the range rate-to-target.

The second AACA function is the determination of the breakaway direction when a breakaway is required which is computed as follows,

$$\text{Roll Direction} = \begin{cases} -\text{sign}(\text{bank angle}) & \text{for load factor} > 1.5 \text{ g's} \\ -\text{sign}(\text{azimuth los rate}) & \text{for load factor} \leq 1.5 \text{ g's} \end{cases}$$

The final AACA task is the execution of the breakaway maneuver. The intent of the breakaway maneuver is to roll orthogonally to the initial breakaway attitude and to command a load factor. The controller mechanizing this task commands five-g's in pitch for five seconds while simultaneously commanding 180 degrees per second roll rate for 0.9 seconds.

The pilot is informed of the time-to-breakaway via the HUD chevrons that were used for the GCA time-to-flyup. The chevrons cue the pilot as to when a breakaway will be required. The breakaway direction indication is displayed in the HUD by enabling only the arming bar on the break-X chevron in the computed roll direction of the breakaway. The break-X chevron is displayed in the HUD in both the manual and automated air-to-air gunnery modes, but the breakaway direction arming bar is only displayed in the automated air-to-air mode.

G-Induced Loss of Consciousness

The third collision-avoidance function is the G-Induced Loss of Consciousness (GLOC) recovery mode. GLOC is a phenomenon that is prevalent in high-performance aircraft that are capable of rapid g-onset and sustained high-g maneuvers. The pilot may experience muscle spasms, confusion or disorientation, apathy, and amnesia when executing these maneuvers. Since the primary causes of GLOC are rapid and unanticipated g-onset, and since the AMAS air-to-air gunnery system has full pitch and roll authority (9 g's pitch combined with rolls), the AFTI/F-16 program is especially involved in the GLOC problem. Therefore, the AFTI/F-16 GLOC system is designed to function in both manual and automated air-to-air modes.

The AFTI/F-16 GLOC design modifies the air-to-surface GCA mechanization to provide a pilot-selectable MSL floor that the aircraft should not penetrate (see Figure 4). A modified GCAA triggers the GLOC recovery to prevent penetration of the MSL floor. This modified GCAA also computes a time-to-auto recovery, which is used to position the HUD break-X chevrons, providing the pilot with an anticipation cue for the GLOC recovery initiation.

When the GLOC recovery is initiated, an attitude-hold autopilot coupler rolls the aircraft to a wings-level attitude, arrests the rate of descent, and maintains an MSL altitude above the selected floor. The pilot then has ample opportunity to recover from the GLOC condition, terminate the auto-recovery system, and resume manual control.

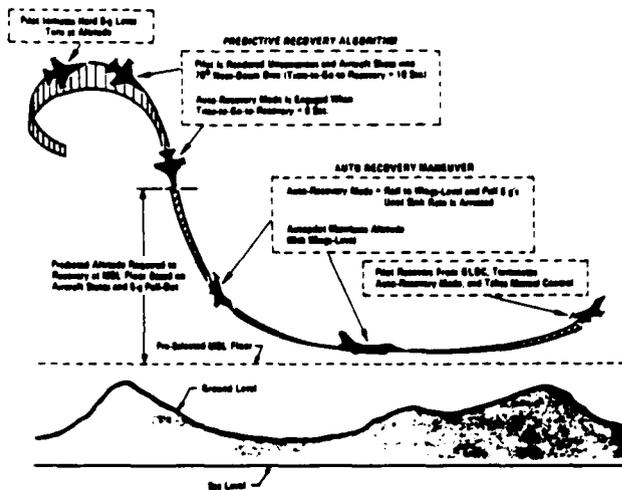


Figure 4 GLOC Auto-Recovery Scenario

FLIGHT CRITICAL SENSOR FUSION

The integration of the avionics suite with the flight control system on the AFTI/F-16 has introduced an entirely new class of sensor monitoring and verification challenges — that being, how to provide safe and reliable system performance with single-thread, flight-critical sensors and computational paths. The AMAS SWIM design has addressed several key aspects in this area. The nucleus of the SWIM design, which makes this capability realizable, is the Digital Flight Control System (DFCS). The fact that the DFCS can communicate with the avionics suite via the MIL-STD-1553 Avionics/Multiplex Bus (AMUX) allows the unprecedented interrogation capability of the single-thread flight-critical paths (see Figure 5). The DFCS, as the final link in the automated control of the aircraft, scrutinizes all avionic communications carefully.

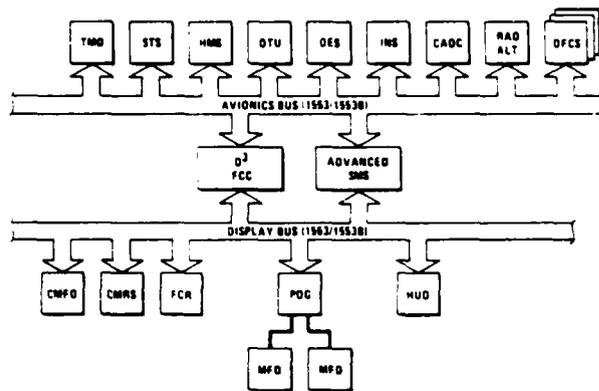


Figure 5 AFTI/F-16 Avionics Bus Architecture

The attitude information from the Inertial Navigation System (INS) is compared with the body rates of the flight-control rate gyros for gross anomalies in the attitude information (see Figure 6). The mode control information from the Stores Management Set (SMS) is required to contain a predefined bit pattern in order for the DFCS to change flight-control modes.

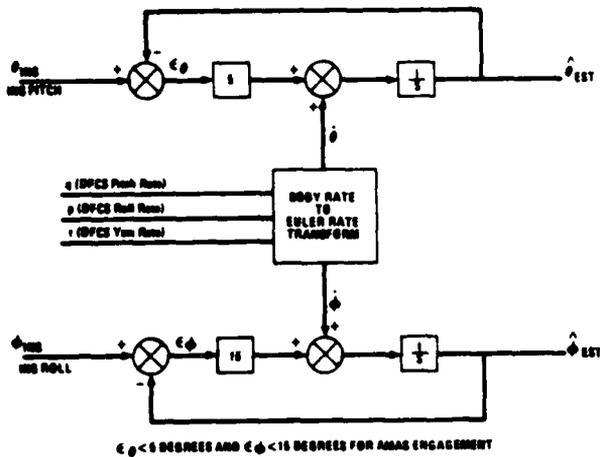


Figure 6 Attitude Estimator

The information from the Fire Control Computer (FCC) to the DFCS is examined thoroughly, as it contains commands directly affecting aircraft flight path. A checksum is computed on the FCC-to-DFCS AMUX block to assure valid communication. The FCC also computes two test problems based on known inputs to the GCAA. The test problem output must (1) be valid, and (2) change periodically for continued AMAS operation to be authorized. During AMAS air-to-surface operation, the FCC AGL altitude is compared with the INS vertical velocity to provide cross checks of the AGL altitude as well as the INS rate data (see Figure 7).

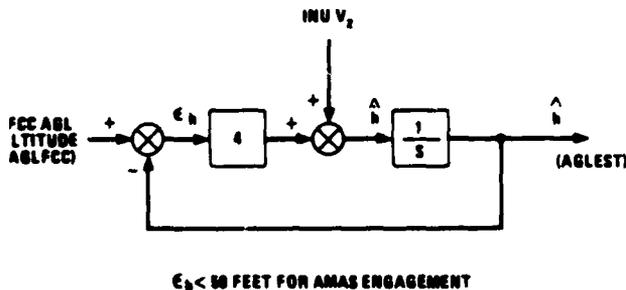


Figure 7 Altitude Estimator

The FCC, as the AMUX bus controller, is also a critical link in the AMAS SWIM design. As such, the FCC performs the avionics sensor comparison and fusion. In air-to-surface operation, this involves a determination that the GCAA has continuous and reliable inputs. The primary GCAA inputs are AGL altitude and AGL altitude rate, and to a lesser extent, roll attitude, roll rate, and load factor. While the APTI/F-16 radar altimeter is a dedicated AGL sensor (with 360 degrees of bank-angle coverage), it only "sees" terrain below the aircraft. The Fire Control Radar provides a "look-ahead" capability, but it has other targeting tasks during some segments of the AMAS air-to-surface delivery. With these system capabilities in mind, the FCC fuses the AGL sensors providing valid AGL altitude estimates that are critical for air-to-surface AMAS.

For air-to-air AMAS, the FCC monitors the target-state estimates from the Sensor Tracker Set (STS) that are inputs to both the AMAS gunnery director and the AACA. These signals are checked for validity and consistency. A MUX block checksum and "heartbeat" signal are also included within the STS-to-FCC AMUX data block.

PHYSICAL CONSTRAINT MONITORS

The physical constraint monitors consist of the Operational Mission Restrictions (OMR). The OMR monitors are based on a priori knowledge about overall system behavior. These monitors detect conditions that are, by definition, out of bounds of the groundrules for normal AMAS behavior. For example, airspeed, altitude, and attitude limits are imposed for AMAS operation. Also, mode protocol checks assure that all critical subsystems (SMS, FCC and DFCS) are operating in consistent modes that can support AMAS operation.

AMAS FAULT PROCESSING

Upon detection of a fault during AMAS operation, a sequence of events is triggered: (1) normal AMAS operation is suspended and a flyup or breakaway is executed if the system is armed; (2) the process, subsystem, or function in error is isolated and catalogued for fault reporting; and (3) an AMAS-disengage warning light and warning tone are activated. There are two primary display vehicles that inform the pilot as to the exact nature of the cause of disengagement. The first is the SWIM fault display on the DFCS page of the Multifunction Display Set (see Figure 8). This message contains the reason the DFCS disengaged AMAS operation. The second display is the Data Entry/Cockpit Interface System pilot fault list which provides the pilot with fault information for a class of avionics faults.

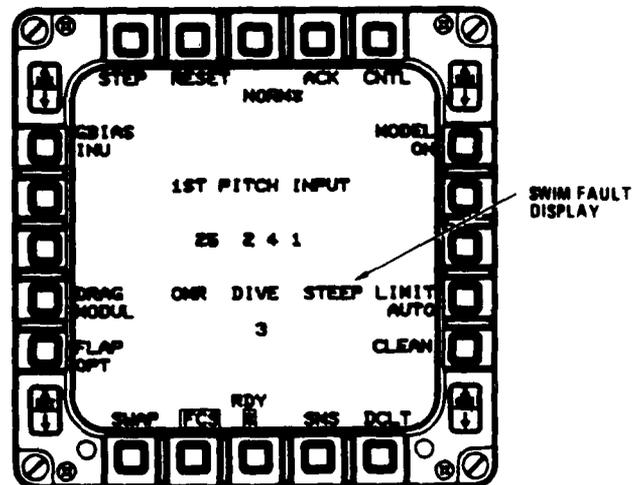


Figure 8 MFD DFCS Display

SUMMARY

The APTI/F-16 SWIM design effort provides a wide spectrum of practical experience applicable to the development of highly integrated avionics and flight control systems. Proven techniques for verifying that single-thread, flight-critical subsystems are functioning properly are especially important for future, automated-flight-path-control systems. Emerging fighter technologies will employ increasingly more complex integrated systems to alleviate pilot workload. To ensure fail-safe operation in this environment a system-wide approach for integrity management must be employed.

AMAS Software Development, Integration and Test

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AMAS SOFTWARE DEVELOPMENT, INTEGRATION AND TEST

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ABSTRACT

The objective of this paper is to describe the development of software targeted for the avionics suite of the AFTI/F-16 demonstrator aircraft. It will deal with all aspects of avionics software including software developed inside and outside of General Dynamics. Primary emphasis will be placed on that avionics software considered significant in fulfilling the objectives of the AMAS Phase of the AFTI/F-16 Program. For the purposes of this paper, the term "software development" will include all efforts necessary in taking an approved system design (and the accompanying subsystem partitioning) and producing a software product capable of supporting all system-level testing. The discussion will approach not only the delivered product, but also the facilities used to develop the product since these facts weigh heavily on the quality of work completed at each step in the development process.

INTRODUCTION

This discussion describes the approach used in implementing software solutions within embedded computer systems on the AFTI/F-16 during the AMAS Phase. Regardless of the type of product software development task, the steps involved in producing the "product" cannot be skipped without some degree of compromise in the quality of the product. Careful analysis of the problem or task must occur at some point in the product life-cycle. The earlier in the development it occurs, the cheaper the resultant product will be and the greater the likelihood that it will be a quality product. The penalty for problem analysis after the fact is loss of the opportunity to repair what is probably a substandard software product or component part of a product. By definition, all aspects of the system design process originate within the system design activity. The system design task frequently receives attention from the detailed design activity (often referred to as system mechanization) and occasionally from the customer/program management level (program policy regarding equipment selection, budget, and development constraints).

DESIGN DOCUMENTATION

Completion of the initial design phase is marked with completion of several key documents. The first document to address the involvement of software engi-

neering in the development of embedded computer software is the Computer Program Development Plan. This document identifies the software development environment, personnel organization, policies, standards, and incremental milestones. Next, in order of required completion, is the Computer Program Development Specification (or B-5) which is a software requirements document usually written at the subsystem level, but in some rare instances it is written for several closely related subsystems. No logic diagrams will be found in this document, but the mapping of software partitioning to functional requirements will be seen for the first time. This document typically segregates and outlines the input, processing, and output requirements for each specific function. Also, the flow of data between functions and into and out of the subsystem is outlined. System mechanization is described at a moderately high level due to gaps inherent in the on-going design process and system level partitioning changes. The Design Change Request (DCR) represents an incremental step in the overall design change process involved in transforming production avionics into AFTI/F-16 avionics. During this transformation, Integrated Fire and Flight Control (IFFC) to the avionics suite was added and the Digital Flight Control System (DFCS) was adapted to support the IFFC modes. Each DCR outlines, in detail, how an individual design objective will function, the affected subsystems and the anticipated results of the design change. The AMAS Avionics System Manual is not a true design guide, but it has been influential in the design process. It discusses all of the hardware assets used on the program as well as any modifications or changes in intended application. System-level mechanization is covered in considerable detail thus making it a valuable document to the mechanization engineer. The Interface Control Document (ICD) provides exactly what its name implies - an accurate description of the interface between subsystems. This makes the ICD one of the most important documents in describing inter-subsystem relationships. Like the Avionics System Manual, it is not a true design document, but inputs, outputs, and the required processing are all directly related to the description of the interface. Figure 1 describes the AFTI/F-16 system architecture and notes the more significant subsystems.

DEMONSTRATION THROUGH INNOVATION

The AFTI/F-16 Program has never advocated the recreation of available product software, but instead uses existing software when the particular application allows.

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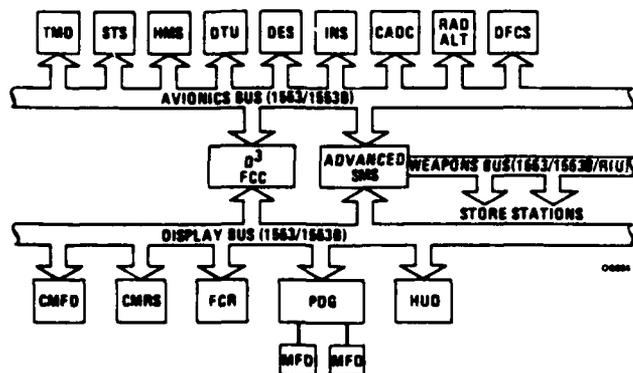


Figure 1 AFTI/F-16 Multiplex Bus Architecture

New or modified software is developed only, out of necessity, to provide a capability that did not previously exist.

In direct contrast to the AFTI/F-16 DFCS Phase in which new (DFCS and VIA) and extensively modified (SMS, FCC) software was abundant, the AMAS Phase consists almost entirely of software originated on other programs and modified, while retaining the original software architecture. The degree of modification varied from subsystem to subsystem and from function to function within a given subsystem. The MSIP program was in its infancy when the decision was made to utilize the core avionics and its accompanying software. The Bendix supplied Color Programmable Display Generator (CPDG) originated with the F-20 Tigershark development program, and the Helmet-Mounted Sight (HMS) originated with the AH-60D helicopter program. The acquired software products, which were still in developmental stages, presented a challenge typical of prototypes: efforts to promote the maturation of the software products had to continue while the features necessary to support the AMAS demonstrations were being installed. The analysis necessary to determine the partitioning of functions to subsystems originates with a DCR.

DESIGN CONSIDERATIONS

The four core avionics subsystems (FCC, SMS, MFDS, and DE/CIS) existed as preproduction assets when their implementation on the AFTI/F-16 began. The constant monitoring of software development by groups supporting the MSIP program, while still designing changes to support the approved demonstrations, required considerable finesse in "dovetailing" changes (which usually means combining corrections from one development source with modifications or enhancements from another) while guarding against inadvertent errors. In more than one occurrence, the subsystem's capacity to accommodate new functions consumed the specified memory and/or timing reserves and forced a decision - either to compromise capability or to decrease reserves. The EFCC's duty cycle and the ASMS and MFDS's memory reserve requirements were relaxed to allow the subsystems to install the functions necessary to support the prescribed AMAS demonstrations. Eventually, the ASMS was rebaselined to a more mature release and the duty cycle reserve of that subsystem was recouped

through software redesign and code optimization. The EFCC duty cycle hovers near the maximum allowable for dependable operation.

The AMAS goals were partitioned between targeted subsystems, and those subsystems' capabilities were examined to determine if any software or hardware changes were necessary. After performing this subsystem-level analysis a decision was made as to (1) which subsystem would be changed, (2) how the change would be performed, and (3) whether or not the change should be partitioned in an alternative subsystem to conserve development costs. Due to cost restrictions, vendor-supplied subsystems were chosen over in-house subsystem modifications only where (1) system performance may have been compromised, or (2) the respective vendor was better equipped to support the task. Wherever possible, the AFTI/F-16 program makes use of off-the-shelf support equipment and ingenuity as a primary means of conserving development resources.

TEST CONSIDERATIONS

A problem was encountered in finding the support equipment to make the necessary AMAS software changes. Although systems were being built at General Dynamics to provide the capability of developing software on the core avionics suite, they were rarely available for use by AFTI/F-16 personnel. This caused an impact on product software delivery schedules. Furthermore, the evolution of those systems away from the AFTI/F-16 hardware resulted in a degradation of the quality of our stand-alone testing. The alternative was to create a separate development and test environment within the AFTI/F-16 AMAS budget. The schedule and cost implications of this alternative were prohibitive. Although the AFTI/F-16 Program could create and maintain its own test station software, no irreversible hardware modifications were allowed. Because the stations were software-intensive and because AFTI/F-16 could maintain its own support software, the systems were productive. The resources necessary to generate the AFTI/F-16 support software were modest when compared to the return realized in system capability. Although the systems possessed many limitations, considerable development and test capabilities were realized for a small investment.

CORE AVIONICS SOFTWARE DEVELOPMENT

The AFTI/F-16 avionics software development did not have a dedicated support facility until mid 1985, when a Digital Equipment Corporation MicroVAX II was acquired to support the Enhanced Fire Control Computer (EFCC) OFP release AF04.

The DFCS Phase avionics hardware was a mixture of vendor-supplied prototypes, custom components fabricated in house, and GFE from the F-16A/B. Because this hardware had limited growth capability, had exceeded its service life (in some cases by a factor of 2 or 3), and was difficult to maintain (because it differed from production hardware), a decision was made to upgrade the AFTI/F-16 avionics suite with advanced hardware, which was being developed for the MSIP program. The MSIP hardware provided several

advantages: (1) spares availability would be improved, (2) prototype hardware would not have to be developed, (3) current facilities for loading OFFs could be used with little change, and (4) most importantly, the MSIP development and test facilities could be utilized - sparing the AFTI/F-16 program the considerable expense and delay associated with developing a dedicated facility.

A common software architecture was developed by MSIP and used on the AFTI/F-16 Program. Each OFF is partitioned into components that are further divided into modules. A module, the simplest form of configurable software, usually defines a single process such as qualifying a weapon to the current master mode, while a component typically defines a complete process such as bus control.

With one exception, all OFFs were developed in the same fashion. A configuration baseline was supplied by the software element manager on a module-by-module basis. The baseline, maintained on the Harris Computer-based Software Engineering System II (SES), was modified by AFTI/F-16 personnel working from Software Change Requests (SCRs). The modified software was transferred by RJE link to the corporate IBM complex for test compilation and the results of the compilation were transferred back to the SES. If the compilation was successful, the modules were used to produce a linked OFF. Module level testing (Computer Program Test and Evaluation, CPT&E) for most of the avionics hardware was performed either on the SES using a processor simulator, or on the Software Test Station (STS) using the target hardware and a system simulation hosted on the STS. The exception was the EFCC OFF, which could not be tested on the SES because the SES did not have a 1750A emulation capability. Instead, the EFCC OFF was tested on either the STS (see Figure 2) or on a Delco Computer Support Equipment (CSE) set. Figure 3 shows resources and their use in each step of the development process. Note the criticality of the STSs for each software product.

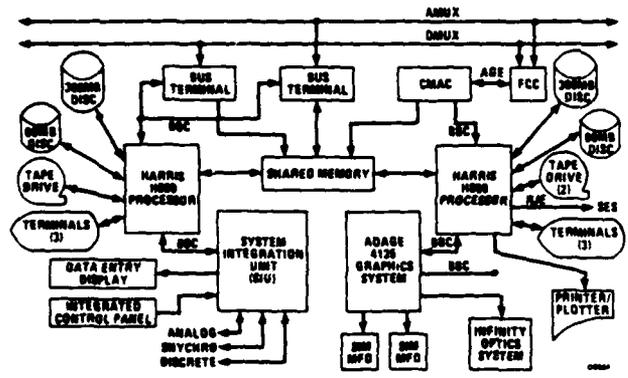


Figure 2 MSIP Software Test Station

After initial CPT&E testing, the OFFs were debugged in the System Integration Laboratory (SIL) on the STSs. One exception was the MPDS, which was debugged with the use of a Tektronix Z8002 in-circuit emulator. When a problem was found, an assembly language patch was installed and became part of the baseline configuration. When all known problems were solved, the OFF was ready for system-level integration

RESOURCE	OFF		FCC		ASMS		PDG		DE/CIS	
	HARDWARE	SOFTWARE	DEV	TEST	DEV	TEST	DEV	TEST	DEV	TEST
IBM 370		JOVIAL SUPPORT S/W	X		X		X		X	
STS		SIMULATION S/W	X	X	X	X	X	X	X	X
R&E FACILITY				X		X		X		X
SES		JOVIAL SUPPORT S/W	X		X		X		X	

Figure 3 Software Resources by Application

and testing, avionics subsystem test (Stand-Alone Verification and Validation, or V&V). Figure 4 outlines each level of software development and relates each level of software testing. AFTI/F-16 personnel had access to MSIP development and test facilities on a non-interference basis; typically, this meant 120 hours per month. When these facilities were unavailable, a DEC VAX-based system was used as an alternative because it had mature JOVIAL compilers, an extensive software toolset (including configuration control) and a good throughput/cost ratio.

TEST	TEST ENVIRONMENT	TEST PHILOSOPHY
•MODULE	OFF Software Software Test Station	Bottom-Up OFF Level Tests
•CPC		
•INTEGRATION		
•STANDALONE	OFF Software/Hardware ETSE	Top-Down System Level Tests
•INTEGRATED SYSTEM	Subsystem OFF System/Hocbench/Simulation	
•AMAS SIMULATION	AMAS System/Aircraft/Simulation	

Figure 4 Software Test Steps

The MicroVAX changed the way an OFF is produced and maintained. The most dramatic result was the greatly reduced turnaround time for OFF production - the compilation of an OFF, which formerly took 24 hours on the IBM, can now be accomplished in 35 minutes on the MicroVAX. Similar results were seen for the linkage editing process. Current tools include a 1750A emulator for the MicroVAX to eliminate dependence on the Delco 1750A computer for CPT&E. This quick turnaround and increased capability also produced a change in procedures; all DCRs which result in an SCR were implemented in high-level language in the actual program module, rather than in assembly language patches in the assembled code. The net result was the virtual elimination of patches and the effort required to maintain them. The long term goal was to have a corrected module compiled in the morning, tested in the afternoon and at the airplane the next day. Figure 5 describes the current MicroVAX II system architecture.

AFTI/F-16 software was baselined from two sources: (1) software developed by other General Dynamics programs (including the avionics software

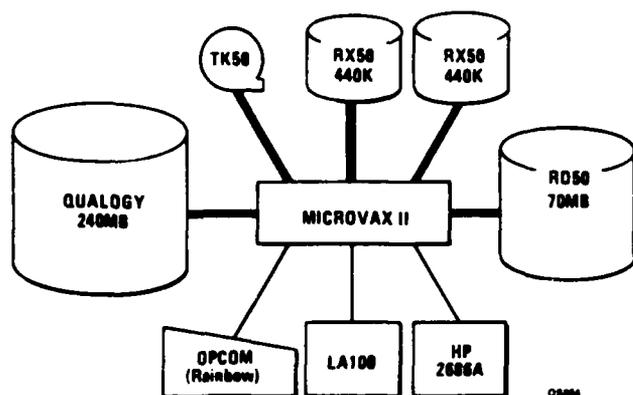


Figure 5 MicroVAX II System Architecture

developed by the MSIP, referred to as the core avionics), and (2) software developed by a vendor for a vendor supplied subsystem (e.g., the sensor tracker set supplied by the Westinghouse Electric Co., Inc.).

General Dynamics-developed avionics software adapted from MSIP baseline software features an architecture composed of several generic components, augmented by application components specific to individual OFPs. The generic components are listed below:

<u>Component Name</u>	<u>Description</u>
EXECUTIVE	Control Program
SYSTEM CONTROL	Task State Executive
INTERFACE CONTROL	1553/1553B & discretes
DATA TRANSFER	I/O passthru and formatting
ERROR HANDLING	Recovery/shutdown procedures
UTILITIES	Misc. service routines
TEST	Subsystem Integrity (BIT & Self-Test)

Although the application components are unique to each OFP and determined by subsystem requirements, they share important traits. Three of the four target processors are Z8002 based; all four are 18-bit processors, and all four OFPs are written primarily in JOVIAL J73. These shared traits allow the use of common programming guidelines and standards, and also allow the use of similar solutions to similar problems. This has afforded the AFTI/F-16 Program the flexibility of shifting its manpower resources among avionics programs, as the need arose, without experiencing long lag times for the programmers to readjust after switching tasks.

Enhanced Fire Control Computer

The EFCC hardware is a GFE Delco 1750A processor model M372 capable of 0.5 million instructions per second (MIPS). The LRU is identical to the MSIP hardware. The first AFTI/F-16 EFCC OFP (AF01) evolved from the MSIP release FF02; it was a rudimentary OFP developed to support IFCC demonstrations on the R&E simulator, capable only of bus control. All other FCC functions, and all other avionics subsystem functions were simulated on the Harris/7 (and later

Harris H1000) R&E simulator. The second EFCC OFP was baselined on MSIP release FF03 (rather than AF01) to take advantage of MSIP developed enhancements and corrections; AFTI/F-16 unique modifications from AF01 were redesigned to work with the new baseline. AF02 was generated primarily to allow open-loop Phase A flight testing. During this testing many important functions and algorithms were tested; these include manual AMAS Pre-planned Target (APPT), manual AMAS Director (ADIR) gun aiming option, System-Wide Integrity Management (SWIM), and Low-Altitude Radar Auto Pilot (LARAP). AF02 also supported the checkout of several avionics subsystems: a 360-degree radar altimeter (RALT), the CPDG, the Color Map Reader System (CMRS) and the Sensor Tracker Set (STS).

EFCC release AF03 broke tradition in that it was based on AF02 rather than the latest MSIP EFCC release. The biggest difference between AF02 and AF03 was that AF03 supported closed-loop (automated) steering. APPT was tested in manual and automated modes, with and without updates from the STS. Extensive STS integration continued and air-to-ground bombing results looked promising.

EFCC release AF04 was baselined from AF03 and included support for several new systems, including the Digital Map Generator (DMG) and Voice Interactive Avionics (VIA). The OFP also contained support for the Standardized Avionics Integrated Fuze (SAIF), G-induced Loss of Consciousness (GLOC) protection, and a more complete implementation of ADIR. It should be noted that the baseline for AF03 and AF04 was the most mature version of the previous OFP; considerable effort was devoted to recoding modules in the new release to eliminate the assembly level patches in the previous release. With AF04, however, all corrections are made in JOVIAL J73 (and hosted on the MicroVAX II) at the module level so that future efforts can focus on incorporating new features, rather than redesigning to correct old problems.

Advanced Stores Management Set (ASMS)

The ASMS consists of an Advanced Central Interface Unit (ACIU) and several Remote Interface Units of various types. The ASMS controls the selection, monitoring, conditioning, and release of stores on the aircraft and maintains an inventory of these stores. In addition, the ASMS acts as a backup bus controller to the EFCC. The ASMS facilitates communication between the pilot's displays, the data entry unit (MFDS and DE/CIS), the weapon delivery avionics, and the RIUs. The ASMS OFP runs on the same ACIU hardware as the MSIP OFP: dual-redundant Z8002 microprocessors running at 3 MHz, 64K of memory, power supplies and other supporting hardware.

The first ASMS OFP (AW01) was baselined on the third MSIP release, WF03, from F-16 Block 25 and included several MSIP patches applicable to AFTI/F-16. MSIP-only patches were not included in the baseline. The plan was to adapt the baseline for AFTI/F-16 by using only assembly language patches without updating the source code, recompiling, or relinking. This approach, different from that used with the other avionics OFPs, was selected to avoid the high cost of linking and compiling; it was thought to be practical because only slight changes to the OFP were believed to be necessary.

These changes included changing the backup bus control, AFTI/F-16 air-to-ground delivery modes and gunnery modes. One limitation of WF03 was its 16-Hz duty cycle whereas AFTI/F-16 core avionics used a 50-Hz duty cycle. This was acceptable since it had only one effect - when the FCC was powered off, the SMS acted as a bus controller and some MUX blocks, which should have been calculated at more than 16 Hz were not. However, this had no safety-of-flight impact.

A new baseline was adopted for the AMAS Phase B OFF. It was determined that it would be easier to base the new OFF on MSIP flight tape WF04 from Block 25A minus the MSIP-only patches than on AW01. In addition to the AFTI/F-16 functions in AW01, AW02 eventually incorporated such functions as autogun firing, SAIF support, and modified backup bus control. A Phase C version of AW02 has been generated that includes all Phase B functions and some SAIF corrections.

Multifunction Display Set

The MFDS hardware has three main parts: the Programmable Display Generator (PDG) and two Multifunction Displays (MFDs). The MFDS OFF was baselined on MSIP OFF MF03, with modifications to support AFTI/F-16 requirements. The modifications included adding base and control pages for the STS and FCS and a Target and Line of Sight Simulation (TALOSS) page. Other modifications included changes to the master menu, data entry page, and hex data entry page. Several MSIP pages were deleted, including the E-O weapons page, the navigation pod page, the target pod page, and the SMS nuclear page.

The Phase A MFDS OFF had two problems: it was large enough to almost fill its allotted memory space (making patches difficult to shoehorn in), and it tended to gradually lose capability, leading to program halts. This degradation was corrected in a later release (AM03) with the use of protected memory. The protected memory allowed test personnel to determine which parts of the program were overwriting other code. Previously, the overwrite was not detected until the OFF failed, and the offending code could not be determined. OFF size remained a problem in later versions of the Phase A OFF; in fact, some test routines were deleted to allow more patch space. The final Phase A OFF completely filled the 32K of allocated memory.

Incorporation of the patches into the OFF produced a Phase B OFF of more reasonable size; other Phase B corrections were minor, including patches to fix STS data entry discrepancies and FCR video intensity problems.

As mentioned earlier, the Phase C release AM03 was the first to use protected memory. Several major design changes were made to take advantage of this feature. First, a data base was used, which separated constant and variable data, to allow constant data to be stored in protected memory. The text display and formatting components were also rewritten to use the new data base. Second, a decision was made to include some MSIP-developed test routines in the recompilation to make the OFF easier to debug. Finally, the OFF included a large VIA component. Testing the OFF revealed numerous problems throughout the component. The problems were extensive enough to warrant a rewriting of the component; however, AFTI/F-16 per-

sonnel hoped to avoid recompiling the OFF. The rewritten component was implemented as an assembled patch that overlaid the old voice component. Further versions of AM03 have included relatively minor changes such as display discrepancies and some minor VIA design changes.

Data Entry/Cockpit Interface Set

The DE/CIS hardware is a microprocessor-based interface between the pilot and the navigation and communications avionics. The hardware consists of a data entry electronics unit (DEEU), which controls the DE/CIS. The DEEU is based on a Z8002 microprocessor running at 3 MHz with 32K of memory. The memory consists of a 20K code space, 4K constant data space (both kept in EEPROM) and 8K of variable data. The other DE/CIS hardware units consist of the data entry display and the integrated keyboard panel, which are used to read and enter data. AFTI/F-16 uses the IKP from the aft station of the F-16D, rather than the HUD-mounted IKP, to allow the AFTI/F-16 HUD to be used without modification.

On the MSIP F-16, the DE/CIS provides a method of entering radio frequencies on UHF, VHF, and also IFF, TACAN and ILS parameters. The AFTI/F-16 Phase A OFF evolved from MSIP release DF03 and while no additions to the OFF were required, the aforementioned functions were deleted.

No major problems were encountered with AD01 in Phase A testing and no modifications were needed to support Phase B testing. The Phase C OFF was based on MSIP release DC12 (Block 25B) with extensive changes (implemented through DCRs) to support the VIA interface.

Vendor-Developed Software

The software targeted for the AFTI/F-16 is provided to General Dynamics on a subcontract basis. General guidelines for vendor-developed software requirements are levied upon the vendor to the extent possible. The following items are considered minimum documentation: (1) the vendor's interpretation of software requirements, (2) a software design description, (3) a user's manual, and (4) an acceptance (or stand-alone) test procedure.

Sensor/Tracker Set

The STS is a forward-looking infrared radar (FLIR) imaging sensor, laser, and closed-loop tracking system which complements the FCR by providing an additional, more accurate sensor for acquisition and tracking. The STS consists of two processors, a MIL-STD-1750A based sensor tracker processor and an Intel 8086 based video tracker processor. The sensor tracker processor is programmed in JOVIAL J73; the video tracker, in Pascal, with time-critical tasks and some I/O tasks in 8086 assembly language.

The STS OFF provides overall control of the STS hardware, output for post flight data analysis, target state estimation and cued acquisition in both air-to-air and air-to-ground modes. In addition, the OFF provides both a built-in test and a self-test capability.

Helmet-Mounted Sight

The helmet-mounted sight was designed to allow the pilot's actual line of sight (LOS) to be used to cue the Fire Control Radar (FCR) and STS, and to allow these sensors to cue the pilot to their line of sight. The system consists of a transmitter, receiver, control panel and a Sight Electronics Assembly (SEA). The transmitter is mounted on the canopy of the aircraft, and it consists of three orthogonal coils aligned to the aircraft's x, y and z axes. An alternating current is applied to each coil; the resulting magnetic field is sensed by three orthogonally mounted coils in the helmet. This receiver senses nine voltages (each receiver coil sensing the three transmitter voltages). The voltages are amplified by preamps in the control panel and multiplexed onto a single channel. The signals are conditioned and converted into a digital matrix. By comparing voltages (matrix elements), the angle between the transmitter and receiver can be determined; by using the magnitude of the voltages, the distance between the pair can be found. This processing and computation is accomplished inside the SEA, which is based on a Honeywell HDP-5301 microprocessor with 2K of RAM and 8K of PROM. Only about 3.2K of the PROM is currently used. The HMS OFP computes helmet position, compensates for helmet and cockpit metal (using data from a cockpit mapping done early in the program), computes the LOS, and conducts a continuous built-in-test.

Digital Terrain Management And Display System

The primary purpose of the DTMDS is to provide a display of topographical maps that move in real time in relation to the motion of the vehicle carrying the DTMDS. The information displayed includes terrain elevation and cultural features and is derived from compressed data stored on a magnetic tape. The DTMDS positions, scales, and orients the map in response to instructions from the pilot or an external computer. The DTMDS comprises four firmware-resident OFPs written in the Z8000 symbolic instruction set (assembly language), executing on separate Z8001 microprocessors, and exchanging data via a global shared RAM. One design goal was an executive common to all four processors. The DMG controller controls operation of the video electronics, processes navigation data to position the map, and decodes commands to adjust map scale, orientation, and other optional features. The symbol generator generates one monochrome video output and seven color digital video overlay outputs. The monochrome output capabilities include flight instrumentation data, color overlay symbology, as well as, point cultural or mission interest features positionally correlated with the terrain elevation map display. The tape controller reads compressed map data off the tape, transmits compressed map data to the DMG subsystem, and transmits point feature data to the symbol generator controller. The auxiliary processor provides an execution environment for the Sandia Inertial Terrain-Aided Navigation (SITAN) algorithm which correlates map data with observed data to compute a navigation error estimate.

Color Map Reader System

The CMRS provided by the Bendix Corporation's Flight Systems Division consists of (1) the Color Map Reader (CMR), (2) the Color Multifunction Display

(CMFD), and (3) the CPDG. The CMRS is an LRU intended for use on the AH-60D helicopter program. It produces a full-color video signal that can be displayed on a color CRT. The video signal consists of a high-contrast image of a flight-navigational moving map from a film-strip produced by the Defense Mapping Agency (DMA). The map image is under control of the OFP in the CMRS and responds appropriately to changes in information received from other avionics subsystems via the 1553B Display Multiplex (DMUX) bus which reflects the aircraft's current position and heading. The CMRS utilizes one Z8002 microprocessor and 16K of EPROM memory of which 7K is currently used. The processor's more significant tasks are 1553B bus interface (remote terminal mode only), map centering, map rotation, and map to raster coordinate data transformation.

The CPDG provides a monochromatic text/video display mix that has been modified to provide a color display capability. The CPDG video signals from the CMR (or potentially from other sources) to the system display device generate various display symbology, text overlays, and map video, process the data required to control the CMR and generate stroke-written electronic, flight-instrument display formats. The CPDG utilizes a dual-MUX interface, a symbol generator, and the necessary display driver circuitry. Each of the two channels contains two Z8002 microprocessors addressing 24K of EPROM memory (expandable to 32K) and 2K of scratchpad RAM; one of each is used in the display function processor board and the system function processor board (AFTI/F-16 is currently utilizing only one channel, or two of the four Z8002s).

The CMFD is a Bendix developmental unit specially configured for AFTI/F-16 unique requirements and is capable of stroke-generated symbology, raster-generated symbology, or a combination of both. The CMFD is the key LRU of the set in that it provides the operator interface to the logic processes of both the CPDG and CMR. The CMFD includes a 5x5-inch, color, CRT monitor configured for hybrid operation, twenty programmable pushbutton switches (push and hold) located along the display perimeter, and four rocker switches used (but not dedicated) to control text brightness, contrast, symbology brightness, and a special function associated with mixing radar and map video together. The CMFD uses one processor to control the video signal necessary for the display and transmission/reception of commands from the CPDG over two RS232 ports.

Fire Control Radar

The fire control radar on the AFTI/F-16 is the Block 15BX AN/APG-66 used on the Block 25 A F-16C/D. The entire subsystem (hardware and software) was developed by the Westinghouse Electric Corporation (WEC). The hardware configuration is divided into the following LRUs: (1) the antenna, (2) the low-power radio frequency (RF), (3) the transmitter, (4) the digital signal processor (DSP), and (5) the rack. The DSP is the OFP host. The hardware configuration remains unchanged while the software received considerable attention in order to meet and achieve the AMAS requirements. The most significant changes to the FCR OFP were modifications to support the two AFTI/F-16 unique modes which are the CUE and LARAP modes. CUE mode allows the FCR to have its line of sight driven by another sensor while LARAP provides a limited terrain-following capability

(restricted to a 2% grade variation) for the purpose of supporting the demonstration objectives of the APTI/F-16 AMAS Phase.

Head-Up Display

The HUD is a combined electro/optical device that provides the pilot with a visual display of essential flight information. This information is superimposed directly in the pilot's LOS through the use of a transparent display medium called a combiner glass. The combiner glass provides the pilot with an undistorted forward field of view by focusing the display symbology to infinity. The symbols represent information relating to the attack, navigation, weapon delivery, and landing modes and to essential aircraft performance (including but not limited to altitude, airspeed, attitude, and heading). The symbolic information is conditionally determined by information obtained from both internal (RSU) and external (1553 multiplex bus and discrete) sources. The HUD consists of three LRUs: (1) the Programmable Display Unit (PDU), (2) the Rate Sensor Unit (RSU), and (3) the Electronics Unit (EU). The software environment consists solely of the EU. The PDU houses the CRT unit assembly and the associated power supply, the video-protect circuits, the video-drive circuits, the auto-brilliance sensor, and a wide-angle conventional coating combiner glass. The EU controls the PDU's construction of symbology and generation of text with computations based on external information received through either a MUX bus (1553) or discrete interface. The HUD OFF resides in 16K of EPROM memory.

The RSU contains pitch, yaw, and roll gyros, and an accelerometer. The outputs of these sensors are used to compute the continuously computed impact line (CCIL) of the stream of bullets, which is displayed in the air-to-air gunnery modes.

AVIONICS TESTING

Four APTI/F-16 avionics subsystems were tested: the Enhanced Fire Control Computer; the Advanced Stores Management Set; the Multifunction Display Set; and the Data Entry/Cockpit Interface Set. Each avionics subsystem was tested, as necessary, at three basic levels: Unit/Module, Integration, and Stand-Alone Verification and Validation. The amount of testing necessary to produce acceptable software was determined separately for each avionics subsystem. The driving consideration was the number and the degree of changes made to the software. Those subsystems that underwent the greatest number of changes were subjected to the most thorough testing. Limiting factors such as test facility availability and capability also entered into the determining process. The level of testing accomplished for each avionics subsystem is described in detail below.

Enhanced Fire Control Computer

The EFCC software testing methodology implemented a bottom-up strategy with all three levels of testing, beginning with the low-level modules and working towards a totally integrated, verified, and validated OFF.

In the first level of testing, CPT&E, the low-level units/modules were first tested in isolation, using test driver programs. For Phases A and B, this was

accomplished on the Delco CSE, and in-house driver software was developed and used. For Phase C, the modules were both developed and unit tested on a MicroVAX II system, again using in-house software. This level of testing exercised all branches of the logic in each module and was performed by the programmers who implemented the software. A majority of the logic, internal interface, and compiler discrepancies were identified and subsequently corrected at this level.

After each module had successfully passed CPT&E, the test procedures and results were signed off by both the programmer/tester and the lead software engineer. These results were then included in the modules' unit development folder (UDF) for documentation purposes.

For Phases A and B, this level of testing was performed only on newly linked versions of the OFF. As the OFF matured, the changes and corrections were implemented by adding patches to the OFF. Patching was preferred to relinking due to the high cost in time and money required by a relink. A relink was therefore performed only when major revisions or additions were implemented. During the time between newly linked OFFs, the unstructured nature of the patched OFF and low availability of the test facilities prohibited the performance of CPT&E on patched OFFs. For Phase C, the MicroVAX II system provided a faster, more economical relink capability, and therefore, patched OFFs were not required. As changes and corrections accumulated and a new OFF became necessary, a relink was performed and CPT&E was subsequently executed.

Following CPT&E of a relinked OFF, or release of a patched OFF, low-level modules were progressively merged (called OFF integration) in a top-down sequence to produce software that performed an increasing number of specified functions. This was accomplished on the MSIP EFCC STS facilities at the SIL, and was performed by the lead mechanization engineer. The mainline control routines were integrated and tested first, using stubs in place of modules. The stubs were then replaced by the actual modules in a functional sequence until the entire program had been integrated and tested. This level of testing focused on the functional compatibility and completeness of the internal logic and interface between the modules of the subsystem.

Upon completion of functional integration the OFF was formally released to the lead test engineer for stand-alone verification and validation testing. The lead OFF development engineer provided a formal release memo which described the OFF's contents and known limitations. The OFF functional capabilities were then formally verified and validated according to the system and software performance requirements specifications. For most functions this was accomplished at the MSIP EFCC STS in the SIL with test procedures developed and performed by an independent group of software test engineers. At this level of test, the external interfaces with other subsystems were provided by modeling the other subsystems on the STS. The EFCC also provided MUX monitor and patch capabilities, MUX and data recording, external discrete controls, and simulated subsystem displays (MFDS and HUD). These facilities and the sophistication of the software models allowed the tester to observe the expected outputs from the EFCC in response to specific subsystem and pilot inputs. The AMAS Preplanned Target (APPT) weapon-delivery mode

was added to the air-to-ground component of the EFCC for AMAS. Due to the closed-loop nature of the APPT algorithm, formal V&V testing of the EFCC required interaction with a flight control system and airframe parameters in a closed-loop, full-cockpit environment; therefore, a flight-control system, airframe parameters, sensor and subsystem models, and MUX/data monitor and recording capabilities were necessary.

Upon completion of stand-alone testing, the test engineer formally annotated the test results in a Software Verification and Validation Stand-Alone Test Report. The test report identified, at the component level, all discrepancies observed during the testing period. Each discrepancy was further described by inclusion of the test procedure section which failed, and a Discrepancy Report which was written against the problem.

As the test procedures and the OFPs matured, an abbreviated version of the test procedures was performed on those portions of the OFP which had not changed, without realizing a loss of confidence in the test results. The test procedures were abbreviated by eliminating redundant test steps, and performing only a representative cross section of the tasks for a particular function. Those OFP functions that had changed were tested to completion, and often required new or updated test procedures. There were three exceptions to this retest methodology. For each OFP release, the test procedures for SWIM, fault reporting, and APPT (closed loop) were always executed to completion due to their flight critical characteristics.

Advanced Stores Management Set

Due to the patched nature of the ASMS software, the testing consisted of the functional integration of each patch to the baseline OFP, followed by formal SAV&V testing of the entire OFP. Unit-level testing had been previously performed on the MSIP baseline OFP and was not performed on the unlinked, patched, AFTI/F-16 baseline OFP. As the patched versions of the OFP were released, each patch was functionally examined by the lead mechanization engineer on the MSIP ASMS STS at the SIL. The ASMS STS provided subsystem models, MUX monitor and patch capabilities, MUX and data recording, external discrete controls, and simulated MFDS displays. This level of testing verified the functional implementation of each patch, as well as the integrity of the unchanged code.

Following integration, the OFP was formally released to stand-alone verification and validation testing by the lead OFP development engineer. A formal release memo describing the contents and known limitations of the OFP was issued to the lead test engineer. After all the new patches had been functionally integrated, the capabilities of the entire OFP were formally verified and validated. This was accomplished by an independent group of software test engineers using test procedures based on the current system and software design requirements. The test engineers utilized the ASMS STS facilities to verify the OFP's expected response to pilot and subsystem inputs. As with the EFCC, the results of ASMS stand-alone testing were described by the test engineer in a Stand-Alone Verification and Validation Test Report.

Multifunction Display Set

The MFDS OFP is a data intensive display generator with a large display data base. Due to the data intensive nature of the software, unit-level testing was deemed inappropriate and was bypassed in favor of integration and formal verification and validation through inspection of each display page. As new OFPs were released, each patched display page was examined for functional correctness. This was accomplished on the Tektronix microprocessor development unit at the SIL, and was performed by the lead mechanization engineer. By inspection of those display pages changed by patches, the integrity of both the display data base and the display generator was verified.

After all new patches were integrated, the entire OFP was formally verified and validated by ensuring that all display pages were correctly generated and functionally operational in accordance with the current design specification. This was accomplished on the MSIP MFDS STS at the SIL by an independent group of software test engineers. The MSIP STS provided subsystem models, MUX monitor/patch capabilities, MUX/data recording, external discrete controls, and MFDS displays. These facilities allowed the tester to verify that the correct page was displayed in response to subsystem and pilot inputs.

Data Entry/Cockpit Interface Set

The DE/CIS OFPs were based on mature existing MSIP OFPs. Due to the maturity of their software, MSIP no longer tested their OFPs at the unit level. Instead, testing consisted of functional integration of each patch, followed by formal SAV&V testing of the entire OFP. This high-level testing methodology was also implemented for the AFTI/F-16 OFPs. As the patched OFPs were released from development, each new patch was examined for functional correctness. This was accomplished at the MSIP DEEU STS in the SIL, and was performed by the lead mechanization engineer on the software test station. Following functional integration of the new patches, the functional integrity of the entire OFP was determined according to the current system design specifications. This was accomplished on the MSIP DEEU STS at the SIL, and was performed by an independent test engineer.

ACRONYMS AND ABBREVIATIONS

ACIU	Advanced Central Interface Unit
ADIR	AMAS Director
AFTI	Advanced Fighter Technology Integration
AMAS	Automated Maneuvering Attack System
APPT	AMAS Pre-Planned Target
ASMS	Advanced Stores Management Set
CCIL	Continuously Computed Impact Lines
CMFD	Color Multifunction Display
CMRS	Color Map Reader System
CPDG	Color Programmable Display Generator
CPT&E	Computer Program Test and Evaluation
CRT	Cathode Ray Tube
CSE	Computer Support Equipment
DCR	Design Change Request
DEC	Digital Equipment Corporation
DE/CIS	Data Entry/Cockpit Interface Set
DEEU	Data Entry Electronics Unit

DFCS	Digital Flight Control System	MUX	Multiplex Bus
DMA	Defense Mapping Agency	OFF	Operational Flight Program
DMG	Digital Map Generator	PDG	Programmable Display Generator
DMUX	Display Multiplex Bus	PDU	Programmable Display Unit
DSP	Digital Signal Processor	PROM	Programmable Read Only Memory
DTMDS	Digital Terrain Management and Display System	R&E	Research and Engineering
EEPROM	Electrically Erasable Programmable Read Only Memory	RALT	Radar Altimeter
EFCC	Enhanced Fire Control Computer	RAM	Random Access Memory
EPRM	Erasable Programmable Read Only Memory	RF	Radio Frequency
FCC	Fire Control Computer	RIU	Remote Interface Unit
FCR	Fire Control Radar	RJE	Remote Job Entry
FCS	Fire Control System	RSU	Remote Station Unit
FLIR	Forward-Looking Infrared Radar	SAIF	Standard Avionics Integrated Fuze
GFE	Government-Furnished Equipment	SAV&V	Stand-Alone Verification and Validation
GLOC	G-Induced Loss-of-Consciousness	SCR	Software Change Request
HMS	Helmet-Mounted Sight	SEA	Sight Electronics Assembly
HUD	Head-up Display	SES	Software Engineering System
ICD	Interface Control Document	SIL	System Integration Laboratory
IFF	Identification Friend or Foe	SITAN	Sandia Inertial Terrain-Aided Navigation
IFFC	Integrated Fire and Flight Control	SMS	Stores Management Set
IKP	Integrated Keyboard Panel	SOW	Statement of Work
I/O	Input/Output	STS	Software Test Station
LARAP	Low-Altitude Radar Auto Pilot	SWIM	System-Wide Integrity Management
LOS	Line-of-Sight	TALOSS	Target and Line-Of-Sight Simulation
LRU	Line Replaceable Unit	TACAN	Tactical Air Navigation
MFDS	Multifunction Display Set	UDF	Unit Development Folder
MIPS	Million Instructions Per Second	V&V	Verification and Validation
MSIP	Multinational Staged Improvement Program	VIA	Voice Interactive Avionics
		WEC	Westinghouse Electric Corporation

Advanced Fighter Technology Integration Automated Maneuvering

Attack System Interim Flight Test Results

D. J. Dowden
D. C. Ford

ADVANCED FIGHTER TECHNOLOGY INTEGRATION
AUTOMATED MANEUVERING ATTACK SYSTEM
INTERIM FLIGHT TEST RESULTS

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ABSTRACT

The Advanced Fighter Technology Integration (AFTI)/F-16 Automated Maneuvering Attack System (AMAS) is in developmental flight testing at the Air Force Flight Test Center (AFFTC), Edwards Air Force Base, California. AMAS testing commenced in September 1984, with one hundred test sorties totaling 158.8 flight hours flown at the time of this interim report. The flight tests are being conducted by the AFTI/F-16 Joint Test Force, which is comprised of AFFTC, NASA-Ames Dryden, and General Dynamics personnel.

The overall thrust of the developmental flight test program is to develop automated guidance and control systems for air-to-ground and air-to-air weapon delivery. The developmental test bed is an NF16-S/N 75-750 which has been modified with an asynchronous digital flight control system, dual avionics multiplex buses, an advanced forward looking infrared sensor-laser ranger sensor, integrated fire/flight control software, advanced cockpit displays/interfaces, and modified core MSIP avionics. This paper will present interim flight test results pertaining to the AMAS development.

ABBREVIATIONS

ADIR - AMAS Director
AFTI - Advanced Fighter Technology Integration
AGL - Above Ground Level
ALC - Automatic Level Control
AMAS - Automated Maneuvering Attack System
APPT - AMAS Pre-Planned Target
ASE - Aeroservoelasticity
DFCS - Digital Flight Control System
DSC - Digital Scan Converter
FCC - Fire Control Computer
FCR - Fire Control Radar
FLIR - Forward Looking Infrared
FOV - Field of View
GCA - Ground Collision Avoidance
HMS - Helmet Mounted Sight
HUD - Head Up Display
IFFC - Integrated Fire Flight Control
INU - Inertial Navigation Unit
KCAS - Knots Calibrated Airspeed
LARAP - Low Altitude Radar Autopilot
LRU - Line Replaceable Unit
MDA - Minimum Descent Altitude
MFD - Multifunction Display
MSIP - Multinational Stage Improvement Program
NWL - Non-Wings Level
PDRR - Pre-Determined Release Range

RALT - Radar Altimeter
STS - Sensor Tracker System
SWIM - System Wide Integrity Management
VPS - Vertical Planning Scale
YAG - Yttrium Aluminum Garnet

INTRODUCTION

The AFTI/F-16 AMAS development flight test program is Phase II of the overall AFTI/F-16 development/demonstration program. Phase I Digital Flight Control System (DFCS), conducted between June 1982 and July 1983, developed and demonstrated a new asynchronous, triplex, digital flight control system; multi-mode task tailored flight control laws; six degree-of-freedom decoupled motion; and new pilot vehicle interfaces.

The AFTI/F-16 flight test program is being accomplished by the AFTI/F-16 Joint Test Force, Edwards Air Force Base, California. The AFTI/F-16 Joint Test Force is comprised of personnel from the Air Force Flight Test Center, NASA-Ames/Dryden, and General Dynamics. The overall AFTI/F-16 test program is managed by the AFTI/F-16 Advanced Development Program Office (ADPO), the Air Force Wright Aeronautical Laboratory (AFWAL), and the Air Force Flight Dynamics Laboratory (AFFDL), Wright-Patterson Air Force Base, Ohio.

PROGRAM SUMMARY

Scope and Objectives

The overall scope of the AFTI/F-16 test program is planned to encompass approximately 170 total test missions over a span of 24 months. The primary program objective of the AFTI/F-16 development program is to develop and demonstrate new technology design alternatives for future fighter aircraft. Specific test objectives of the AFTI/F-16 Phase II AMAS flight test program are as follows:

1. Demonstrate the weapon delivery capability and quantify accuracy of the AMAS.
2. Assess the increase in survivability during the weapon delivery phase achievable as a result of the AMAS maneuvering profile.
3. Determine the pilot acceptance, adaptability, and workload associated with AMAS.

4. Demonstrate the weapon delivery capability achievable from the integration of multi-sensor (e.g. wing strake-mounted FLIR, HMS, fire control radar, and radar altimeter).

5. Establish design criteria and recommendations for AMAS technology application and integration of associated technologies.

The above major objectives are the main reason for conducting the extensive AFTI/F-16 flight test program; however, the vehicle also contains significant technological improvements in specific subsystems in addition to their integrated usage for automatic weapon delivery. A series of sub-objectives has been established to collect data concerning their performance and utility. The sub-objectives of the AMAS flight test are to:

1. Demonstrate the target acquisition/tracking capability of a wing strake-mounted sensor tracker pod in maneuvering weapon delivery.

2. Demonstrate the off-boresight target designation capabilities of the helmet mounted sight system.

3. Assess the cockpit displays, controls, and methodology for pilot vehicle interface.

4. Demonstrate low altitude radar auto pilot (ARAP) capabilities at low altitude.

5. Validate the effectiveness of the system de integrity management (SWIM) concept, including collision avoidance.

Test Approach

In order to achieve the aforementioned program objectives, the AMAS flight test development program was segmented into two distinct stages; Phase A - uncoupled manual development of the air-to-ground AMAS system, ensuing flight envelope expansion, and new sensor tracker set (STS) forward looking infrared system functional checkout; Phase B - coupled automated air-to-ground and air-to-air weapon system development integrated with the STS as the primary target sensor.

Test Summary

The overall AMAS test program has been in progress since September 1984. A total of 100 test sorties, totalling 158.5 flight hours have been flown to date in development of AMAS. Figure 1 and Figure 2 provide a summary of test flight hours flown and specific test development activities respectively. Phase A and Phase B test summaries are as follows:

AFTI/F-16 FLIGHT TEST SUMMARY

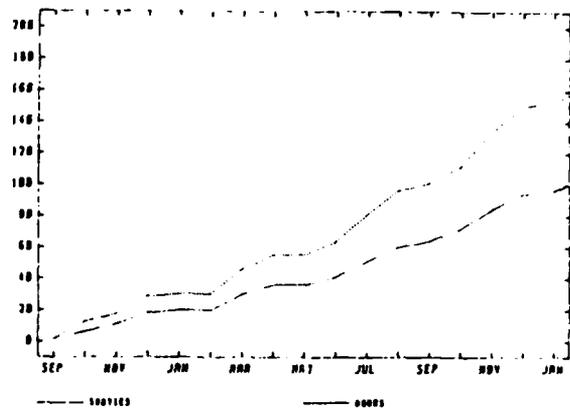


Figure 1 AFTI/F-16 Flight Test Summary

AMAS FLIGHT TEST SUMMARY

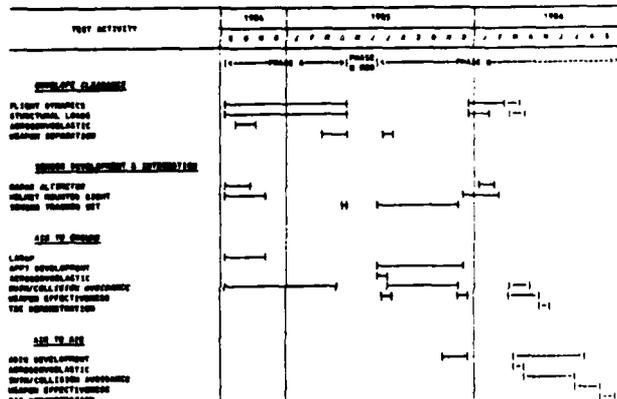


Figure 2 AMAS Flight Test Summary

Phase A commenced in September 1984 and ended in April 1985 with a total of 41 test sorties totalling 62.5 flight hours. Manual air-to-ground AMAS control law envelopes were developed, system wide integrity management was developed, low altitude radar auto pilot was demonstrated, structural roll rate limiter tested, and a limited STS development and BDU-33 bomb envelope cleared for non-wings level (NWL) delivery.

Phase B commenced in June 1985 and was still in progress at the time this paper was written. Phase B test activity to date has been 59 test sorties totalling 96 flight hours. Major test emphasis in Phase B has been in coupled air-to-ground AMAS envelope development; STS air-to-ground tracking with laser ranging; AMAS BDU-33 weapon delivery; aeroservoelasticity (ASE) coupled envelope clearance; air-to-ground collision avoidance SWIM testing; cockpit display evaluations; and the completion of structural roll rate limiter testing left over from Phase A.

TEST ARTICLE DESCRIPTION

The AMAS phase of the AFTI/F-16 program has built on the technologies demonstrated in the DFCS phase to achieve automated maneuvering weapon delivery. Additional sensors were added to acquire and track the target, determine target state information, and measure altitude above ground level. The integrated fire and flight control (IFFC) system has provided automated maneuvering weapon delivery, requiring only pilot consent for weapon release. A SWIM system protects against potentially catastrophic component/system miscalculations or failures of single strand components. The pilot will be able to maintain tactical situation awareness and keep abreast of system performance through enhanced pilot-vehicle interface controls and displays.

Test Aircraft Configuration

The AFTI/F-16 is a highly modified F-16A aircraft. The modifications include an asynchronous operation, triplex digital flight control system, which provides multiple in-flight-selectable task-tailored flight control laws, including six-degree-of-freedom decoupled aircraft motions. Vertical canards are mounted from actuators in each side of the lower portion of the engine inlet. A fuselage dorsal fairing was added to provide more room for avionics and instrumentation hardware. A 10.5 inch diameter forward looking infrared (FLIR)/neodymium (YAG) laser STS is mounted conformally in the right wing root with an aerodynamically similar "dummy pod" mounted in the left wing root. A nearly "all attitude" radar altimeter is installed utilizing a four antenna pattern around the forward fuselage. See Figure 3 for overall aircraft configuration. A helmet mounted sight (HMS) system is installed in the cockpit. New and modified cockpit controls and displays include a redesigned sidestick controller incorporating eight switches, a linear motion throttle with a twist action grip for controlling longitudinal decoupled motion and AMAS functions, a conventional optics wide field-of-view head-up display, and three multifunction display cathode ray tubes for system control and display. See Figure 4 for cockpit layout.

**AFTI/F-16 Technology Demonstrator
A Proven Testbed for Advanced Ideas**

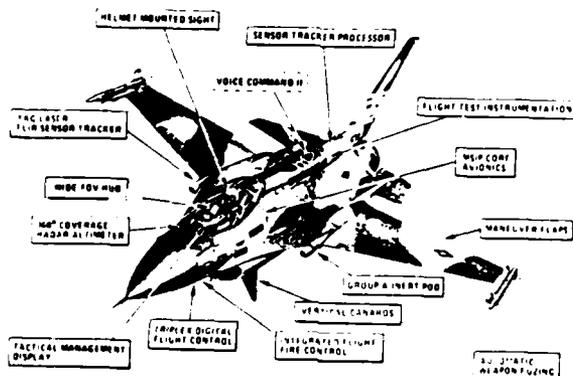


Figure 3 AFTI/F-16 Aircraft Configuration

AMAS Cockpit Arrangement

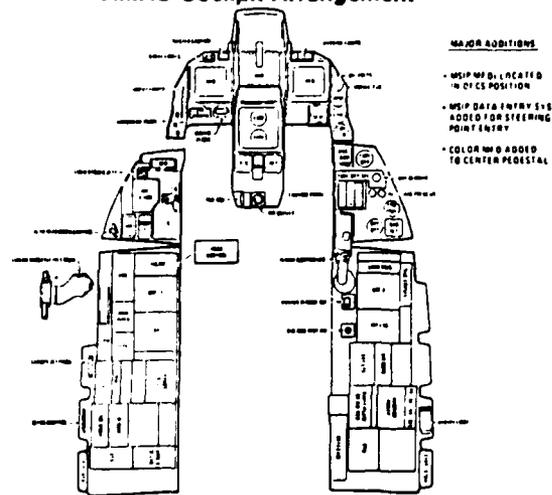


Figure 4 AMAS Cockpit

The core avionic hardware and software for AMAS is the F-16 Multinational Staged Improvement Program (MSIP) system. The hardware is essentially unmodified and the software is highly modified to accomplish AMAS functions. The integration of sensors, fire control, flight control, stores management, and cockpit displays is accomplished through a bus architecture of three 1553 multiplex buses as shown in Figure 5.

**The AMAS System Derives Its Hardware and Software
from Three Major Sources**

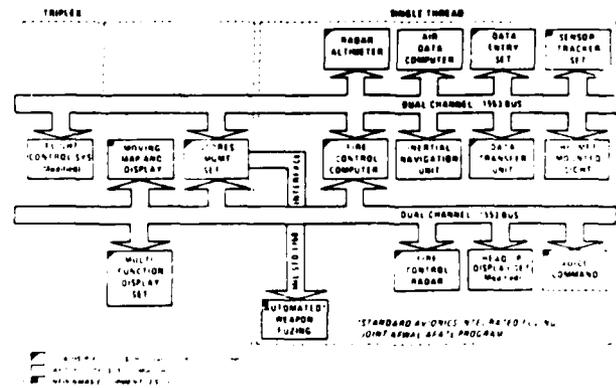


Figure 5 AMAS Avionics Multiplex Bus Configuration

The aircraft is very heavily instrumented which provides the capability to conduct multi-discipline flight tests on any given flight or series of flights with no hardware or software modifications (i.e. flying qualities, structural loads, flutter, aeroservoelasticity, weapon separation, avionic subsystem development and performance, and AMAS development and performance data can be recorded and monitored simultaneously). The Airborne Data Acquisition System includes a

14-track magnetic tape recorder, time correlation system, two PCM subsystems, two MUX bus interface systems, video recorder system, weapon separation camera system and a telemetry system. The total on-board recording capability includes 200 hard wired data parameters (PCM #1), 400 selected A and D MUX parameters (PCM #2), total A and D MUX traffic, audio, and one video channel. The telemetry system consists of four down links continuously transmitted to the ground. Capability includes 200 hard wired data parameters (PCM #1), 400 selected A and D MUX parameters, one video channel and an audio channel. All of these are available for real time monitoring in the ground control station.

AMAS Design Mission

It is apparent that our potential adversaries continue to produce more sophisticated and capable surface and airborne weapon systems imposing an increasingly higher threat environment. We must counter this threat by minimizing the exposure. AMAS is designed to do this by conducting effective weapon deliveries from less predictable flight path maneuvers and accomplishing the weapon deliveries at low altitude where the threats are less effective. The primary AMAS objective is to do this while maintaining or exceeding previous levels of weapon accuracy and with no increase in pilot workload.

The AMAS approach is to conduct air-to-surface weapon deliveries out of a curvilinear flight path at very low altitudes (200 ft AGL). The design mission is separated into three distinct parts: ingress, curvilinear steering, and egress (see Figure 6). Ingress to the target is accomplished with the assistance of the LARAP for altitude control and destination steering for azimuth control. Upon target visual identification, the pilot may hand the target off from the radar inertial navigation system (INS) or the HMS to the forward looking infrared radar (FLIR), lock the FLIR on the target, and engage IFPC. Ingress continues on LARAP and steering sets up for a curvilinear weapons delivery. Based on aircraft position and velocity relative to the target, weapon ballistics, and predetermined release range (PDRR), the fire control computer (FCC) computes a curvilinear bombing maneuver with load factors up to 5 "g" which will achieve a weapon delivery solution. The computed maneuver profile is symbolically presented in a vertical planning scale in the HUD for manual control of curvilinear bombing. In automatic operation, the FCC sends commands to the DFCS in the form of bank angle and load factor to accomplish the computed bombing maneuver. When IFPC is engaged the pilot need only to consent for weapon release, and the weapon will be released automatically when the computed accuracy of the weapon delivery solution satisfies preset criteria. Upon release of the weapon, the system immediately enters an egress mode. Egress consists of a descending turn to the minimum descent altitude (MDA) that the pilot has preselected. Once the MDA is obtained, the pilot resumes manual aircraft control.

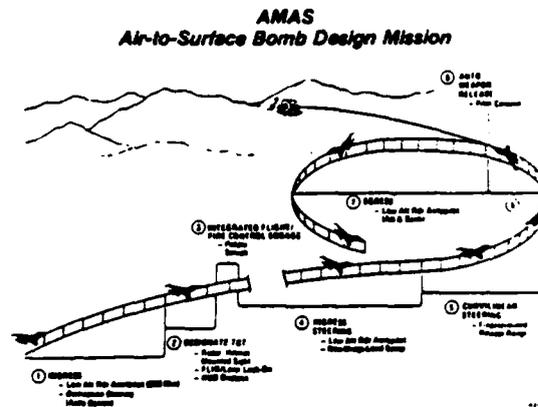


Figure 6 AMAS Air-to-Surface Design Mission

When conducting missions at very low altitudes (down to 200 feet AGL), the primary concern is quite naturally aircraft and system safety. AMAS includes two unique design features intended to enhance aircraft and system safety. SWIM provides for ground and target collision avoidance and system failure monitoring. Ground collision avoidance is based on the concept of a pilot-selectable minimum descent altitude (i.e. floor) that the aircraft is not allowed to penetrate. Should penetration be predicted, an automatic 5 "g" fly-up maneuver is activated. In air combat, a breakaway maneuver is activated when a minimum avoidance criteria is violated. SWIM also provides system failure monitoring through the use of subsystem self test, interactive built-in test, and FCC and DFCS fault monitors which provide a measure of system operating integrity. SWIM provides a rapid assessment of situation hazards resulting from malfunction or miscalculation of the subsystems. Based on these assessments, timely action follows to provide 1) a safe recovery from the situation, 2) detection of suspected subsystem, 3) orderly resumption of manual pilot control, and 4) proper identification and annunciation of faults. The use of a SWIM system is essential in the case of the AFTI/F-16 where many systems and sensors that control coupled flight are only single strand.

The integration of these systems, subsystems, and design features has provided a truly automated maneuvering attack system. Since the AFTI/F-16 project is an advanced technology development/demonstration program, it was only intended to validate the design concept and not produce a production ready product. Therefore, AMAS does have some undesirable limitations (i.e. ground collision avoidance operation could only be validated over terrain with less than 2 percent slope because the system had no forward looking capability) that would not be present in an operational ready system.

FLIGHT TEST RESULTS

Aircraft Flight Envelope Clearance

At the conclusion of the DFCS phase of the flight test program the aircraft had been cleared for a Mach/altitude/maneuver flight envelope essentially the same as the F-16 flight envelope, below 1.2 Mach. This clearance included the task tailored modes of normal, air-to-air gun, air-to-surface gun, and air-to-surface bomb.

The aircraft modifications to install AMAS in the aircraft and the modifications to improve DFCS operation for AMAS invalidated portions of the DFCS flight envelope clearance requiring retest or flight envelope expansion tests for new modes/capabilities. The AMAS modifications included MSIP core avionics hardware, modified MSIP avionics software, a new STS, a modified radar altimeter (RALT), low altitude radar autopilot (LARAP) software, a helmet mounted sight (HMS), AMAS pre-planned target (APPT) algorithm for air-to-ground, and an AMAS director (ADIR) algorithm for air-to-air. The DFCS improvement modifications included one hardware change and several flight control law changes. The following sections detail the flight envelope clearance flight tests accomplished to provide the flight envelopes presented in Figures 7a and 7b.

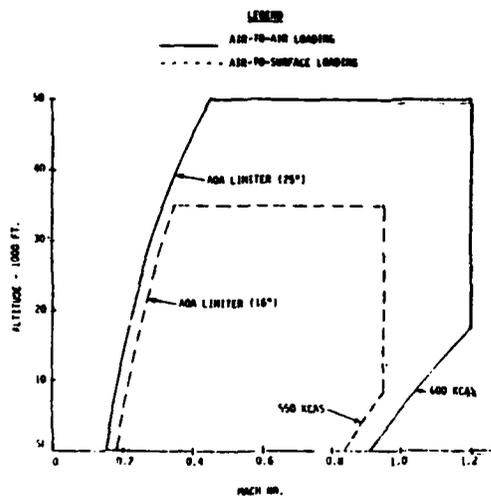


Figure 7a AFTI/F-16 Flight Envelopes

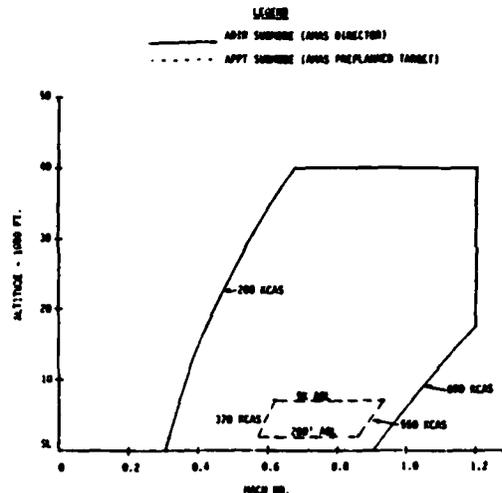


Figure 7b AFTI/F-16 AMAS Flight Envelope

Flight Dynamics

The addition of the pod mounted STS, the DFCS rate gyro input impedance change, and the DFCS control law changes dictated that the aircraft flying qualities be rechecked throughout the flight envelope, including high angle of attack. Predominantly open loop maneuvers were utilized to recheck the normal, air-to-surface bomb and air-to-air gun flight control modes.

The STS installation had no significant effect on flying qualities, buffet, or drag. No specific tests were accomplished to quantify buffet or drag, but pilot comments indicated the effects were minimal. The aircraft flying qualities/handling qualities were retested, including high angle of attack, with no degradation noted from DFCS flight test. One possible small adverse effect was noted; angle of sideslip during rolling maneuvers at midrange angles of attack increased approximately 2 degrees.

DFCS flight test results showed that maximum attainable load factor and maximum pitch rate were deficient. Late in the DFCS test program, an error was found in the impedance balancing of the DFCS rate gyros. This imbalance was corrected and AMAS flight tests demonstrated that the major DFCS shortcomings of low maneuvering "g" onset rate and low attainable load factor were corrected.

Phase I DFCS results showed a tendency for the pilot to overcontrol in the roll axis, resulting in a phenomenon called roll ratcheting. A variable lead-lag filter was added to the lateral axis of the DFCS. AMAS flight tests were inconclusive but indicate little or no improvement in roll ratcheting. However, at high speed (>450 KIAS) the pilots report less tendency for roll ratchet than the F-16.

Also, DFCS test results showed it was possible to depart the aircraft from controlled flight when rolling in combination with yaw pointing (roll

coupling). The DFCS was modified to reduce roll rate command as a function of rudder pedal command and reduce rudder pedal command as a function of roll rate and angle of attack. AMAS high angle of attack tests demonstrated that the departure susceptibility problem had been improved.

For AMAS, the DFCS was modified to automatically limit roll rate command above 5.86 "g" to reduce structural loads (discussed in detail under Structural Loads). Since the F-16 and the AFTI/F-16 had never flight tested rolling maneuvers above 5.86 "g", the aircraft flying qualities were closely monitored during these structural loads tests. They were satisfactory with one exception; on two occasions when elevated load factor rolls were conducted in the transonic speed range (0.96 Mach) below 20K altitude, the aircraft exceeded the flight control system "g" limiter setting by approximately 1.0 "g". It appears that the transonic pitch-up experienced as the aircraft accelerates between 0.95 and 0.92 Mach (caused by a forward center of pressure shift) is defeating the DFCS "g" limiter function. The "g" limiter is designed to limit pitch command as required to obtain 9.0 "g" and if 9.0 "g" is exceeded, it backs out the command. Apparently, if the pitch-up onset rate is high enough, the DFCS compensation rate is not sufficient for the dynamics of the maneuver. This problem is under investigation at the present time.

Aeroservoelastic Tests

The development of these advanced task tailored control modes and three functionally different closed loop automated modes (LARAP, APPT, and ADIR) dictated that flight tests be conducted to demonstrate freedom from ASE instabilities. The basic aircraft structure and flight control surface stiffness was not changed, therefore flutter tests were not required.

The DFCS pitch rate gyro impedance change modified the pitch channel gains sufficiently to require ASE retest of the basic DFCS modes. There is a small decrease in damping in the antisymmetric wing tip missile pitch vibration mode. Within the aircraft flight envelope, the damping levels exceeded 0.03 damping ratio and were satisfactory.

ASE flight tests were conducted in LARAP and APPT modes across the allowable speed range (maximum speed of 0.95 Mach/600 KCAS). All ASE damping levels exceeded 0.03 damping ratio and were satisfactory. ASE flight tests in ADIR have not been conducted as of this writing.

Structural Loads

The primary structural loads for all allowable F-16 and AFTI/F-16 maneuvers have been determined from flight test data. For gross weights below the aircraft design weight (22,500 lbs), structural loads for all maneuvers tested including AFTI peculiar maneuvers (i.e. flat turn, yaw pointing, etc.) remain below 100 percent design limit load with one exception; the AFTI/F-16 is an F-16A FSD

aircraft and has a slightly lower wing bending moment structural load limit (fuselage bulkhead strength limit) than the production F-16A. Above 0.9 Mach and below 15K feet, the allowable gross weight for 9.0 "g" is reduced by 1300 lbs, and the allowable normal load factor above that weight is reduced to 8.5 "g".

Structural load monitoring during automated APPT operation, LARAP operation, and SWIM automated fly-ups has shown that the loads remain well within 100 percent design limit loads.

The automated ADIR air-to-air mode has full control authority throughout the flight envelope, the same authority as the pilot. The F-16 and other fighter aircraft have handbook restrictions against rolling at elevated normal load factors (normally above 5.86 "g"). This full authority required the design and development of a roll rate limiter in order to maintain 9 "g" automated air-to-air maneuver capability and keep structural loads within limits. The roll rate limiter reduces DFCS roll rate command as a function of "g" to maintain wing bending moment/torsion within limits. The limiter design/operation was validated in the AFTI/F-16 simulator and flight test is in progress. Preliminary test results show that the limiter does limit roll rate as a function of "g" and keeps structural loads within limits; however, it appears that there will be a small area in the lower right corner of the flight envelope where rolls above approximately 8.0 "g" at design gross weight will not be allowed. The reason for this limit is the same as the wing bending moment limit previously discussed. The addition of a roll maneuver on top of the symmetric maneuver is expected to make the limit slightly more restrictive. The exact limits have not been defined.

The control law design flexibility permitted by the digital flight control system has proved to be an invaluable tool. It is now possible to tailor aircraft maneuver capabilities and resultant structural loads to a specified level within the strength envelope. This capability can be used in future applications to more efficiently utilize aircraft structural capability. The AFTI/F-16 program, as we know it, could not have been accomplished without this capability.

Weapon Separation

The basic F-16 BDU-33 weapon separation clearance was no longer valid due to AFTI/F-16 aerodynamic changes (vertical canards), flight control system control law changes (six degree-of-freedom motion and maneuvering flap deflections), and advanced weapon delivery capabilities (curvilinear non-wings level elevated load factor deliveries). Nine weapon separation clearance runs were accomplished. The aircraft is cleared to release BDU-33 practice bombs within the following limits; ± 180 deg bank angle, 0.5 to 5.0 "g", 0 "g" lateral acceleration, ± 1.0 deg sideslip, 0 deg/sec roll rate, and ± 10 deg angle of attack.

Air-to-Ground AMAS System

The air-to-ground AMAS flight test development consisted of envelope clearance of system submode features that when integrated provided the APPT system. The submode or system tests that supported APPT development were: LARAP for ingress and egress; SWIM for aircraft system status and state; APPT guidance and control for curvilinear deliveries; and integrated APPT weapon delivery performance.

Overall, automated APPT system performance has been consistent, repeatable, and reduced pilot workload during the curvilinear portion of the weapon delivery. Limited manual deliveries have been evaluated using APPT displays, but it should be noted that manual APPT deliveries may be as consistent and repeatable as the automated task but only at the expense of increased pilot workload and reduced tactical situation awareness.

The following sections provide specific test results pertaining to APPT system submode and weapon performance development.

Low Altitude Radar Auto Pilot (LARAP)

The LARAP system performance has been adequate over flat terrain (terrain elevation changes of less than 2 deg slope) during wings-level flight. The system has demonstrated low damping when acquiring a reference altitude. Pilots have noted a rough ride quality when using LARAP over rolling terrain. To date, performance of LARAP during elevated bank angles has been poor with the control system not rolling out enough to counter descent rates causing large (200 ft) penetrations of desired altitude. Future control law development looks promising and should correct this problem.

Pilot blending was evaluated and was judged adequate in roll but sensitive in the pitch nose down direction. The LARAP system has been cleared for operation in the following envelope: airspeed 267-550 KIAS, 500 feet-20K feet AGL with 360 deg rolls.

In summary, LARAP performance has been as good as can be expected for a system with no look-ahead capability for changing terrain features. Testing on the AFTI/F-16 has proved that a system with look-ahead capability is mandatory for a low altitude autopilot.

System Wide Integrity Management (SWIM)

The SWIM system has performed its design function satisfactorily. These functions include: monitoring of sensor data and sensor selection, subsystem failure detection and monitoring, aircraft state monitoring and corresponding restrictions for IPFC operation, and fault reporting.

SWIM was robust as well as being conservative when envelope design limits were approached. It either disconnected APPT/LARAP and/or generated aircraft flyups. One case of this conservative nature worth mentioning was the high rate toggling

(50 Hz) between the fire control radar (FCR) and RALT sensor data for source selection. This would consistently cause system disengagements. All other functions performed by SWIM worked in a desirable manner.

The SWIM concept has proven to date to be a reliable means of providing an increased artificial level of avionics redundancy with regard to single strand computers and sensors integrated with a triply redundant flight control system. SWIM has reduced risks of flight tests of AMAS.

Ground Collision Avoidance (GCA): Initial flight test development of the empirically derived GCA flyup algorithm demonstrated problems with penetrations of minimum descent altitude (MDA). MDA penetrations of up to 350 feet occurred due to slow "g" onset rates at flyup initiation. The "g" onset rates were increased by altering several prefilters in the control laws. This minimized MDA penetrations; however, small penetrations were still experienced. Algorithms were altered to be more conservative and to provide a flyup initiation altitude equivalent to a one-second pilot reaction time. This reaction time was defined by minimum above ground level (AGL) altitude divided by vertical velocity at flyup initiation.

These changes to the GCA algorithm have fundamentally resolved any MDA penetrations with GCA exhibiting a conservative, reliable, and predictable performance.

GCA was evaluated on various combinations of airspeed, dive angle, roll angles, roll rates, load factors, and gross weight/CG's. Data show increased conservatism (larger altitude pad) at envelope extremes. Alternate sensor configurations were evaluated for GCA using RALT and FCR as AGL sensors; however, the FCR mechanization proved inadequate as a source for AGL data at bank angles greater than 15 degrees. No development was attempted on the FCR for this application.

Overall, 61 test runs on the developed GCA algorithm have been flown to date with no MDA penetrations attributed to system performance. Two MDA penetrations did occur inadvertently but were explained due to a pilot input on one and outside GCA design limits on the second. Ninety percent of all runs down to 500 ft AGL have demonstrated a minimum flyup initiation reaction time of .8 seconds, which was what was desired by the AFTI/F-16 pilots. The .8 second minimum reaction time is the time allowed after which the pilot must initiate a 5 "g" pull to avoid MDA penetration. The smallest margins of recovery altitude above MDA and minimum reaction times were at high airspeed and low dive angles.

APPT Control Law Development

Three separate control laws are used in an APPT delivery: ingress, curvilinear, and egress. These control laws were tested both separately and in a combined sense. The characteristics, complexity, and development of these control laws

were all different, and the level of refinement is different for each.

Ingress steering was the most simplistic of the three control laws. The pitch axis was controlled by LARAP, its function being to maintain constant AGL altitude. Ingress performance was adequate for level terrain but had the same problems associated with LARAP (see LARAP test results for further details). The ingress roll axis was similar to LARAP but included the added task of acquiring the appropriate heading for the setup of curvilinear steering. The basic roll axis also had the same problems as LARAP; allowing as much as 200 feet of altitude loss during high bank turns when correcting for large target bearing errors. At the writing of this paper a change to the LARAP roll axis has been made which should correct this problem. Ingress steering also used flat turn for the final angular correction. The performance of flat turn was adequate for making these small corrections. Both the roll and flat turn of ingress steering were well damped and demonstrated no tendencies for overshoots. The ride quality of ingress steering was satisfactory in pitch and roll with crisp aggressive responses. The ride quality of flat turn on the other hand was not satisfactory. Pilots found that when controlled manually, flat turn was not uncomfortable and proved very useful. During coupled flight, the pilot had little indication to anticipate flat turn. Also, flat turn is an unnatural aircraft response (sideforce), and when performed automatically it proved unsettling to the pilot. Flat turn will continue to be developed for more acceptable ride quality.

Curvilinear development resulted in a relatively robust and consistent weapon delivery system. All responses were well damped and attained desired values (load factor, roll rate, bank angle) with a fair degree of accuracy. Last minute target jumps of up to 1500 feet, seconds before release, could be withstood and still result in successful deliveries. Only diving deliveries resulting in recovery altitudes close to the MDA demonstrated less than acceptable success. This deficiency was primarily due to inaccuracies in the delivery profile prediction coupled with the GCA system. The APPT-calculated profile release condition was below the MDA and thereby aborted the APPT bombing pass. The most significant developmental change to curvilinear steering was changing from a maneuver centered about the target to a maneuver centered about a ballistically determined point above the target. Prior to this change, deliveries were inconsistent especially in the case of lofting deliveries. The ratio of aborted deliveries to successful was on the order of one out of five prior to the change, whereafter this ratio was around one out of fifteen.

After the change, the ride quality of curvilinear steering was acceptable with "crisp" roll and "g" onsets. The pilot could also blend with curvilinear steering to alter the delivery profile. Although blending was possible, it was difficult due to inadequate displays and an unsatisfactory flat turn response caused solely by the blending.

Because of this, pilots preferred the automated system over the manual system.

Egress to date has had very little success. The egress control laws were very similar to LARAP and because egress always used high bank angles, it performed poorly due to LARAP's shortcomings at these conditions; however, with changes being implemented at the writing of this paper, egress performance is expected to be greatly improved. The ride quality of egress was considered good during its initial roll and pull maneuver but its steady state decent was too gradual. At the writing of this paper a more aggressive egress has been implemented but has not yet been evaluated. At its best, egress must live with the LARAP 2 percent terrain slope limitation. With a look-ahead capability, an automatic egress as implemented on the APTI/F-16 could be very useful.

Sensor Development

The AMAS design added three new sensors to the aircraft. A modified F-16 RALT system was installed for accurate AGL information at any bank angle for operation in LARAP. A new FLIR/laser STS was incorporated to provide accurate target position data. A HMS was installed in the cockpit for the pilot's use in cueing the STS to the target.

Radar Altimeter (RALT)

The RALT installation includes four antennas located 90 deg apart around the fuselage that are switched as a function of roll angle to provide AGL altitude data through 360 deg roll angle. RALT performance data was collected during steady state and dynamic maneuvers at altitudes down to 500 ft AGL and was found to be reliable and consistent. The maximum measured error (RALT vs. phototheodolite data) was 30 ft high, i.e. the RALT indicates 30 ft higher than the aircraft really is. This error was a function of pitch angle. There were no measured errors as a function of speed, altitude roll angle, or antenna switching. At 0 deg pitch angle, RALT error was near zero; and as pitch angle increased, the RALT error increased in a smooth and consistent pattern. During all testing (rolls and dynamic elevated load factor maneuvers), the RALT antenna switched smoothly with no noticeable effect on performance. The RALT has supported LARAP, IFFC, and ground collision avoidance flight tests with consistent reliable operation. RALT operation above 5K AGL is somewhat limited but does not impact project goals.

The integration of RALT into AMAS resulted in some system integration problems. The AGL rate output from RALT had occasional one frame dropouts that resulted in nuisance DFCS single failures when flying the system closed loop in LARAP mode. Since the DFCS is an asynchronous system (operates with time skew between computers), it was possible for two computers to see the AGL rate dropout and the other one not to see it in the same frame. This resulted in a large difference between computers in total computed output to the flight control surfaces. The DFCS redundancy management system monitors total computed output commands, compares

them; and if they differ by more than approximately 15 percent of full surface travel, the offending computer is voted off line. Early in LARAP flight test, this happened several times. The fault was reset, and the flight continued. The problem was corrected by installing two software modifications in AMAS. A filter was installed in the FCC to limit the magnitude of the AGL rate change in one frame to a specified value. This would limit the change in DFCS total computed output commands to a smaller value. The LARAP control laws in DFCS had an iteration rate of 32 Hz. This rate was changed to 64 Hz which decreased the probability of the DFCS computers miscomparing. LARAP has been extensively flight tested subsequent to these changes and the anomaly has not reoccurred.

Early in LARAP flight test, it was determined that RALT does not have an AGL rate output at altitudes greater than 5K AGL. Implementation of AGL rate data was changed such that inertial vertical velocity was used above 5K, blended with RALT AGL rate between 5K and 3K, and RALT AGL rate used below 3K AGL. This implementation produced satisfactory results and made LARAP usable above 5K altitude. Other early LARAP flight test showed LARAP to have much less damping in the pitch axis than was anticipated through simulation. It was found that no attention had been paid to the dynamic response to altitude change of the RALT. After the appropriate dynamic characteristics had been modeled, LARAP was modified to compensate for the altitude lag of the RALT and appropriate damping resulted.

Sensor Tracker System

The Westinghouse STS consists of three line replaceable units (LRUs) - the STS head, conformally mounted in the right strake; the processor, installed in the dorsal bay; and the auxiliary power supply, installed in the right side inlet bay. The STS is an integrated FLIR sensor, laser ranger, processor, and closed loop tracking system which was designed to complement the fire control functions of the AFTI/F-16 avionics. The FLIR utilizes infrared radiation emitted naturally by all objects to produce a TV-display-compatible image of the temperature differences in the scene. The FLIR has three fields-of-view (FOV) selectable by the pilot. The laser ranger operates in two modes. A narrow beam air-to-ground mode and a wide beam air-to-air mode. The STS capabilities include: 1) tracking of air-to-ground and air-to-air targets, 2) accurate target line-of-sight measurements, 3) FLIR video imaging of target, 4) accurate laser ranging at low grazing angles, and 5) accurate target state estimates of position, velocity, and acceleration.

The initial step was a functional test where the STS acquired and tracked a ground target. STS video quality, target acquisition, sensor control, and tracking capabilities were evaluated. Next, automated wings-level and curvilinear air-to-ground weapon delivery runs were accomplished to evaluate STS line-of-sight measurements and target state calculations using INS information for slant range. The next step was to integrate the laser ranger for

slant range target information. The last step was a demonstration of the STS during APPT weapon delivery test.

Several problems were encountered in STS flight test that required correction/development. In general, the STS has supported AMAS flight test very well, when you consider that its first flight was in April 1985. The STS development improvements included video image quality, tracking, pitch stability, laser range, system reliability, and mechanization changes. The following paragraphs discuss STS problems encountered during flight test and how they were corrected.

Early in flight test it was recognized that the video's automatic level control (ALC) in the tracker was marginal and was suspected of causing tracking problems. The ALC histogram's resolution algorithm was expanded from 6 bit to 8 bit to improve the auto level control and thermal reference control. This change improved brightness stability/video image quality. Tracking performance was also affected by non-reliable operation of the digital scan converter (DSC). The solder joints on leadless chip carriers have been a continuous source of trouble requiring an abnormal amount of maintenance. These DSC problems result in various forms of line structure across the video. A new technique to add solder post legs to the leadless chip carrier is in the works. The STS tracking performance has supported flight test goals but additional improvements are needed.

STS head stability has affected the ability of the pilot to control the STS during target acquisition. Head stability has not been a problem when locked on a target. Head stability was most affected when the aircraft was maneuvered (even small maneuvers) and when acquiring a target left or right of the aircraft. As target relative bearing increased, pilot workload during target acquisition increased. An improvement in head stability was made by replacing the HUD pitch rate input with a calculated pitch rate based on INU pitch attitude change. The HUD pitch rate has a time delay that rendered it ineffective. An additional change is in work. Time line execution within the STS operation flight program (input processing of heading change) is being improved. The major head stability deficiencies are caused by time delays between aircraft maneuvering and STS head response.

Initially, the laser had serious performance deficiencies during ground test and flight test. The laser would not range at ranges below approximately 3500 feet, and had marginal ranging success against low reflective targets at longer ranges. Investigation in the laboratory revealed the laser had backscatter from the optics reflected into the receiver. The backscatter was caused by laser energy reflections from damaged lens coatings. The backscatter blinds the receiver for a short time and lowers the receiver gain. A side effect of this was noted: at short ranges, the laser reported zero range to the FLIR causing it to unlock.

Since there is no requirement for air-to-ground laser ranges less than 1000 feet, the STS was programmed not to accept laser ranges less than 1000 feet. As a temporary resolution for ranging on low reflective targets, the target was augmented with a more reflective surface. This resolved the short term goal of utilizing laser range for AMAS development. Re-coating the optical lenses was not an option because the project has only one STS, and this would put it out of service for some time. A modification has been made to the laser and will be tested soon. The receiver was modified to decrease the recovery time of the laser threshold detector. Also, an increased receiver gain should provide for ranging on lower reflective targets.

As experience was gained by the pilots, it was determined that the STS mechanization was not optimum for use in flight. The field-of-view (FOV) switching order was mechanized to go from wide to medium to narrow. Target acquisition and tracking was best accomplished in narrow FOV and as range decreased switch to medium and wide. Mechanization was changed to allow this. The scaling of the cursor controlling STS line-of-sight was not optimum and made target acquisition difficult. Installation of pilot selectable scaling improved the acquisition task. In addition, the FCC OPF is being modified to give the pilot selectable cursor gains. One of the pilot selectable video display formats was "track up". The display was oriented with aircraft track (heading) at the top of the screen. When tracking a target with a substantial relative bearing, the display was confusing to the pilot because the target orientation was rotated from the vertical an amount equal to the relative bearing (i.e. a relative bearing of 90 deg rotated the target display 90 deg). "Track up" was changed to "sky up" and target orientation was always aligned with the horizon.

Helmet Mounted Sight

The Honeywell helmet mounted sight (HMS) installation consists of four line replaceable units: helmet mounted unit, transmitter, control panel, and sight electronics assembly. The function of the HMS is to provide the capability to cue the STS to off boresight ground targets and to increase the speed and ease of acquiring airborne targets by cueing the radar and STS. It has been demonstrated in flight test that the HMS is capable of successful "hand offs" to the radar and STS; however, at the present stage of development, the results have not been acceptable due to boresight errors.

The HMS has successfully cued the radar to air-to-air target line-of-sight within the radar gimbal limits resulting in radar lockons; however, HMS cueing of the STS has been unsatisfactory. Successful STS "hand offs" require the pilot to "slew" the STS acquisition gate over the target by moving his head after designate, while monitoring the FLIR video. This technique is not satisfactory for operational use. HMS reverse cueing errors from radar targets range from 20 to 70 milliradians. The errors appear to be a function of target azimuth with the larger errors for targets

further from the nose of the aircraft. The pilots generally agree that HMS reverse cueing error is of sufficient magnitude that it is unusable outside approximately 1NM. As presently mechanized, the STS requires cueing accuracies within 8 mils (2 miles narrow field of view) for successful handoff.

The presently known sources of HMS error are inaccuracies in cockpit magnetic field mapping and aircraft/systems boresight. The cockpit mapping was accomplished to obtain correction factors for cockpit magnetic field effects on the transmitter. The accuracy of the cockpit mapping is questionable because the mapping fixture did not fit the cockpit properly and 100 percent coverage of the cockpit magnetic field was not possible. The cockpit will be re-mapped with a modified fixture. In addition, the aircraft/systems boresight will be accomplished with a new boresight procedure. The original procedure boresighted all systems (INU, HUD, PCR, STS) with respect to the aircraft. The new procedure adds the requirement to boresight systems with respect to each other in order to reduce error.

Human Factors

Human factors evaluations of the AMAS and associated technologies has been limited due to developmental problems; however, some comments and observations are in order concerning APPT development and the color moving map.

Controls

During early AMAS weapon deliveries inadvertent sidestick inputs were detected. This problem was caused by a combination of two factors: 1) the G-force acting on the pilot's right hand and 2) the G-forces acting on the mass of the sidestick. With the pilot's hand on the weapon release button, up to six pounds of sidestick force were recorded. The intermediate solution to this problem was to have the pilot release the weapon with the alternate release button and retain "hands-on" the sidestick during APPT deliveries. The sidestick hysteresis band was eventually expanded to prevent G-forces from commanding undesired stick force inputs during AMAS deliveries.

Display

One of the cockpit displays used during an AMAS air-to-ground delivery mode is the vertical planning scale (VPS). The VPS is displayed in the HUD and provides the pilot his predicted APPT delivery profile (climbing, descending, or level 5 "g" release), anticipated release altitude, and climb or dive angle. Pilots agree with the VPS concept but do not like its mechanization. Some of the problems noted are: the VPS does not appear until late in the ingress steering which leaves little time to adjust the delivery profile through pilot blending or release range changes; the VPS does not smoothly transition from lofting to diving deliveries during pilot blending or release range changes; the digital data is not always found in the same location; and the display is not intuitive.

Helmet Mounted Sight (HMS)

The HMS was incorporated on the APTI/F-16 to provide the capability to designate off boresight ground targets of opportunity for the STS. It was also designed to improve the speed and ease of acquiring airborne targets by cueing the radar and STS. The use of the HMS is extremely simple. It is normally preselected as the acquisition sensor by the sensor manager. If not, it can be selected with one movement of the hands-on display management switch. Once the HMS is selected, the pilot simply places the HMS reticle over the target and designates/releases. The radar will then acquire and track the target.

Another useful feature of the HMS is reverse cueing. Once a target is tracked, the HMS can be used to locate the target by following the reticle discretely. A light discrete commands head movement in the vertical and/or horizontal plane. Once the target is within a small angle error, all discretely are extinguished.

Boresighting the HMS is as simple as its use. HMS bit is selected on the MFD BIT page. The reticle appears and is placed over the boresight cross on the HUD test pattern. The pilot designates and the boresight is complete.

The HMS is simple and natural to use, but its effectiveness has been poor. Because the STS FOV is very narrow, the boresight of both the HMS and STS must be very accurate to achieve satisfactory results. The radar with its larger FOV consistently achieves target acquisition after being cued by the HMS. The STS does not. Another problem is pilot head position. If the pilot's head varies much from the boresight head position, an error is introduced in the cueing. Opening and closing the helmet visor or moving the visor slightly also introduces cueing errors and requires a re-boresight.

The HMS adds a much needed off boresight capability and is simple for the pilot to use; however, at the present stage of testing, the HMS and STS boresight have not been accurate enough to produce acceptable results.

Ride Qualities

Overall, the pilots have accepted automated guidance inputs for the APPT guidance system (ingress, curvilinear delivery, and egress maneuvering). The automated aircraft responses are similar to a pilot's manual inputs and are intuitive to the pilot. Because of this, the AMAS air-to-ground ride quality is acceptable by all pilots with the exception of flat turn (direct side force) maneuvering. Flat turn is addressed in more detail in following paragraphs.

Flat Turn: The APPT guidance and control system incorporates flat turn (a direct side force) in nulling small heading errors to the weapon release point. It was however, incorporated without regard to its effects of spatial

disorientation to the pilots. Ride qualities using flat turn have been objectional by the pilots.

When a pilot is flying in wings-level flight with no lateral acceleration, the only acceleration sensed by him is gravity. With the addition of direct side force, however, lateral acceleration causes the acceleration vector to tilt. In daylight and in good visibility, the pilot can see the horizon and then knows that he is in wings-level flight with lateral acceleration present. In poor visibility or at night, however, the pilot perceives the acceleration vector to be pointing toward the center of the earth, and he therefore misinterprets his roll attitude to be banked. This spatial disorientation will be uncomfortable at best but under such conditions as low altitude and high speed will be intolerable and will result in aborted weapons delivery runs.

In fact, even control laws using only bank angle, when applied by an autopilot, can induce roll disorientation through use of improper roll accelerations. It is hoped, however, that the optimization or elimination of direct side force will provide a set control laws that are suitable for autopilot use at night or in low visibility.

Workload

Quantitized data has not been obtained to determine reductions in pilot workload due to AMAS. However, it is apparent from pilot comments that the automated air-to-ground system is intuitive and provides predictive displays that reduce pilot anxiety. These factors coupled with the fact the pilot is literally along for the ride once APPT is activated have provided the pilot the opportunity to monitor other aspects of his cockpit or outside world while performing a 5 "g" low level curvilinear delivery. His overall workload may not be reduced, just redistributed to other tasks. This in itself is a major benefit with potential pay-offs.

Color Map Display

The color map display evaluated was a film map displayed via video processing on the center 5 in x 5 in MFD. Pilots noted that the map was useful and aided in cultural feature identification. No extensive evaluations of this map were conducted to determine its optimum utility. It was noted that the color display was washed out under direct sunlight. Also, the 5 in x 5 in size of the center MFD may not be optimum (large enough) to allow the pilot to quickly grasp displayed information. A new digital database map display system will be evaluated in the near future.

SUMMARY

It is premature to provide overall assessments at this time as AMAS air-to-ground and air-to-air have yet to be fully developed or demonstrated; however, it is worth noting that AMAS air-to-ground development test results are promising, indicating there may be payoffs in low level curvilinear weapons delivery. This opens a new area of

capability while achieving weapon accuracy and reducing pilot workload.

Preliminary results also indicate that specific AFTI/F-16 DFCS designs may have significant potential for future applications. The first is the system wide integrity management and ground collision avoidance system which has demonstrated enhanced flight safety for low level flight of automated systems. The second is the control law design flexibility permitted by the digital flight control system that allows effective utilization of available aircraft structural capability (i.e. AFTI/F-16 elevated load factor roll rate limiter).

The AFTI/F-16 developmental activity throughout the remainder of the test program will focus emphasis in the following areas: air-to-ground weapon performance and tactical demonstration, integrated voice systems, digital terrain map, standard avionics integrated fuzing tactical munitions dispenser, and air-to-air AMAS. Results from their developmental tests will be presented in subsequent updates to this technical paper.

Pilot Vehicle Interface on the Advanced Fighter

Technology Integration F-16

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**PILOT VEHICLE INTERFACE ON THE
ADVANCED FIGHTER TECHNOLOGY INTEGRATION F-16**

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ABSTRACT

The Advanced Fighter Technology Integration (AFTI)/F-16 test program has been conducting developmental test flights on new technologies designed to enhance the weapons system effectiveness and survivability of fighter aircraft. This paper will focus on the workload aspects of the pilot vehicle interface in regard to the new technologies tested during the automated maneuvering attack system (AMAS) Phase II. Subjects discussed in this paper include: a wide field-of-view head up display; automated maneuvering attack system/sensor tracker system; master modes that configure flight controls and mission avionics; a modified helmet mounted sight; improved multifunction display capability; a voice interactive command system; ride qualities during automated weapon delivery; a color moving map; an advanced digital map display; and a g-induced loss-of-consciousness and spatial disorientation auto-recovery system. The authors will discuss preliminary findings to date and provide insight as to potential payoffs of the emerging technologies.

ABBREVIATIONS

ADIR - AMAS Director
AFTI - Advanced Fighter Technology Integration
AGL - Above Ground Level
ALC - Automatic Level Control
AMAS - Automated Maneuvering Attack System
APPT - AMAS Pre-Planned Target
ASE - Aeroservoelasticity
DFCS - Digital Flight Control System
DSC - Digital Scan Converter
FCC - Fire Control Computer
FCR - Fire Control Radar
FLIR - Forward Looking Infrared
FOV - Field of View
GCA - Ground Collision Avoidance
HMS - Helmet Mounted Sight
HUD - Head Up Display
IFFC - Integrated Fire Flight Control
INU - Inertial Navigation Unit
KCAS - Knots Calibrated Airspeed
LARAP - Low Altitude Radar Autopilot
LRU - Line Replaceable Unit
MDA - Minimum Descent Altitude
MFD - Multifunction Display
MSIP - Multinational Stage Improvement Program
NWL - Non-Wings Level
PDRR - Pre-Determined Release Range
RALT - Radar Altimeter

STS - Sensor Tracker System
SWIM - System Wide Integrity Management
VPS - Vertical Planning Scale
YAG - Yttrium Aluminum Garnet

INTRODUCTION

In the early days of aerial warfare, the best stick and rudder man won the battle. Today, the pilot with the best available technology and the most manageable cockpit will have a clear advantage. To maintain this clear advantage, pilot workload considerations can no longer be ignored as in early days of flight when pilot vehicle interfaces (PVI) were addressed as an afterthought. This was primarily due to simple cockpit configurations (a few switches and even fewer displays). In today's environment of supersonic closure rates, multiple weapons, multiple sensors, and counter measures, the key to success is rapid assessment of available information and equally quick employment of the right weapon. The pilot who does not have the sensor information readily available in an easily interpreted format or who stumbles during switch actions to employ weapons will lose in training and die in combat. The ability to design a pilot-friendly cockpit has become as important if not more so than the new weapon and system technologies themselves. To illustrate the problem of pilot workload, a comparison of the relative complexity of aircraft from World War I to the present is presented in Table 1 by listing the number of sensors, weapons, and avionics available. The sheer numbers of today's cockpit systems are challenging, not to mention their increased complexity. Each of the listed systems have cockpit switches and displays for the pilot to operate and manage. In addition, as the capability of each system is improved, the number of switches and complexity also increase.

One of the primary objectives of the AFTI/F-16 development program is to assess the PVI of new technologies and to provide assessments as to interfaces, workload, and utility. Technologies discussed with these objectives in mind include: wide field-of-view head up display; automated maneuvering attack system/sensor tracker system; master modes; helmet mounted sight (HMS); multifunction displays (MFD); voice interactive command system; ride qualities during automated weapon delivery; color moving map/digital map generator; and a g-induced loss-of-consciousness (GLOC) and spatial disorientation auto-recovery system.

Test Aircraft Configuration Summary

The AFTI/F-16 (Figure 1) is a highly modified F-16 aircraft. The modifications include an asynchronous operation triplex digital flight control system, which provides multiple in-flight-selectable task tailored flight control laws, including six-degree-of-freedom decoupled aircraft motions. Twin canards are mounted from actuators in each side of the lower portion of the engine inlet. A fuselage dorsal fairing was added to provide more room for avionics and instrumentation hardware. A 10.5 inch diameter forward-looking infrared (FLIR)/YAG laser STS is mounted conformally in the right wing root with an aerodynamically similar "dummy pod" mounted in the left wing root. A nearly "all attitude" radar altimeter is installed utilizing a four antenna pattern around the forward fuselage. A helmet mounted sight (HMS) system is installed in the cockpit. New and modified cockpit controls and displays include a redesigned sidestick controller incorporating eight switches, a linear motion throttle with a twist action controller for vertical decoupled motion and controlling AMAS functions, a conventional optics wide field-of-view head up display, and three multifunction display cathode ray tubes for system control and display. See Figure 2 for cockpit layout.

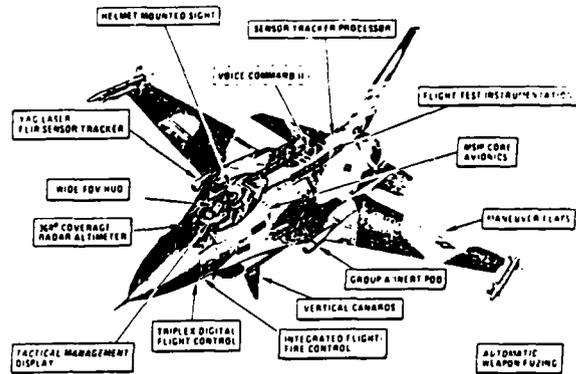


Figure 1 AFTI/F-16 Aircraft Configuration

Table 1 Pilot Workload		
WORLD WAR I		
SENSORS	WEAPONS	AVIONICS
Eyeball	Gun	
None	Dumb bombs	
1950's		
SENSORS	WEAPONS	AVIONICS
Eyeball	Gun	
Radar	IR Missiles	
IR Detection	Dumb Bombs	
	Rockets	
TODAY		
SENSORS	WEAPONS	AVIONICS
Eyeball	Gun	Fire Control Computer
Radar Altimeter	IR Missiles	Stores Management Computer
Radar	Radar Missiles	Digital Map
Forward Looking Infrared	- Active	Global Positioning
Helmet Mounted Sight	- Semi-active	Voice Control
Radar Warning Receiver	Bombs	Multifunction Displays
Laser Tracker	- Gravity	Inertial Navigation
Head Up Display	- TV	Automated Maneuvering
	- IR	Attack System
	- Laser	Task Tailoring
	- Millimeter Wave	Sensor Tracker System
	- Data Link	Data Transfer Equipment
	Rockets	Secure Voice
	A-C Missiles	Precision Location
	- TV	Strike System
	- IR	Airborne Self-Protection
	- Laser	Jammer
	- Millimeter Wave	Joint Tactical Information Distribution System
	- Radar Homing	

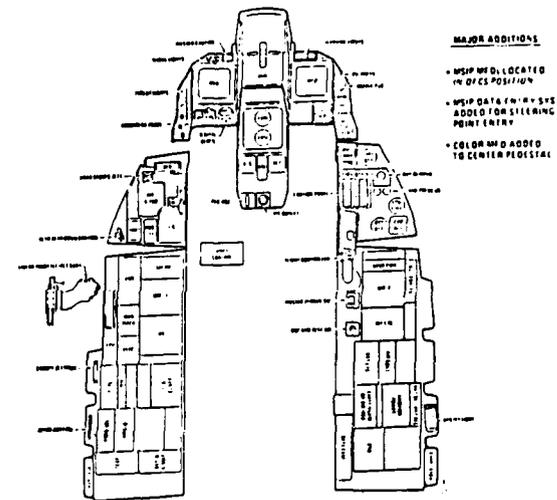


Figure 2 AMAS Cockpit

The core avionic hardware and software for AMAS is the F-16 Multi-Stage Improvement Program (MSIP) system. The hardware is essentially unmodified and the software is highly modified to accomplish AMAS functions. The integration of sensors, fire control, flight control, stores management, and cockpit displays were accomplished via the avionics bus structure depicted in Figure 3.

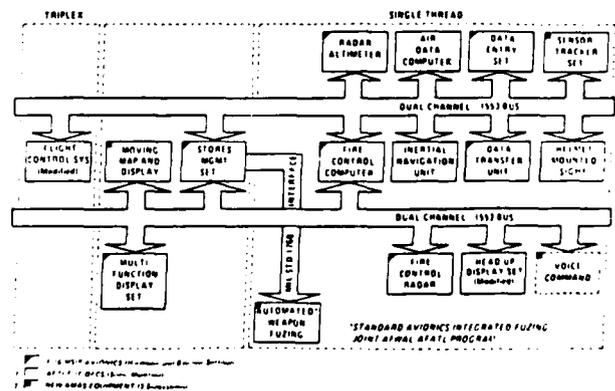


Figure 3 AMAS Avionics Multiplex Bus Configuration

WIDE FIELD-OF-VIEW HEAD UP DISPLAY

DESCRIPTION

The AFTI/F-16 head up display (HUD) (Figure 4) is a conventional optics design which provides an increased field of view (FOV) over the basic F-16A HUD. The two HUDs can be compared in Table 2.

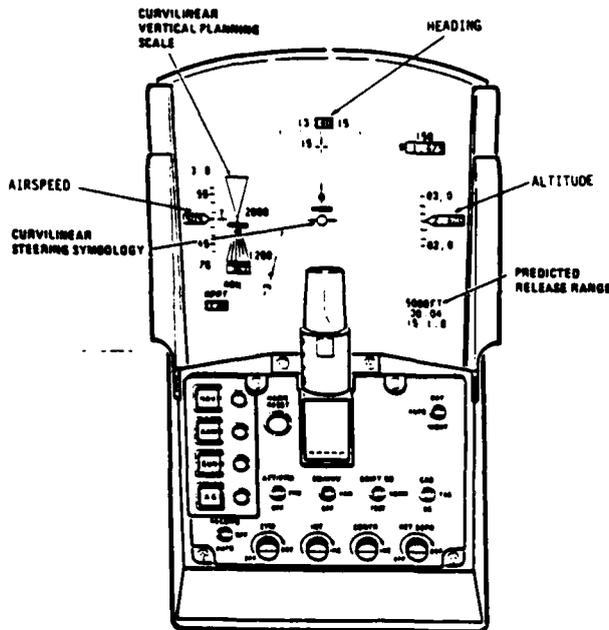


Figure 4 Wide Field of View Head Up Display

Table 2 AFTI/F-16 and F-16A HUD Fields of View

	AFTI/F-16	F-16A
Instantaneous	15° x 20°	9° x 13°
Total	25°	20°

The HUD set is a combined electronic/optical device that provides a visual display of flight information in the form of stroke-written symbols. The symbols represent information relating to the attack, navigation, weapon, aiming, and landing modes. It also provides symbols for essential aircraft performance data including altitude, airspeed, attitude, and heading. The symbols are generated in response to command and data input signals supplied by the fire control computer and various other systems and sensors of the aircraft avionic network.

All information is displayed via a combining glass assembly mounted in the forward field-of-view at eye level, thus eliminating the pilot's need for multi-indicator scanning during high pilot workload phases of the mission. The stroke symbology is focused at infinity and superimposed upon the

outside world along the flight path of the aircraft, thereby supplementing the pilot's forward field-of-view.

The HUD set consists of the following line-replaceable units (LRU):

1. Pilot's Display Unit (PDU)
2. Electronics Unit (EU)
3. Rate Sensor Unit (RSU)

(The HUD PDU mount and the RSU rack are designated to be replaced without any re-boresighting requirements).

ASSESSMENT

The AFTI HUD has a 5 degree larger total FOV which reduces the soda straw effect and minimizes aircraft maneuvering to locate targets, steerpoints, etc. It also provides more real estate for less cluttered symbology and better target status and trend information. The most significant contribution, however, is the increase in instantaneous FOV from a 9 x 13 degree display to a 15 x 20 degree display. This improvement allows rapid dissemination of available information without timely and sometimes awkward head movements. Pilots are unanimous in their praise of the wide FOV feature of the AFTI HUD.

The AFTI HUD is also equipped with digital readouts for airspeed, altitude, and heading, and new increment markings for the analog displayed airspeed and altitude. The digital readouts are a significant improvement for instantaneous interpretation of airspeed, altitude, and heading. The analog scale was retained for trend information during rapid changes in parameters and is valuable for this purpose. The change in scaling factors, however, has not been so well received. Airspeed was changed from 10 KTS to 25 KTS increments and altitude was changed from 100 feet to 250 feet increments. Whether it is a result of training or other factors, pilots have difficulty in rapidly interpreting the new scale increments. The digital boxes also occlude the scale markings which causes confusion when trying to interpret the scale with a quick glance.

The greater FOV of the AFTI HUD is a significant improvement over the F-16A HUD and earned high marks from all AFTI pilots. The AFTI pilots also liked the digital displays for accurate, instantaneous readouts, and the analog scale for trend information. The new analog scale increments for altitude and airspeed were unsatisfactory as were the digital readout positions.

The WFOV HUD has been incorporated in the production F-16. The digital displays of airspeed, altitude, and heading, and the new analog scale increments were not used.

AUTOMATED MANEUVERING ATTACK SYSTEM/SENSOR TRACKER SYSTEM

DESCRIPTION

The AMAS will only be discussed as it pertains to air-to-ground weapons deliveries since this is the only testing accomplished as of this writing. The AMAS air-to-ground function is called the AMAS pre-planned target mode (APPT). The delivery mode is designed to increase survivability by using a low altitude 5 g turning delivery with laser ranging to enhance weapon system accuracy. The weapon deliveries are conducted on pre-planned targets using INS target coordinates for steering and sensor cueing. The bombing geometry can be updated using the radar, HUD, or STS. Targets of opportunity can also be attacked by using the HMS to cue the radar and STS.

The automatic delivery consists of ingress steering to an appropriate offset, 5 g curvilinear delivery, and egress steering. The delivery is depicted in Figure 5.

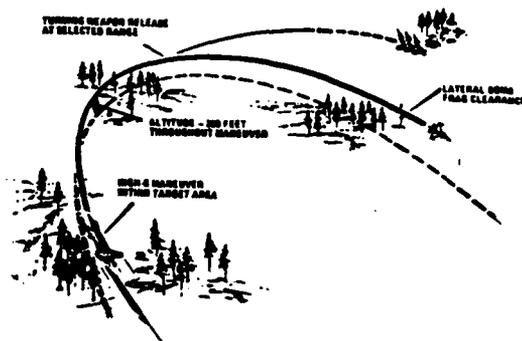


Figure 5 Automated Maneuvering Attack System
Air-to-Ground Profile

The STS is an integrated forward-looking infrared sensor, laser ranger processor, and closed loop tracking system which has been designed to complement the fire control functions of the AFTI/F-16 avionics. The STS consists of three LRUs: the STS head conformally mounted in the right strake, the STS processor installed in the dorsal bay, and the auxiliary power supply installed in the right side inlet bay. A dummy sensor head is mounted on the left strake to aerodynamically simulate the STS subsystem.

The FLIR sensor utilizes infrared radiation emitted naturally by all objects to produce a TV display-compatible image of the temperature differences in the scene. The FLIR sensitivity is designed such that useable imagery is available day or night and in most weather conditions. System performance is degraded most severely by

high humidity and by aerosols, especially large-particle maritime fogs.

The FLIR has three fields-of-view (FOV) which are selectable automatically, in some instances, or manually by the pilot. The FOVs are listed in Table 3.

Table 3 Fields of View

	<u>FOV</u>	<u>Width @ 10K ft</u>
Wide	3.8 x 3.8 deg	666 feet
Medium	1.7 x 1.7 deg	296 feet
Small	0.85 x 0.85 deg	148 feet

The laser ranger determines range by transmitting extremely focused pulses of near infrared radiation to a one-half milliradian spot on the ground and then measures the time to receive the reflected energy.

The field of regard of the STS includes all points in the forward hemisphere and a look-back angle of 30 degrees. In other words, all points from boresight direction to 120 degrees from boresight are usable. The exception is the aircraft fuselage which masks part of the left field of regard for the right strake installation. This limitation would be overcome in a production configuration by installing another FLIR on the left inboard strake.

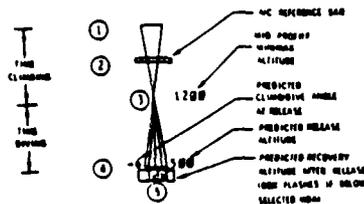
ASSESSMENT

The automated delivery is simple using INS steering. It requires only two hands-on switch actions in the target area: integrated fire and flight control system (IFFC) engaged and weapon consent button depressed. Other required switch actions such as radar altimeter on, APPT mode select, release range, and the correct target steerpoint can all be preselected. Once IFFC is engaged, the pilot is free to do other tasks such as look for bandits, monitor other systems, and control airspeed with the throttle.

Unfortunately, the INS is not accurate enough to achieve desired weapons accuracy. The preferred method is through FLIR tracking and laser ranging. In addition to being more accurate, this method also provides a night target detection and weapons delivery capability. However, as of this writing, acceptable performance has not been achieved. The FLIR target detection range is adequate but its target track range and target track reliability are not consistent. The target tracking gate is also fixed in size which contributes to the tracking problem. As the target grows larger than the tracking gate, the STS will sometimes break lock. The pilot can compensate for this by manually changing STS FOVs from narrow to medium to wide as the target grows in size. These problems force the pilot to continually monitor the STS track status and thus preclude a major benefit of the AMAS system. In addition, off boresight FLIR slewing is difficult due to undetermined reasons. The problem manifests itself as a target drift in the FLIR

video and an inconsistent slow rate dependent on the direction the cursors are slewed. All these problems together have increased the pilot workload to an intolerable level. However, these difficulties have been overcome on similar systems, and we anticipate it is only a matter of time before the same is true for AFTI.

One of the cockpit displays used during an AMAS air-to-ground delivery mode is the vertical planning scale (VPS) shown in Figure 6. The VPS is displayed in the HUD and provides the pilot his predicted APFT delivery profile (climbing, descending, or level 5 g release), anticipated release altitude, and climb or dive angle. Pilots agree with the VPS concept but do not like its mechanization. Some of the problems noted are: the VPS does not appear until late in the ingress steering which leaves little time to adjust the delivery profile through pilot blending or release range changes; the VPS does not smoothly transition from lofting to diving deliveries during pilot blending or release range changes; the digital data is not always found in the same location; and the display is not intuitive.



(A) Top Triangle Form (Climb Then Dive)

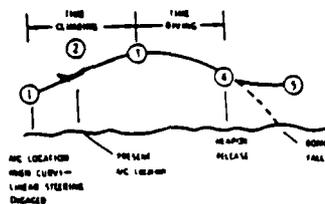


Figure 6 Vertical Planning Scale

The AFTI pilots found the AMAS system simple to use and tactically sound in its mechanization. Assuming the problems with the STS are overcome, the AMAS air-to-ground weapons delivery mode holds great promise for increasing survivability, reducing workload, increasing accuracy, and providing an additional night capability.

MASTER MODES

DESCRIPTION

The "master mode" concept was designed to allow single switch selection of "task tailored" flight control modes and "pre-programmed" avionics

set-up. The following eight master modes are available in the AFTI/F-16: dogfight, missile override, navigation, air-to-air missiles, air-to-air and air-to-ground gun, air-to-ground, selective jettison, and emergency jettison. Three master modes are selected by a hands-on throttle switch, four on the HUD control panel, one on the landing gear panel, and one on the MFD. The master mode switches on the throttle and HUD are depicted in Figure 7.

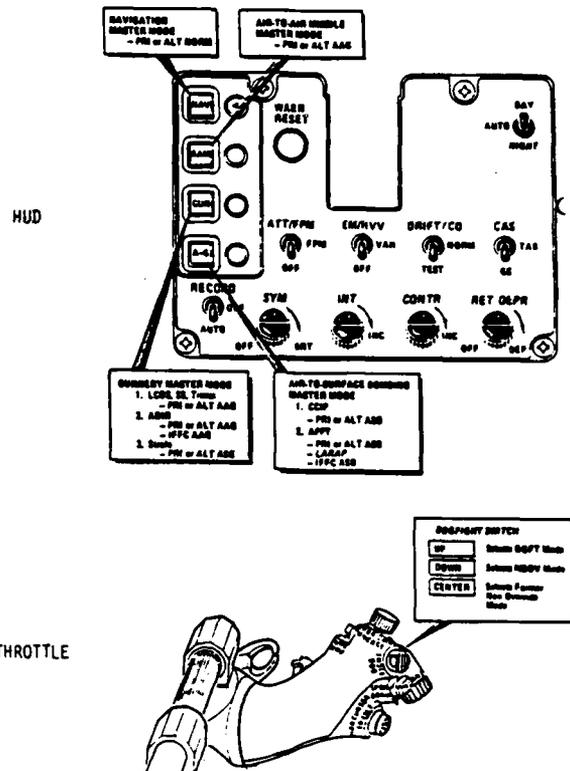


Figure 7 Master Mode Switches

Task tailoring the flight control system is achieved through modification of the digital flight control laws to optimize aircraft performance for selected missions. Included in the eight master modes are four distinct flight control modes; normal, air-to-surface bombing, air-to-surface gun, and air-to-air gun. These modes are optimized for the tasks described by their title. As an example, the air-to-surface gun mode is a g command design used to optimize strafing, while the air-to-air gun mode is a combination g and pitch rate command design used to optimize air-to-air tracking. For flight test purposes an alternate flight control mode was provided for each of the four primary modes. In addition, there are slight modifications to the flight controls for the gear down configuration and for air-to-air refueling.

The other function of the master modes is to use a single switch action to configure the avionics for a specific task. Each of the master modes can be "pre-programmed" such that the next selection of a mode automatically reconfigures the

cockpit to the pilot's last selections for that mode. The programmable parameters include: weapon type, profile for air-to-ground (release pulses, fusing, interval, etc.), delivery mode, sighting option for air-to-air, MFD formats, and radar mode. Furthermore, each of the submodes can be pre-programmed for even greater flexibility.

ASSESSMENT

The master mode function significantly reduces pilot workload while optimizing aircraft performance. APTI pilots found this concept to be both simple to use and effective for improving weapon system effectiveness.

The master modes are easily accessed through hands-on switches or up-front controls. The up-front controls are located on the HUD control panel and require little hand and eye movement to activate. In addition, the single switch action to select both avionics and flight control modes is outstanding.

The capability to pre-program the avionics and weapons for selected missions saves the pilot much valuable time in the air. It also allows the pilot to rapidly transition from one type mission to another. One example is the transition from an air-to-ground weapons delivery profile to an air-to-air weapons employment when unexpectedly confronted by an airborne adversary. The only switch action required is to either depress the AAM master mode button on the HUD control panel or move the hands-on master mode switch to dogfight or missile override.

Two major benefits are derived from task tailoring the flight controls. First and most importantly, aircraft performance is optimized for selected mission scenarios. Secondly, aircraft handling qualities are also optimized. Both these factors combine to reduce pilot workload and improve performance.

The use of master modes for the "pre-programmed" avionics set up has been incorporated in the production F-16. Task tailoring the flight control laws is planned once the production F-16 has a digital flight control computer.

HELMET MOUNTED SIGHT

DESCRIPTION

The HMS was incorporated on the APTI/F-16 to provide the capability to designate off boresight ground targets of opportunity for the STS. It was also designed to improve the speed and ease of acquiring airborne targets by cueing the radar and STS.

The HMS consists of a minicomputer, a transmitter located on the canopy which develops a magnetic field, a receiver on the helmet which senses the magnetic field, a control panel, and an LED array under the helmet visor housing which

projects the reticle and discrete display (Figure 8) on the helmet visor.

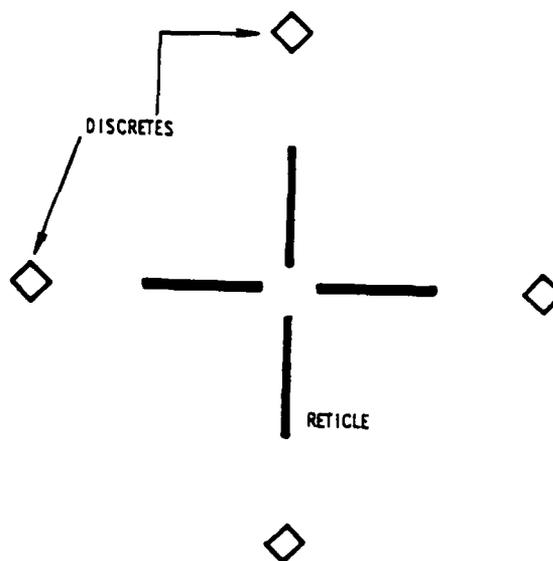


Figure 8 HMS Sight Reticle and Discretes

It is normally preselected as the acquisition sensor by the sensor manager. If not, it can be selected with one movement of the hands-on display management switch. Once the HMS is selected, the pilot places the HMS reticle over the target and designates/releases. The STS/radar will then acquire and track the target.

Another feature of the HMS is reverse cueing. Once a target is tracked, the HMS can be used to locate the target by following the reticle discretes. A light discrete commands head movement in the vertical and/or horizontal plane. Once the target is within a small angle error, all discretes are extinguished.

Boresighting the HMS is achieved by selecting HMS bit on the MFD BIT page. The reticle appears and is placed over the boresight cross on the HUD test pattern. The pilot designates and the boresight is complete.

ASSESSMENT

The HMS is simple and natural to use, but its effectiveness cueing the STS has been limited. Because the STS FOV is very narrow, the boresight of both the HMS and STS must be very accurate to achieve satisfactory results. The radar with its larger FOV consistently achieves target acquisition after being cued by the HMS. The STS does not.

Another problem is pilot head position. If the pilot's head varies much from the boresight head position, an error is introduced in the cueing. Opening and closing the helmet visor or

adjusting the visor slightly also introduces cueing errors and requires a re-boresight.

The reverse cueing feature of the HMS is very useful and easy to use. This feature narrows the pilot's visual search pattern to a very small piece of the sky and reduces the time required for visual acquisition. This significantly reduces his workload and greatly improves his chances for survival in a hostile environment.

The boresight procedures are also very simple and can be completed in a few seconds on the ground or in the air. However, the boresight is difficult to perform accurately because a small head movement produces a relatively large HMS reticle movement on the HUD. This problem is multiplied when trying to boresight while airborne due to normal aircraft vibration and turbulence.

MULTIFUNCTION DISPLAYS

DESCRIPTION

The multifunction displays (MFD) shown in Figure 9 are monochromatic CRT-type displays capable of presenting a high contrast image of processed video to the pilot in a high ambient cockpit lighting environment without the use of shades or hoods. The displayed video is used to assist the pilot in performing avionic system management functions such as sensor system monitoring and control, stores management mode selection, weapon aiming, etc. The control function is provided through the use of 20 option selection switches (OSS's) contained in a bezel around the display screen of each MFD. The keyswitch panel provides the pilot with the ability to interact with aircraft avionics, select display presentation modes, and adjust the display indicator brightness, contrast, and symbology intensity.

The mechanization for display brightness and intensity is quite advanced. Once each display mode is set up, a "memory" condition is established in the programmable display generator (PDG) such that when the pilot returns to that particular mode, a readjustment of brightness, contrast, and symbology intensity will not be necessary. Four rocker-type switches on each MFD allow slewing action to increase and decrease the display parameters as required. When a switch is depressed up or down, the PDG software will slew the parameter chosen until the switch is released. This allows the switch direction and position to be digitally stored in "memory" for a later return to that mode.

The MFD features a raster-driven CRT which offers the advantage of low power consumption and adaptability to video recording that cannot be accommodated in a stroke CRT display system. Standard line-scan video and sync signals are provided to the displays from the PDG. The MFD communicates by digital encoded messages to the PDG for interactive switch information and the brightness slew functions. The major functional sections of the MFD include a video amplifier, horizontal and vertical deflection amplifiers, a high-voltage power supply, and a CRT/Yoke/Harmonization

assembly. The CRT is a 4-inch square display with a high-brightness P-43 green phosphor capable of providing six shades of gray in a 10,000 foot-lambert ambient light condition.

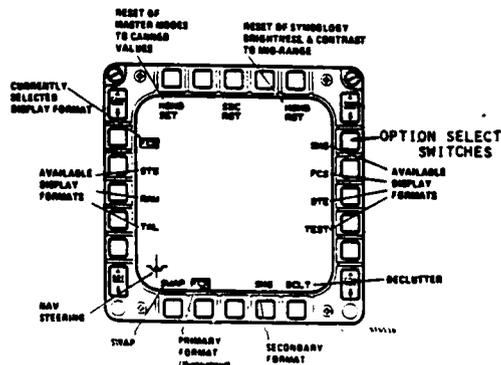
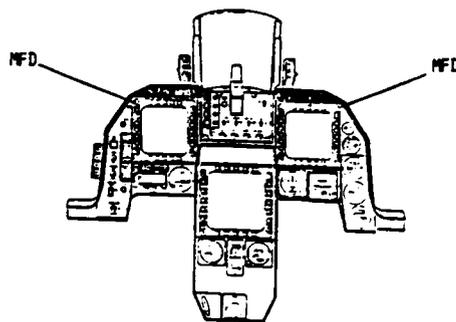


Figure 9 Multifunction Displays

ASSESSMENT

The multifunction feature of the MFDs and their location high on the instrument panel result in many advantages over conventional displays and switchology. The primary advantages are listed below.

1. Probably the most important advantage is rapid visual acquisition and interpretation. The MFDs are located high enough on the instrument panel that normally only eye movement (rather than timely and potentially disorienting head movement) from the outside scene to the MFD is required. Although this time savings may seem small, in a tactical environment split second decisions may mean the difference between success and failure.
2. The short distance between outside scene and MFD make target reacquisition much easier.
3. The MFDs are not obstructed visually as is sometimes the case when switches or displays are located low on the instrument panel or on the side consoles.
4. The MFDs are easily accessed with either hand. It is a very comfortable and natural movement to go from either the stick or throttle to the

MFDs. This feature reduces the time for switch actuation and results in more rapid weapon system configuration and employment.

5. Spatial disorientation problems are reduced. This is achieved by moving approximately 40 switches up front on the MFDs and eliminating the potentially disorienting head movements to look down on the side consoles.

6. The multifunction feature of the MFDs resulted in a reduction of displays from six to two, and a reduction of switches from approximately 60 to 46. This produced a "cleaner" cockpit which is easier to manage and has more room for systems growth.

7. The MFDs have growth potential for more sensor/weapon displays and avionics control functions.

Although there were many advantages derived from the use of MFDs, there were also some disadvantages. The following is a list of the less desirable features.

1. The MFDs are more complicated than dedicated displays and control panels. As an example, pilots must remember non-displayed information, sequences of operation, short mnemonic codes, and operating logic.

2. Some MFD functions may take longer to complete than the corresponding function on a dedicated panel. An example is the flight control page. In production F-16s, a flight control malfunction is assessed by glancing at a dedicated flight control display. In AFTI, as many as three switch actions may be required to call up the same display.

Overall, the advantages of the MFDs far outweigh the disadvantages. The MFDs create a more easily managed cockpit allowing the pilot to optimize the avionics and weapons available. In addition, the MFDs can accommodate more systems growth in the future.

MFDs are presently being installed on production F-16s. These MFDs do not control as many systems as the present AFTI configuration.

VOICE COMMAND SYSTEM

Perhaps no other technology aboard the AFTI/F-16 has captured the imaginations of aerospace watchers as has voice command. The public envisions a futuristic cockpit wherein a laid-back fighter pilot, probably played by Robert Redford, intones the words, "Gear down." An external scene of the airplane then shows the landing gear extending, and the airplane turns away from the camera and lands into the setting sun while closing credits flash on the screen.

Such a system could be implemented today, in which the landing gear would extend upon receipt of the pilot's verbal command. With present word recognition rates, however, the airplane would

experience so many gear-up landings that it would also have to be equipped with a Teflon belly.

In Phase I (the digital flight control development phase) of the AFTI/F-16 flight test program, we looked at two early designs of an airborne voice recognition system. Each design encompassed a 34 word vocabulary which was not noded or compartmented; that is, when a word was spoken, the recognizer had to scan the entire vocabulary in an attempt to find the desired word. Recognition rates were assayed at one, two, three, four, and five g's. Words had to be spoken individually; there was no connective speech recognition capability.

The primary finding of the Phase I voice command flight testing was that recognition rates were unsatisfactory but did demonstrate feasibility. Rates at one g, using the best system evaluated, varied from 81 to over 92 percent among the five pilots tested. If these had been baseball batting averages, they would have been excellent; in the operation of a fighter airplane they were unacceptable. Bland Smith just spoke of the battle being won by the most manageable cockpit. In a battle environment, indeed in any airborne situation, 95 percent word recognition is unacceptable. The desired recognition percentage is 100; something slightly less may be acceptable.

In the current phase (AMAS) of the AFTI/F-16, we are evaluating a more advanced recognition scheme. One advanced feature is that the vocabulary is noded or compartmented so that at the first word or phrase the recognizer hears, it transfers into a node of limited vocabulary. For example, if the pilot says, "Radar," the word recognizer takes the system to the radar node. In this node, after the next command, the recognizer has to scan only for words that would be applicable to radar operation. Theoretically, this compartmenting should lead to higher recognition rates.

Another feature of the second generation recognition system currently being evaluated is connective speech capability. If it was desired to enter a new destination latitude into memory using the Phase I recognizer, it was necessary for the user to say, "North...three...four...five...seven...zero," with a pause for recognition between each word. With the connective speech capability, it is hoped that the pilot can say the entire latitude without pause and have it recognized.

As stated earlier, there was agreement among the pilots who evaluated Phase I voice command that the recognition rate was unacceptable. But there was very little evaluation of voice command in tactical situations and very little speculation among pilots as to what tasks, if accomplished by voice command, would most benefit the pilot. One task that has almost universal acceptance among pilots as a candidate for voice command is radio frequency changing while flying close formation. In this case, the wingman resents having to take his eyes off the lead aircraft for even a split second due to the high potential for a midair collision. Other potential uses for voice command do not share such a unanimous approval. Hopefully,

one of the contributions of the current phase of AFTI/F-16 testing will be to determine uses for voice command that make the tactical pilot's job easier.

RIDE QUALITIES DURING AUTOMATIC WEAPON DELIVERY

The principle tactical capability under development in the AMAS phase of AFTI/F-16 testing is automatic bomb delivery. A forward-looking infrared sensor and a laser range-finder are used for precise target location relative to the aircraft. Target position is then input to the autopilot to allow automatic lateral-toss bomb deliveries.

The geometry of the lateral-toss maneuver is shown in Figure 10. At engagement, the autopilot commands a combination of direct side force (generated by deflection of the canards and rudder) and bank angle to achieve the required offset angle for the maneuver. Figure 11 shows a typical level of lateral acceleration used to develop offset angle. As the maneuver progresses, direct side force again is used to fine-tune the offset geometry immediately prior to banking for the curvilinear steering.

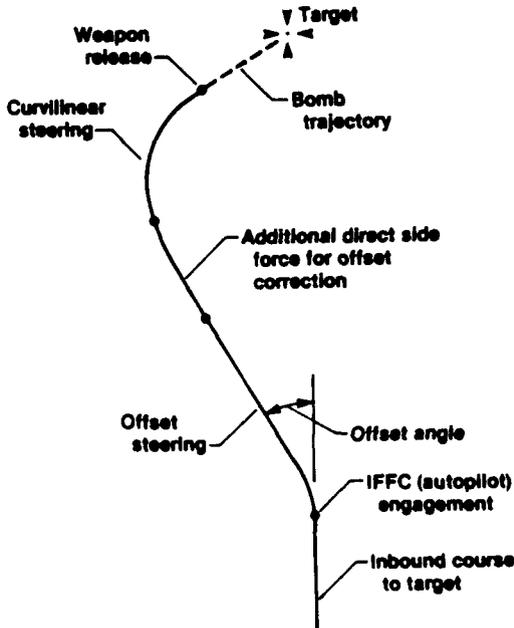


Figure 10 Lateral-Toss Bomb Delivery Geometry

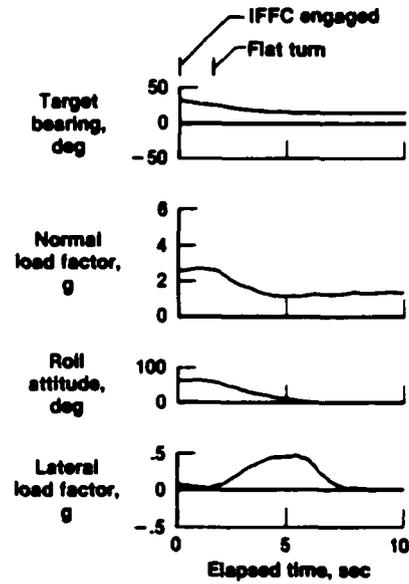


Figure 11 Acceleration During Automatic Lateral-Toss Bomb Maneuver

This direct side force was used in the maneuver because it was available in the aircraft and because the lateral toss maneuver was a task in which to display its effectivity in changing heading. It was incorporated, however, without regard for its effect on the pilot's spatial orientation.

When a pilot is flying in wings-level flight with no lateral acceleration, the only acceleration sensed by him is gravity (Figure 12a). With the addition of direct side force, however, lateral acceleration causes the acceleration vector to tilt (Figure 12b). In daylight, in good visibility, the pilot can see the horizon and then knows that he is in wings-level flight with lateral acceleration present. In poor visibility or at night, however, the pilot perceives the acceleration vector to be pointing toward the center of the earth, and he therefore misinterprets his roll attitude to be banked (Figure 12c). This spatial disorientation will be uncomfortable at best, but under such conditions as low altitude and high speed, will be intolerable and will result in aborted weapons delivery runs.

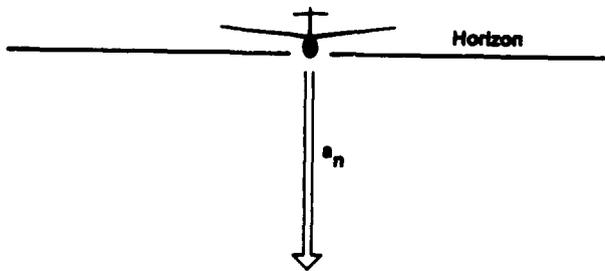


Figure 12a Acceleration Acting on an Airplane in Straight and Level Flight

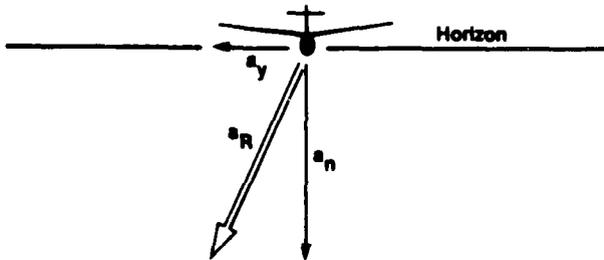


Figure 12b Resultant Acceleration on an Airplane in Wings-Level Flight With Lateral Acceleration Present

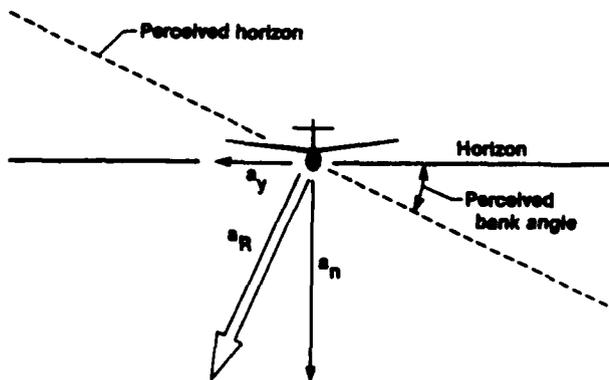


Figure 12c Perceived Bank Angle, Unbanked Flight With Lateral Acceleration, No Actual Horizon Visible

The author has been aware of this potential for disorientation since the initial design of the AMAS control laws but has not yet been successful in having the lateral acceleration term removed from the steering algorithm. It is planned to install a set of control laws utilizing only bank

angle for generating turning flight prior to the conclusion of the AMAS phase in order that the pilots may evaluate its ride qualities.

In fact, even control laws using only bank angle, when applied by an autopilot, can induce roll disorientation through use of improper roll accelerations. It is our hope, however, that the elimination of direct side force will provide a set of control laws that, with tuning, are suitable for autopilot use at night or in low visibility.

COLOR MOVING MAP

Before tactical aircraft were equipped with inertial navigation systems, the tactical pilot spent a great deal of his time lost. At low altitude, his radio navigation equipment was not functional, and he found that navigation by map alone at low altitude and high speed is a difficult and sometimes impossible task.

The availability of inertial navigation has relieved the pilot of being completely ignorant of his location. It is still necessary, however, for the pilot to carry a map to correlate the terrain he is flying over to that which he should be over. Cross-checking this map while maintaining control of the airplane requires great skills such as being able to fly the airplane by holding the stick between one's knees. The color moving map will eliminate the necessity for those skills by placing the map on a five-inch cathode ray tube mounted in the instrument panel (Figure 13).

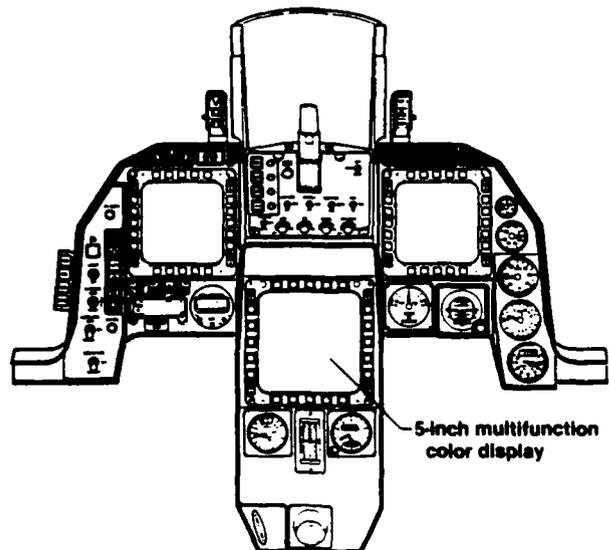


Figure 13 AFTI/F-16 Instrument Panel

The map translates so as to continuously present the terrain over which the airplane is flying. The map has the capability to:

1. Place the aircraft reference symbol at the edge of the map so that the entire map presents terrain forward of the aircraft (Figure 14a) or to place the aircraft reference symbol at the center of the map so that the pilot may correlate features to the sides or aft of the aircraft (Figure 14b).



Figure 14a Color Moving Map with Aircraft Reference Symbol at the Edge



Figure 14b Color Moving Map with Aircraft Reference at the Center

2. Present the map with track up which orients the terrain on the map similarly to the way it appears when looking out the windscreen or to present the map with north up (Figure 14c) which allows for convenient reading of place names and elevations.



Figure 14c Color Moving Map with North Up

3. Vary the scale of the map. Present capability allows scales of from 10 x 10 miles, to 80 x 80 miles.

4. Generate a course line between the last previous steerpoint and the next steerpoint (Figure 15). This capability has the very desirable feature of being able to project whether the planned track will penetrate an area of known hazard such as a restricted area, neutral country, or other location that must be avoided.



Figure 15 Color Moving Map with Course Line Displayed

5. Present a map of the destination rather than the aircraft's present position, in order that the pilot may familiarize himself with terrain or cultural features surrounding his destination prior to reaching it.

The color moving map is at present a digital portrayal of a printed map, read from a film strip. It is very usable in its present mechanization although it currently is able to carry only two scale options, either 10 x 10 and 40 x 40, or 20 x 20 and 80 x 80 miles. The map, as presently mechanized, also possesses insufficient brightness for use in bright daylight. A subsequent version of the color CRT is planned to correct this deficiency.

The pending mechanization, to be flight tested this spring, will store and reconstruct terrain elevation and cultural data from a Defense Mapping Agency database. This map will have the ability to display slope shading, to vary the interval of contour lines, to present all terrain above the aircraft's present altitude in a contrasting color and to provide an infinite number of scales.

G-INDUCED LOSS-OF-CONSCIOUSNESS AND SPATIAL DISORIENTATION AUTO-RECOVERY SYSTEM

DESCRIPTION

A g-induced loss-of-consciousness (GLOC) and spatial disorientation auto-recovery system has been developed and tested on the AFTI aircraft. The pilot controls the operation of this system by entering an MSL altitude and manually arming the system. Engagement conditions of the auto-recovery maneuver are controlled by aircraft speed,

altitude, attitude, and the set recovery altitude and do not depend upon any determination of pilot physiological condition. Initiation of the recovery maneuver is preceded by visual and aural warnings which continue until the pilot resumes control. The auto-recovery maneuver consists of a roll to wings-level and a 5 g pull to level flight altitude-hold. The pilot always has the capability to override or disengage the auto-recovery maneuver.

This system provides the pilot protection from ground collision in most air-to-air training environments.

Flight testing began at Edwards AFB on February 20, 1986. The basic auto-recovery system including displays and warnings, operated correctly from the beginning of flight test. At most dive angles and airspeeds, the auto-recovery maneuver was satisfactory. Some improvements, however, will be made at steep dive angles where the system is too conservative when upright and results in some penetrations of the floor when inverted.

As a result of flight tests, the auto-recovery system is operational on the AFTI/F-16 providing protection to the pilot when required. Flight testing of the auto-recovery system will continue through Spring 1986 as changes are made to improve system performance.

ASSESSMENT

Unlike programs being pursued to find a suitable physiological sensor of loss-of-consciousness, an auto-recovery system based upon aircraft altitude, attitude, and airspeed in relation to a set recovery altitude is applicable to most cases of spatial disorientation and loss-of-consciousness. The AFTI/F-16 auto-recovery system is based upon a pilot-selected MSL altitude floor and is operational today. This system should be incorporated into current tactical aircraft as soon as possible.

As long as system operation is indicated to the pilot, the auto-recovery system need not be redundant or require extensive aircraft modifications. When incorporated on a tactical aircraft, the system will use a computer to determine when the auto-recovery is required; an autopilot to fly the recovery, and an appropriate pilot vehicle interface.

Future auto-recovery systems should be developed to use AGL altitude which will provide automatic operation, increased authority, and combat capabilities.

SUMMARY

The following is a summary of the workload aspects of the FVI in regard to the new technologies tested on the AFTI/F-16.

WIDE FIELD-OF-VIEW HEAD UP DISPLAY

AFTI pilots were unanimous in their praise of the wide FOV feature of the AFTI HUD. The AFTI HUD

minimizes aircraft maneuvering to locate targets/steerpoints, displays less cluttered symbology, and allows rapid dissemination of displayed HUD information without head movements. The pilots also liked the digital airspeed, altitude, and heading displays but feel it is necessary to keep the analogue displays for trend information. The analog scale increments was the only AFTI HUD feature the pilots did not like.

The WFOV HUD is now being used on the production F-16. The digital displays of airspeed, altitude, and heading, and the new analog scale increments were not used.

AUTOMATED MANEUVERING ATTACK SYSTEM/SENSOR TRACKER SET

The AFTI pilots found the AMAS system simple to use and tactically sound in its mechanization. Assuming the problems with the STS are overcome, the AMAS air-to-ground weapons delivery mode holds great promise for increasing survivability, reducing workload, increasing accuracy, and providing an additional night capability.

MASTER MODES

The master mode function significantly reduces pilot workload while optimizing aircraft performance. AFTI pilots found this concept to be both simple to use and effective for improving weapon system effectiveness.

The use of master modes for the "pre-programmed" avionics set up has been incorporated in the production F-16. Task tailoring the flight control laws is planned once the production F-16 has a digital flight control computer.

HELMET MOUNTED SIGHT

The HMS is simple and natural to use, but its effectiveness cueing the STS has been limited. These limits are due to inaccuracies in boresighting the HMS and STS, loss of HMS boresight due to helmet/visor movement on the pilots head, and inaccurate sensing of the HMS orientation if used in a position other than the boresight position.

The HMS has great potential for reducing pilot workload if the problems described above can be resolved.

MULTIFUNCTION DISPLAYS

The MFDs create a more easily managed cockpit allowing the pilot to optimize the avionics and weapons available. These advantages were achieved by moving the MFDs high up on the front instrument panel, making them easy to access both visually and physically. The multifunction aspect of the MFDs also reduce the number of displays and switches in the cockpit, allowing for more systems growth in the future.

These advantages far outweigh the disadvantages of more complicated operation and sometimes a longer time to complete a function.

MFDs are presently being installed on production F-16s. These MFDs do not control as many systems as the present AFTI configuration.

VOICE COMMAND SYSTEM

AFTI pilots agree the voice command system must have a recognition rate close to 100 percent in order to be useful. During the first phase of testing, recognition rates were between 80 and 90 percent. The next phase of testing will be trying to improve the recognition rate and determine the usefulness of voice command in realistic tactical scenarios.

RIDE QUALITIES DURING AUTOMATIC WEAPON DELIVERY

AFTI pilots were satisfied with the ride qualities during automatic weapon delivery with the exception of direct side force. Pilots are concerned that the direct side force will cause disorientation at night or in low visibility testing. New control laws without direct side force will be tested prior to the conclusion of AMAS phase.

COLOR MOVING MAP

All AFTI pilots agree the color moving map is very useful for reducing pilot workload for navigation and situation awareness. A digital map will be tested soon to try and improve terrain and cultural feature recognition.

G-INDUCED LOSS OF CONSCIOUSNESS AND SPATIAL DISORIENTATION AUTO-RECOVERY SYSTEM

The system is applicable to both spatial disorientation and loss-of-consciousness situations and will auto-recover the aircraft based on aircraft altitude, airspeed, and attitude in regard to a set recovery altitude. The GLOC system is very promising for reducing aircraft losses and will be flight tested on AFTI starting in Feb 86.

Standardized Avionics Integrated Fuzing

W. G. Smith

J. P. Boone

STANDARDIZED AVIONICS INTEGRATED FUZZING

Walter G. Smith

Joseph P. Boone

Air Force Armament Laboratory
Eglin AFB, FL

Air Force Wright
Aeronautical Laboratories
Wright-Patterson AFB, Ohio

The Standardized Avionics Integrated Fuzing (SAIF) concept is to optimize weapon effectiveness and minimize pilot tasks and flight limitations using avionics to compute in real-time release parameters such as: time to release, submunition ejection force, time from release to fin deployment, submunition release time, parachute deployment time, and rocket firing time. Presently these parameters are set prior to the flight and cannot be changed in flight. SAIF payoffs are in the area of operational flexibility and optimal weapon fuzing while removing the flight restrictions inherent in present fixed fuze weapon deliveries. The SAIF demonstration uses the AFTI/F-16 weapon delivery system and a digital fuzing system module for a Tactical Munitions Dispenser (TMD). This demonstration is limited to a TMD weapon but the concept is transferable to other fuzed munitions including the MK-80 series of general purpose bombs. The munition used for the AFTI demonstration is a CBU-89 consisting of a SUU-66 dispenser filled with 94 Gator mines.

BACKGROUND

Because existing fuzes for Tactical Munitions Dispensers (TMD's) must be ground set for specific delivery conditions and targets, the aircraft weapon delivery parameters and targets are also fixed prior to takeoff. SAIF will, however, have the capability of functioning as an avionics-set impact/delay fuze or an avionics-set dispenser timer. A fuze with an avionics-set capability is needed in the near term to eliminate the inflexibility of current fuzes and timers which must be ground set, and, therefore, allow only very limited tactical flexibility in the severely hostile and diverse target environments. In the far term, this avionics-set fuze is on the critical path to achieving the capability for unconstrained weapons delivery while maneuvering the aircraft. SAIF will fully utilize the computer capability of current aircraft, thus reducing the complexity of fuzes/timers, and will significantly reduce the requirement for ECM-susceptible dispenser proximity sensors. The provision for accurate and timely bomb and dispenser fuze settings at weapon release will increase

tactical flexibility, weapon effectiveness, and aircraft survivability. Real-time update of dispenser fuze settings will permit better submunition pattern control and enhance multiple target kill capability.

SAIF CONCEPT

The principal elements of the SAIF concept are illustrated in Figure 1. Information on the target (type and position relative to the aircraft) and aircraft state are input from the aircraft avionics into the Fire Control Computer (FCC) fuzing algorithm. The computer calculates optimum fuzing parameters for the selected target and actual release conditions. Depending on the particular munition under consideration the fuzing parameters calculated could include, time from release to fin deployment, submunition ejection force, submunition dispense time, parachute deployment time, and rocket firing time, and others. In the case for the TMD, pattern control over a range of delivery conditions is achieved by varying time-to-start spin (freefall) and spin rate, and these two commands are calculated and sent to the TMD via a MIL-STD-1760 interface just prior to weapon release.

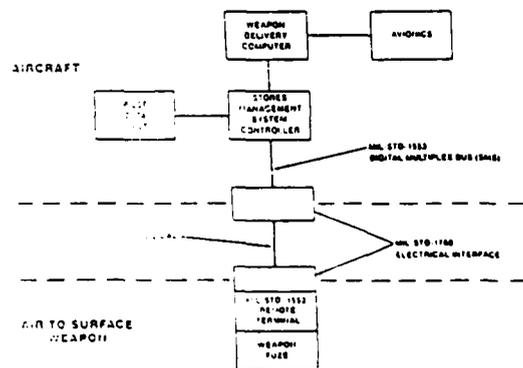


Figure 1. SAIF Concept Elements

The SAIF concept can be extrapolated to provide fuze control to unitary warhead bombs. Employed on the MK-82, for example, SAIF could control safe separation timing thereby allowing lower altitude delivery than with existing fuzes. Deployment time of the drag

(retardation) device on the MK-82 could be controlled by SAIF, and thus provide control of impact angle with weapon effectiveness being strongly influenced by impact angle.

TACTICAL MUNITION DISPENSER (TMD)

The TMD is a 1000 pound-class, unpowered and unguided ballistic trajectory weapon. See Figure 2. It is opened by a linear-shaped charge explosive cutting network initiated by the fuze system after safe separation and after achieving a preset time, Height of Burst (HOB), or spin rate. The dispenser function event for the current TMD can be controlled in one of three modes. A FZU-39/B proximity sensor provides a fixed Height of Burst (HOB); a variable delay timer provides a fixed time to dispense; or a centrifugal force-activated spin allow the pilot to select the dispenser function mode. The variable time and spin rate parameters, as well as the HOB selected for the FZU-39/B, must be preset on the ground by switches located on the munition. The timer can be set from 0.64 to 4.32 seconds in 12 increments to provide dispenser function and arming signals. The spin switch has six incremental settings from 0 to 2500 revolutions per minute (RPM). The FZU-39/B proximity sensor provides ten incremental settings between 300 and 3000 feet HOB. The SAIF fuze module will provide all the functions now performed by the timer and FZU-39/B, but will be optimally set and will not be susceptible to countermeasures.

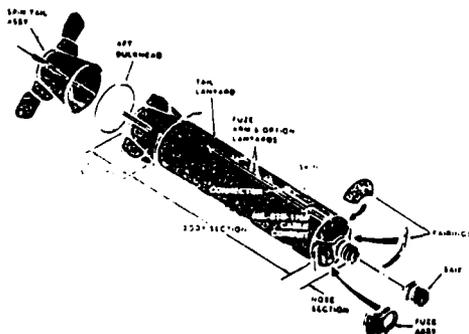


Figure 2. Modified TMD

The TMD functions that are controlled by SAIF commands via the MIL-STD-1760 interface are shown in Figure 3.

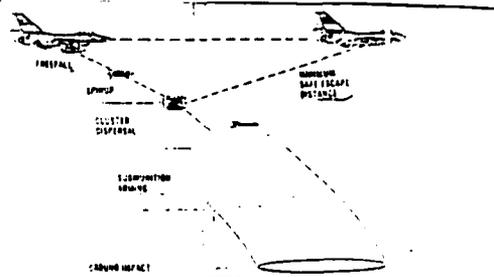


Figure 3. TMD Functions

MIL-STD-1760 Interface

The SAIF designed for demonstration on a modified Tactical Munitions Dispenser (TMD) contains a MIL-STD-1760 electrical interface to the AFTI/F-16, a controller, a power converter, and an interface to the TMD electromechanical fuze. As part of the MIL-STD-1760 interface, a dual MIL-STD-1553B mux bus conveys fuze data to the SAIF, which in turn provides time-to-fin-cant and HOB fire pulses to the TMD.

The SAIF module is configured as a standard avionics mux bus terminal. It receives commands from the aircraft, performs standard MIL-STD-1553 functions including error checking, and sends data to the aircraft. Data sent to the aircraft includes a reflection of received commands (wrap-around data) and results of SAIF internal status check.

The SAIF is designed with standard CMOS logic circuits and commercially available LSI integrated circuits to perform the MIL-STD-1553 mux bus control functions. A Motorola MG146805E2 microprocessor performs controller functions. Pre-release power consumption is 11 watts and post-release power consumption is 2.5 watts (excluding the TMD power interface circuit, post-release power is 16 milliwatts).

This interface is exercised by selecting the TMD on the Multi-Function Display (MFD) (Figure 4). The pilot then selects a dispersion pattern (Formation, Truck, Tank) via the MFD. This pattern is transmitted via the D Mux to the FCC. The FCC calculates the time to release submunitions and the release altitude based on target position and flight conditions and sends this data to the MFD for display to the pilot. Simultaneously, the FCC sends to the SAIF the time to release submunitions. This "time to release" is computed and sent to the TMD at 25 Hz.

The modified TMD upon receiving the submunition release time buffers the information for transfer to the fuze upon receipt of a release command. The SAIF then wraps-around the submunition release time to the FCC and sends a status word containing the results of an internal self-test routine. The FCC verifies that the wrapped-around data and self test results are correct and acceptable. If not, the SMS will not allow the TMD to be released. The weapon release procedure is consistent with that of the F-16 automatic weapon release method. The Head-Up Display (HUD) fuze arming cue is mechanized to show the pilot that there was sufficient altitude for the weapon to function properly. If there is insufficient altitude, the FCC notifies the SMS to inhibit release. The SMS will then not allow the TMD to be released. The SMS also provides inventory control on the MFD.

Implementation of the SAIF concept on an operational basis is dependent upon the availability of a standard interface; that is, the interface cannot be a "unique fuze only" interface. There is no way that any one weapon concept can justify funding the installation of the MIL-STD-1760 interface. The AFTI/F-16 experience showed the necessity for a dedicated weapon mux for a "clean" implementation of MIL-STD-1760. The interoperability payoff in cost reductions due a common interface is enormous but is even exceeded by the cost reductions due to increased weapon effectiveness.

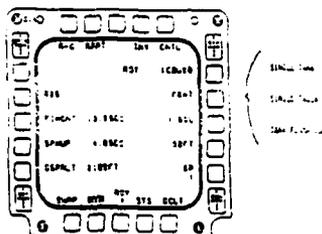


Figure 4. SAIF Page on MFD

AFTI/F-16 EFFECTIVENESS ANALYSIS

An indepth analysis of the ability of SAIF to increase the effectiveness of a wide range of weapons including the TMD indicated significant potential. The effectiveness improvements which could be expected by adding an automated maneuvering attack capability were also estimated. Figure 5 summarizes these estimates for two unitary subunits. Improvements attributable to automated maneuvering delivery are due to a reduced attrition rate.

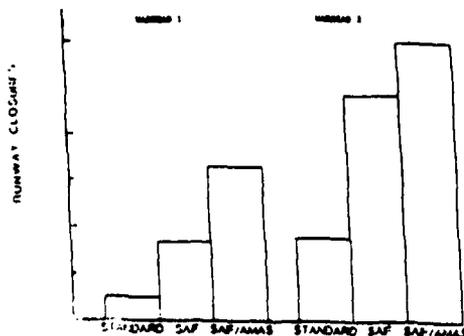


Figure 5. Relative Effectiveness

AFTI/F-16 Voice Interactive Avionics

F. A. Rosenhoover

AFTI/F-16 VOICE INTERACTIVE AVIONICS

F. Allan Rosenhoover
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ABSTRACT

The integration of voice technology into tactical fighters is an attempt to provide the pilot with increased capabilities. The AFTI/F-16 Voice Interactive Avionics (VIA) program encompasses the development of voice applications to (1) reduce pilot workloads, (2) increase survivability by allowing more time for hands-on/head-out flying, and (3) allow the pilot to expand his mission capabilities.

This paper will discuss the integration of voice in a fighter environment, including workload assessments and the approach used to solve the workload demands on the pilot. Tasks within the crewstation are identified according to their ability to increase the pilot's awareness of his environment and ability to maintain his mission objectives with minimal error. A discussion of the areas of evaluation during various mission profiles will be presented to establish interactive needs for mission success. Included will be an explanation of problems associated with establishing this technology in today's tactical fighters.

INTRODUCTION

Numerous studies and observations have been made in previous years to evaluate methods of helping the pilot perform his mission with increased efficiency and effectiveness, thus decreasing his workload. The pilot is exposed to several environments in his cockpit and each affects his performance and mission objectives in some way. Two key environments that have a significant influence on the pilot are the operational and work environments (See Figure 1). His brain has to be able to process the information available to him, whether it comes from his eyes or ears, and be able to translate that information into reactions that will control his hands, feet or voice at the appropriate time. One of the main purposes of today's technology is to aid the user by increasing his capability. For that reason, the addition of voice technology to a fighter pilot's cockpit is our goal. The pilot's mission survivability during high workload conditions is highly dependent on how well he is able to perform a task and not deviate from his objective. If he is able to keep his hands on the controls and his head out of the cockpit, the higher his chances will be for a successful mission, therefore allowing him to increase his mission capability.

The objective of the AFTI/F-16 VIA program is to identify ways that will help to reduce the pilot's workload. For voice technology to be fully effective, additional objectives must be emphasized.

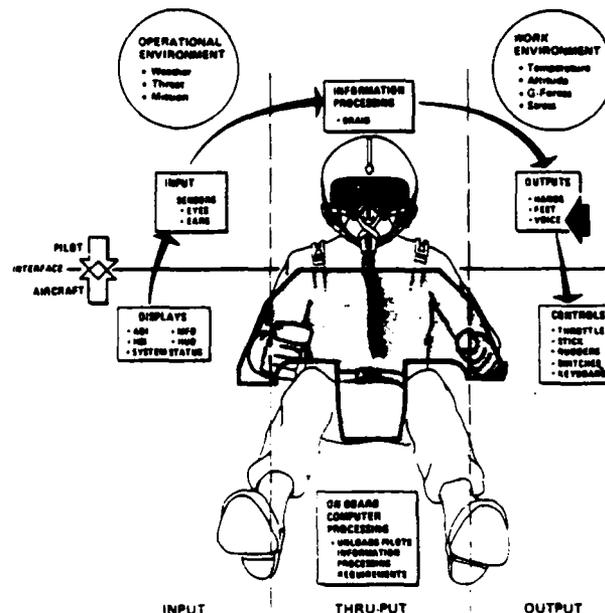


Figure 1 Workload - The Total Demand Placed on the Pilot

PREVIOUS EXPERIMENTS

Voice technology has been investigated on the AFTI/F-16 Program for a number of years. Sequential phases of study and evaluation have been conducted since the late 70's. The initial phase, Phase 0, (See Figure 2) was started as a cooperative effort between General Dynamics and Lear Siegler, Inc. (LSI) in 1978. Human factor studies were conducted initially to determine the need for voice technology in a fighter cockpit. These studies helped in the development of a data base for the environment that a pilot would be exposed to. Subsequent phases of voice technology investigation built on these studies.

Phase I involved the flight demonstration of voice technology in a fighter environment. A second vendor, ITT Defense Communications Division (ITT/DCD), was added to this cooperative effort to introduce their approach to word recognition. Upon completion of the Phase I program, the results clearly indicated that voice in the tactical environment would work, and that speech synthesis should be added; thus, the introduction of Voice Interactive Avionics (VIA).

* Portions of the material contained within this paper are funded under USAF Contract F33615-78-C-3822, with Air Force Wright Aeronautical Laboratories, AFWAL/F11, WPAFB.

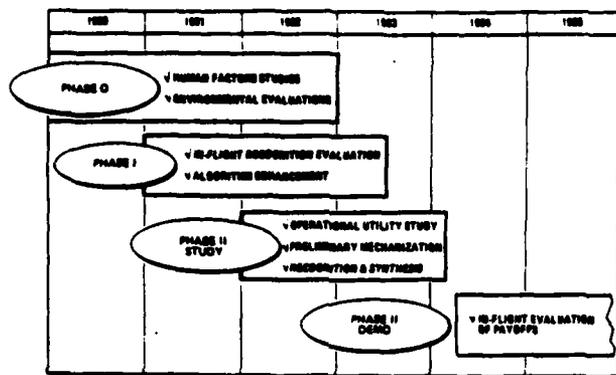


Figure 2 AFTI/F-16 Voice Interactive Program Roadmap

VOICE APPLICATIONS STUDY

Once the decision was made during Phase I that voice would actually work in the airborne environment, the next step was to determine the utility of the technology. Between Phases I and II, a study of interactive voice was conducted to prioritize candidate tasks where voice technology would best aid the pilot.

One key issue was kept in mind during this study, that voice not only had to perform various tasks in the crewstation, but it had to relieve the pilot of much of his workload. The mechanization should be viable enough that the use of voice would be intuitive. Therefore, the vocabulary had to be familiar to the pilot for the application usage. If the pilot had to learn a new vocabulary or method of delivery, the objectives of voice utilization would be defeated. Therefore, it had to do exactly what the pilot wanted, and if it could accomplish the task faster, so be it. A preliminary mechanization approach of the voice application was included in this study. Care was taken to ensure that voice would not only perform the task, but the pilot should not have to learn something that creates a workload in itself.

In addition to gathering data during this study, a concerted effort was made to define a flight demonstration that would build on the study results. For example, the pilot would have to be placed in situations that would force him to increase his workload, and the use of voice would hopefully relieve some of the stress felt during the workload. The effects of stress will also be evaluated during flight test to provide the voice industry with data that will help to determine how stress in the cockpit affects the speech template, or voice patterns, themselves.

The intent of integrating interactive voice technology in a tactical fighter, is not only to perform selective tasks to reduce pilot workload, but also to allow the pilot increasingly more capabilities. The trend in fighter design over the past few years has been to create a cockpit that will allow multiple functions and solve certain Pilot/Vehicle Interface (PVI) issues (See Figure 3). We are building cockpits with fewer instruments and switches, and at the same time trying to reduce the dependence on a hierarchical data structure. If voice can solve many of these issues, it will support this trend in cockpit evolution.

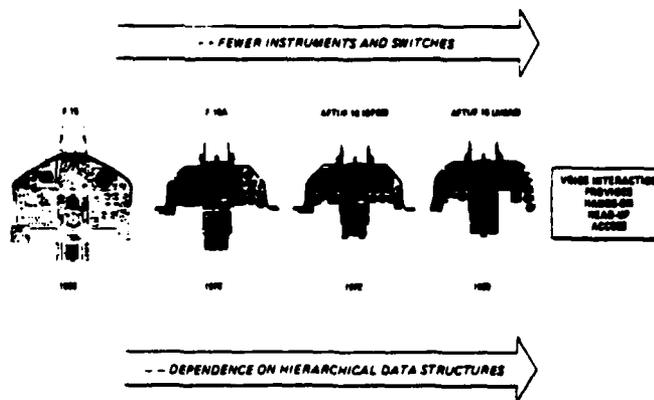


Figure 3 Evolution Towards Multifunction Cockpits and the PVI Implications

As part of the study, pilots were asked to evaluate a given mission profile to (1) determine their ability to maintain a hands-on/head-out capability, and (2) determine their ability to time-share the two with little mission error or course deviation. Once the data were compiled, a rating of the various mission tasks was created. This rating helped to define cockpit tasks where voice should be evaluated during flight test.

PHASE II EXPERIMENTS

Vendor Selection

A decision was made in late 1983 to start the competition for the Phase II VIA development and flight test program. Figure 4 delineates the VIA specifications used for the competition. However, since the time the specifications were written, the technology had advanced enough that those requirements no longer pushed the present day technology. The 95% word recognition goal is no longer a goal, but now a reality. The connected speech capability is common place. Two vendors were

- 90% RECOGNITION PERFORMANCE
- 95% GOAL
- 0' FORCE RECOGNITION
 - 3 'G' - No Degradation
 - 4 'G' - 10% Degradation
 - 5 'G' - 15% Degradation
- RESPONSE TIME LESS THAN 0.5 SECONDS
- ALLOW FOR SLIGHT DELAYS BETWEEN SWITCH DEPRESSION AND VOICE ENTRY
- LIMITED CONNECTED WORD CAPABILITY GOAL
- BUT EFFECTS OF STRESS/ANXIETY ARE UNKNOWN

MINIMUM REQUIREMENTS FOR MEANINGFUL FIGHTER APPLICATIONS

Figure 4 VIA Specification Requirements

finally selected for the development and flight test effort, (1) Lear Siegler, Inc. (LSI), whose voice equipment was flown on the AFTI/F-16 during the Phase I Flight Test Program, and (2) Texas Instruments (TI) (see Figure 5).

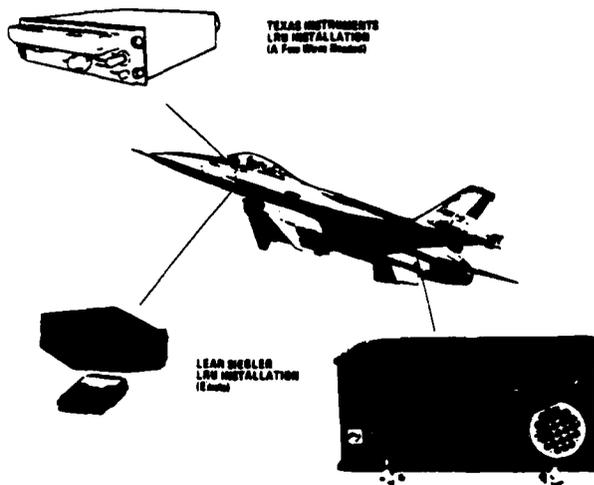


Figure 5 Location of VIA Hardware on the AFTI/F-16

LSI is providing the same form factor hardware used during Phase I with additional capabilities. They will be adding (1) speech synthesis to meet the interactive requirement, and (2) connected speech capability, the beginning of a new approach and long-desired method of recognition for our pilots.

TI is offering a new hardware approach. They essentially condensed the speech technology, recognition, synthesis, and I/O modules into hardware the size of a car radio. This was very desirable for AFTI/F-16 since the aircraft can now fly with a Tactical Air Navigation (TACAN). The LSI hardware is missionized with the TACAN located in the dorsal fairing; therefore, preventing the TACAN from being used. The block diagram in Figure 6 briefly illustrates the hardware modules or functions that are located in the vendor's equipment.

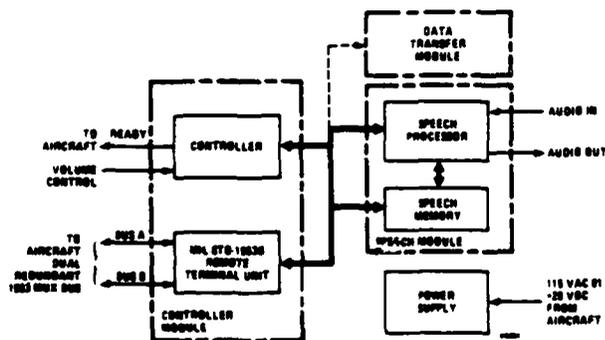


Figure 6 Block Diagram of the Voice Interactive System

System Design

In order for the voice hardware to interface effectively with all the other subsystems on the aircraft, it had to become as much a subsystem as other avionics equipment (See Figure 7). The voice system was not intended to be an appendage, dependent on one subsystem for its interface, as happened during the Phase I Flight Test Program. It will be able to receive instructions and data from other subsystems, and be able to respond according to the design requirements outlined for the Voice Interactive Set (VIS).

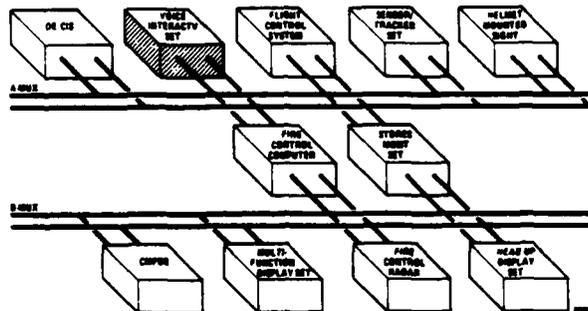


Figure 7 VIA Architecture Supports Functional Partitioning and Design Requirements

The applications to be tested with voice were selected from those tasks the pilots felt would best reduce pilot workload if voice interaction was used. A wide variety of tasks were chosen for evaluation. With voice commands, the pilot will be able to perform multiple data entry functions accomplished by the F-16 Data Entry/Cockpit Interface Set (DE/CIS), make page selection and manipulation of nearly all Multifunction Display (MFD) pages, and have the ability of simultaneously selecting a particular weapon or gun, while at the same time automatically selecting the proper mission phase for his weapon choice.

In addition to emulating button depressions in the cockpit by way of voice commands, the VIS is able to set and monitor various aircraft parameters, and then inform the pilot that the conditions have been met. If a failure occurs on the aircraft, whether it is a warning or a caution, the appropriate subsystem responsible for monitoring that condition will instruct the VIS to synthesize the message that best describes the condition.

An option also exists to train recognition templates. This allows the pilot to perform minimal in-flight training of speech templates to improve recognition. The pilot also has the capability of choosing which types of synthesis phrases he will receive during a mission. During a heavy-workload environment, the pilot has the option of placing the synthesis into a combat mode that will only synthesize certain messages, or he can also turn the synthesis off all together.

instances where the volume control knob could possibly be turned down. This forces the volume to override the knob control and to help identify the urgency of the message.

Because there may be words that will not perform during flight test with the certain templates that were trained on the ground, a means was provided to allow minimal in-flight training. This process is strictly an interactive voice procedure and requires no visual feedback of the word to be trained. To initiate this option, the pilot informs the VIS of the identification (ID) code for the problem word (for words that are digits, the ID code does not contain the same value); then the VIS synthesizes to the pilot which word is to be trained.

There was also concern that the nodes should be organized in such a manner as to increase recognition accuracy and still make sense to the pilot. This is a difficult task because of the restrictions in the grammar and design. Some learning will be required for this design, but as the technology improves, an increase in the size and speed of the vocabulary will be realized, and the ease of usage will also improve.

Flight Demonstration

The true test will be how well the pilot is able to accomplish his mission and still say that voice contributed to its success (See Figure 9). The APTI/F-16 pilots will be required to fly identical scenarios alternating between the use of voice tasks and normal manual tasks. The data acquired during the voice task scenarios will be compared against the same scenarios flown strictly by manual operation. This data will allow subjective and objective evaluations of whether or not the pilot's workload was reduced. In preparation to this final evaluation, selected runs will be flown. Besides helping the pilot become familiar with the use of voice, environmental and template recognition data will be collected for future analysis and algorithm development. These data points will include (1) speaking at elevated g's (up to 7 g's), (2) speaking loudly, and (3) speaking while looking over the shoulder and pulling a 5-g maneuver.

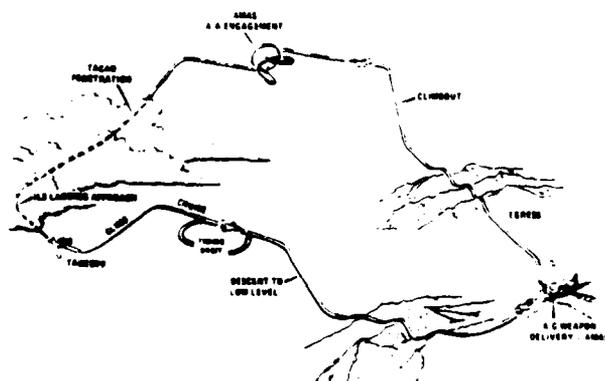


Figure 9 VIA Demonstration Testing

CONCLUSION

The APTI/F-16 Voice Interactive Avionics program has developed as a natural extension of previous studies and evaluations. At the completion of the APTI/F-16 program, sufficient data will be available to (1) determine how voice technology can effectively decrease pilot workload, and (2) determine the utility of voice technology in fighter environments (See Figure 10). Additionally, data gathered during the flight demonstration will be useful in (1) identifying characteristics that affect voice patterns, thereby enhancing future algorithm development to increase recognition accuracy; and (2) determining production requirements for future programs, such as, internal architecture, memory requirements, and throughput.

- HIGH WORKLOAD APPLICATIONS
- SUBSYSTEM PARTITIONING
- IMPROVED VOICE RECOGNITION
- DETERMINE PRODUCTION HARDWARE REQUIREMENTS
 - ✓ Internal Architecture
 - ✓ Memory
 - ✓ Through-Put

Figure 10 VIA Objectives Remain Unchanged

AFTI/F-16 Digital Terrain Management and Display System

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J. S. Eckel
G. W. Cantrell

AO-A104 941

AFTI/F16 AUTOMATED MANEUVERING ATTACK SYSTEM TEST
REPORTS/SPECIAL TECHNOLOGIES AND OUTLOOK(U) GENERAL
DYNAMICS FORT WORTH TX FORT WORTH DIV 11 JUL 86

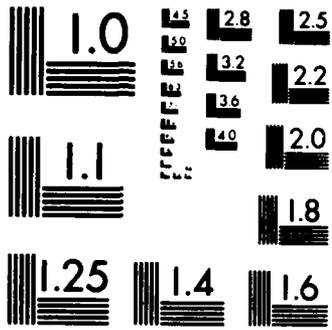
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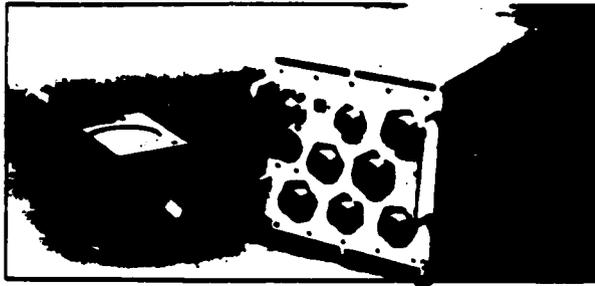
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NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



BENEFITS

- REAL TIME MOVING MAP
- MANY MAP SCALES
- 7 COLORS
- IN-FLIGHT SYMBOLOGY UPDATE
- 3-D TERRAIN SHADING
- MTAN TERRAIN CORRELATION
- IN-FLIGHT WRITE TO TAPE
- TARGET AREA LOOK AHEAD
- DMA DATA BASE
- COLOR GRAPHICS
- COLOR TEXT
- LARGE AREA COVERAGE
- FLIGHT PLAN DISPLAY
- DECLUTTER OPTIONS

STATUS

- 1st ASSET DELIVERED NOVEMBER 1988
- CURRENTLY IN FLIGHT TEST
- FIRST FLIGHT 26 FEBRUARY 1988

FEATURES

- MULTIPROCESSOR
- LIGHT DUTY CYCLE ON CURRENT PROCESSORS
- GROWTH FOR FUTURE PROCESSORS
- HIGH DATA COMPRESSION RATE
- SHARED RAM
- SYMBOL GENERATOR

Figure 2 The AFTI/F-16 DTMDS System

consists principally of switch labels and not map feature data. The hybrid video is then displayed on the Bendix CMPD.

DESIGN OBJECTIVES

The design objectives of the DMG emerged from a need for highspeed, low-altitude, all-weather, automatic flight and a need for tactical situation awareness. These parameters, when optimized, provide the pilot with the basis for maximum survivability. However, without sensor input this becomes an increasingly-high-workload task and at some point saturates the pilot's ability to respond to various mission parameters that need to be addressed for maximum survivability. The digital map goal was to reduce this task by eliminating the need for paper maps as a primary source of navigation, and to provide the pilot with a situational awareness that was not previously possible. Also, a digital data base was to allow many future, overall, aircraft improvements that were not previously possible in the sensor fusion arena. A secondary, but necessary, design objective resulted from placement of the CMFD in the center pedestal. This location of the CMFD displaced the flight-critical ADI and HSI flight instruments. Therefore, it became necessary to design synthetic, electronic, flight instruments to replace the ADI and HSI.

HUMAN FACTORS

In this digital-data-management system, digital data displayed to the pilot are presented with real-time translation and rotation synchronized to aircraft motion. Additional modes provide stationary, look-ahead views. The ability to electronically synthesize displays allows for constantly-changing information to be updated in real-time. For example, colors can be allocated to specific terrain heights above and/or below aircraft altitude. Therefore, as the aircraft moves vertically,

these "highlighted" regions contract and expand depicting potentially hazardous areas. Displays of electronic, primary, flight instruments and flight control system faults are also available. It should be noted, however, that display of terrain (the main format) offers little advantage over simple digitized paper maps. The capability of extracting and manipulating elevation data is the main advantage of the digital map.

The synergism between the available terrain data onboard the aircraft and the ability to achieve improved navigational accuracies is apparent. Sensor data, which are obtained as the aircraft flies, can be correlated to stored terrain data and automatically linked to update the inertial navigation system to minimize pilot/system errors. The Sandia Inertial Terrain-Aided Navigation (SITAN) algorithm has already achieved improved potential accuracies of less than 100 meters. Because the pilot obtains some 78% of his information from the visual sense, it is important to maximize the transference of these data through properly designed displays. Some of the experiments that are scheduled to be performed to support the AFTI/F-16 map development, and to support the transition of the displays from monochromatic to emissive chromatic are listed in Table 1.

Table 1 HUMAN FACTORS EXPERIMENTS FOR THE DIGITAL MAP SYSTEM

Experiment	Objective
1. High Resolution CRTs	1. Ascertain acceptable saturation levels
2. Scale/Feature Prioritization	2. Determine types and number of color features required for appropriate map scales
3. Size/Shape/Color Coding	3. Determine types and numbers of color features required for appropriate map scales
4. Color Coding Scheme	4. Evaluate number and chromatic coordinates of usable colors
5. High/Low Ambient Light	5. Optimize automatic display brightness controls
6. Chromostereopsis Uses	6. Ascertain uses of chromostereopsis
7. Accommodative Efforts to Multi-Color Displays as a Function of Color Intensity	7. Determine optimum saturation

PHYSICAL DESCRIPTION

The DTMDS is physically configured in preproduction form and incorporates state-of-the-art packaging as well as functional technologies. For the DMG, a low-volume, packaging technique is utilized which mechanically integrates the electronics and housing into a solid structure, thus affording maximum protection to the electronics. The DMG is shock mounted to enable it to meet the gunfiring vibration environment, and aircraft cooling air is required to enable it to operate through the temperature environment. The MTL is a militarized production unit, Model 6425-01, manufactured by Raymond Engineering, Inc.

The DMG consists of 21 electronic modules or SRAs and a power supply module housed in a 9.04 inches high x 8.5 inches wide x 18.25 inches long enclosure. It has a volume of 1400 cubic inches, weighs 62.87 pounds (including an isolator mounting tray) and dissipates 494 watts maximum. The power for the DTMDS is of two

types: 115-volt, 3-phase, 400-Hz AC power for the DMG and 28 Vdc for discrettes. In addition to the 21 electronic modules and power supply, the enclosure contains the I/O connectors, a motherboard, and a rigid-flex, printed wiring board to interface the I/O connector with the motherboard.

The MTL is partitioned into three subassemblies, namely the electronics unit, the Tape Transport Cartridge (TTC), and the cradle and cable assembly. The electronics unit provides power, tape control, and processing functions. It interfaces with the DMG by means of the MTL interface unit in the DMG. The TTC is a removable unit containing the magnetic storage media, tape drive mechanisms, and read/write components. The TTC plugs into the cradle and cable assembly which is in turn connected to the electronics unit. The power for each MTL is 28 VDC and is consumed at the rate of 28 watts. A vibration mounting tray was designed for the TTC in order to withstand both aircraft and gunfire vibration. The electronics unit weight, excluding the installation specific cable, is 3.0 pounds in a volume of 78 cubic inches. The TTC weight is 1.7 pounds in a volume of 23 cubic inches. Cooling provided for the DTMDS system is provided in two forms. The DMG is forced-air cooled and is designed around the AFTI constraints shown in Figure 3. The MTLs require only convection cooling.

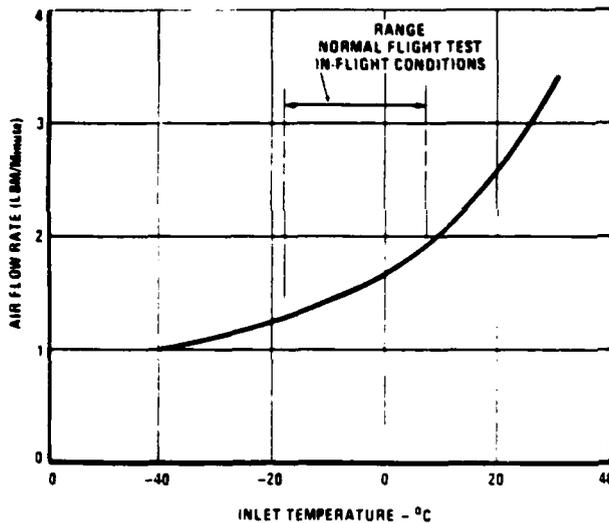


Figure 3 LRU Maximum Required Cooling Air Flow Data

DMG ARCHITECTURE

As described earlier, the DTMDS comprises the DMG unit and either 1 or 2 MTL units. While the MTL is simply the Raymond Model 6425 Tape Unit, with its plug-in tape transport cartridge, the DMG contains several complex subsystems. The major subsystems that constitute the DMG are the Global Subsystem, the Digital Map Generator (DMG) Subsystem, the Symbol Generator Subsystem, the MTL Control Subsystem, and the SITAN Processor. The following will provide an overview description of these major subsystems.

Global Subsystem Functional Description

The DTMDS is an organization of embedded subsystems operating independently and in parallel, yet

communicating among one another and with external systems, by means of a shared global bus. There are five subsystem elements that communicate with one another on the global bus, as shown in Figure 4. Communication outside of the DTMDS is provided by the Bus Interface Unit (BIU). The primary function of the DTMDS is provided by the Digital Map Generator (DMG) function, which interfaces directly with the global bus. The interface to the two MTLs is also structured as a subsystem and is shown in the figure as the "tape controller". The other two subsystems are the symbol generator and the auxiliary/Sandia Inertial Terrain-Aided Navigation (SITAN) subsystems. While all of the above subsystems are bus masters (capable of arbitrating for the bus and controlling access to the bus once given control by the arbitrator), the shared RAM functions as a bus slave (a passive device which can send and receive data only when commanded by a bus master).

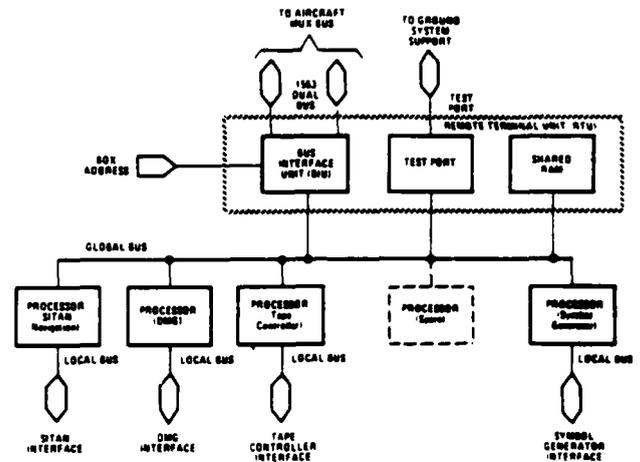


Figure 4 DMG Global Bus Configuration

Global Bus

The global bus is organized as a word-wide (16 bit) interconnect system operating at a functional one-megahertz rate (16 megabits per second). Access to the global bus is on a priority basis, with the BIU having the highest priority. Communication among the subsystem elements, including the BIU, is through the global memory (shared RAM). The "mailbox" concept, which is used in global memory utilization, alleviates many of the synchronization problems inherent in multiprocessor systems. For example, data from processor A destined for processor B are entered in the appropriate "mailbox" in global memory. At any time later, processor B can retrieve the data from the "mailbox". This concept is especially efficient, since precise synchronization among the processors is not necessary and processor synchronization to the BIU frame iteration rate is not necessary.

Bus Interface Unit (BIU)

The BIU provides access to the shared RAM for an external user via a redundant MIL-STD-1553B data bus. Transmit and receive command messages via the 1553B bus are mapped to memory buffers on the shared RAM by direct memory access over the global bus.

Test Port

The test port provides VAX DR11W to global bus interface capability by means of the Interface Adapter Unit (IAU), which is a module external to the DTMD5 flight hardware for use only on the ground. The IAU supports block transfers of data up to 4K words. Commands, data, and test programs may be uploaded or downloaded through the IAU. The IAU can functionally replace the 1553B interface.

Digital Map Generator (DMG)

The DMG controller is the processor primarily responsible for DMG operation. In addition, the DMG controller manages the on-line, digital map data base, formats and manipulates those data, provides them on request to other (sub) systems/users, and is the controlling function for real-time video presentation in the cockpit.

Tape Controller

The tape controller provides the necessary interface between the MTLs and the DMG. The tape controller's function includes the data and data rate buffering necessary to support MTL timing. This is an independent operation of the DMG. The tape controller accommodates data both to and from the MTLs. When data are being transferred to the MTLs, the tape controller arranges and transfers the data consistent with an established MTL data format.

Symbol Generator

The symbol generator function provides the map overlay graphics and any necessary alphanumerics associated with the overlay symbology. The symbol generator is a subsystem by itself. It can generate full-screen graphics independent of the map display in the form of an electronic flight instrument. In the map display modes, the symbol generator output is registered geographically with the DMG output, ensuring ease of recognition and comprehension by the pilot.

Auxiliary (SITAN) Processor

The auxiliary processor performs navigation correlation computations utilizing the SITAN algorithm. Periodic navigation updates are provided by the SITAN algorithm based on the aircraft altitude measurement data input over the 1553B data bus.

Shared RAM

The shared RAM is a global 16k word memory which provides storage for inter-processor communications and external DTMD5 communications.

Tape Control Subsystem Functional Description

The Tape Control Subsystem performs several data transfer functions:

1. Copy from tape to tape,
2. Transfer from tape to internal DMG memory as well as the reverse, and

3. Transfer from internal DMG memory to a DMG microprocessor as well as the reverse.

DMG Subsystem Functional Description

The DMG subsystem is responsible for reconstructing the compressed, digital data in the Intermediate Memory (IM) and using the reconstructed data to generate the various video display modes. The DMG subsystem produces both color and monochrome video outputs in RS-170 format. The video outputs will display the topographic map generated by the DMG and/or alphanumerics/graphics from the symbol generator subsystem. The topographic display portrays both terrain elevation and cultural features and accommodates real-time rotation and translation of the display. The DMG subsystem also provides terrain elevation and cultural feature data for use by other subsystems.

Symbol Generator Subsystem Functional Description

The symbol generator subsystem provides high speed MTLs from its internal storage, and from the 1553B data bus for these displays. Data received over the bus are new data, and may include flight plans, targets, threats, and friendly symbols. The symbol generator ensures that text is presented in a screen-up orientation, no matter what the orientation of the map may be.

Graphics are registered with the map data even during translation and rotation. Symbols are positioned with a resolution of 1 pixel over a screen spatial resolution of 480 x 480 pixels. Symbols intersecting the edge of the display screen scroll onto the screen smoothly in a pixel-by-pixel fashion.

The display is refreshed at the rate of 60 Hz and updated at the following rates:

Symbol Usage	Rate
Synthetic Instruments	30 Hz
Map Point Features	15 Hz
Fixed Position Symbology	5 Hz

There are two independent channels of symbology maintained by the symbol generator. Channel 2 data consists simply of a two-level, monochrome symbology, while Channel 1 provides symbology for the DMG RS-170 RGB color video display. Channel 1 is capable of displaying seven colors simultaneously from a possible range of 16,777,216 colors. Color selection is loaded from tape into the DMG at initialization. Seven colors have been specified to maximize the color contrast of points and lines against area backgrounds. In addition to these seven colors, an eighth color, transparent, is provided. The transparent color allows terrain data to show through the open parts of the symbols.

The specific types of symbols available can be categorized into alphanumerics, circles, lines, and point features. Alphanumerics, which include the standard ASCII characters, are available in 2 font sizes - 10 x 13 pixels (font 1) and 14 x 18 pixels (font 2) - with a line width of 2 pixels. A total of 52 sizes of circles can be generated with a range radius of 7 to 1024 pixels. Lines may be displayed with selectable length, slope, and end points. Point features are specified as having a

particular geographic location, and each point feature may have a four-character label (font 1) associated with it. There are two types of point features: (1) global interest points and (2) local geographic points. Characteristics of the two types of point features are summarized in Table 2.

Table 2 DTMDS POINT FEATURES

	GLOBAL	LOCAL
• QUANTITY	96	"UNLIMITED USABLE"
• SHAPE AND COLOR INDEPENDENCE FROM OTHER POINTS	YES	YES
• CONNECT BY LINES (Color)	YES	NO
• HOW DEFINED	MISSION PLANNING	OMA DATA
• CHANGEABLE IN FLIGHT	YES	NO
• 256 SHAPES (Color)	YES	YES
• OCCLUSION ZONE (Color)	YES	YES
• ASSOCIATED TEXT (Color)	YES	YES
• ASSOCIATED CIRCLE (Color)	YES	NO
• WRITE TO TAPE	YES	NO
• FLASH	YES	NO
• ROTATION (On/Off)	64/96	NO
• NOSE VECTOR LENGTH (On/Off)	64/96	NO

Other capabilities of the symbol generator include the following: (1) symbol flashing (2.5 Hz, 50% duty cycle); (2) rotating of symbols; (3) an occlusion zone (which prevents background video from showing through) around a symbol of selectable color (any of the seven symbol colors); (4) area fill, which allows a large area of the screen to be drawn in a specified color; (5) declutter, which provides a means of removing symbology from the screen in order to prevent overcrowding of the display; and (6) an electronic flight instrument display mode, which is a symbology-only mode (the map display is deselected).

SITAN Operating Description

Sandia Inertial Terrain-Aided Navigation (SITAN) is an extended Kalman filter navigation algorithm which utilizes outputs from the radar altimeter (which measures ground clearance), the Inertial Navigation System (INS), and the Digital Terrain Elevation Database (DTED) to produce corrections to the INS indicated position and velocity. Typical unaided inertial navigation systems develop horizontal position errors on the order of several miles per hour, whereas SITAN can reduce these errors to the order of 100 meters or less. This navigational accuracy improvement is a result of making periodic adjustments to the INS computations by comparing ground clearance measurements with a predicted ground clearance, as determined from the DTED. These adjustments typically occur every 100 meters of distance traveled. Figure 5 shows the basic SITAN configuration. This configuration is valid for aircraft altitudes below 500 meters above ground level (AGL). When there is a large error in the initial aircraft position, a single SITAN filter may take a long time to converge to the true position, or it may possibly never converge. Thus, when a large initial uncertainty is expected, several SITAN filters spaced approximately 500 meters apart are run in parallel, each estimating the aircraft position within a smaller uncertainty region. When one of these parallel filters can be reliably chosen as having converged to the true aircraft position, a single SITAN filter can then be initialized at this position.

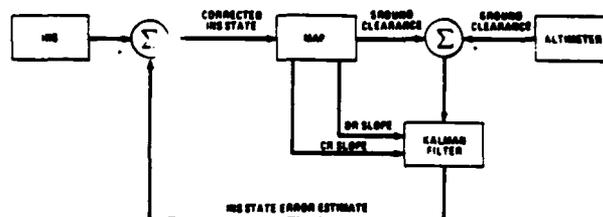


Figure 5 SITAN Functional Configuration

Through this procedure SITAN produces a corrected INS state which is used to update the aircraft's position on the map. This output could be coupled to update the INS, but is not accomplished in this implementation.

DTMDS OPERATION

Detailed Operating Mode Descriptions

The different mode commands that can be processed by the DTMDS are described in this section. Included in the mode commands are general on/off controls (On-line/Off-line, Map On/Off, Center/Decenter, SPI, BIT/Self-test, and SITAN Mode Select), DMG feature selections (shades of gray, sun-angle shading, terrain above a set altitude, contour lines, cultural data, color assignments, display scales, and scene memory usage), and symbology selections (colors, symbol blink, alphanumeric, graphics, point features, and an IFD).

General On/Off Controls

On-line/Off-line. A single bit in the initialization data is used to determine whether the DTMDS is in the off-line mode or the on-line mode. In the off-line mode all video displays are blanked except for test patterns used in BIT. The off-line mode is used for all block transfers through either the 1553B bus or the test port. The on-line mode is the normal operational mode during which video outputs are maintained. This mode is commanded by means of the 1553B bus.

Map On/Off. A symbology-only-mode can be displayed by a 1553B bus command. In this mode a programmable background color is displayed everywhere the symbol generator is inactive.

Center/Decenter. The DTMDS display can be centered or decentered (77% down from the top of the display) at the specified navigation update position. An indication of the aircraft position on the display (centered or decentered) is provided by an aircraft symbol. The decenter position provides more look-ahead display area.

System Point of Interest (SPI). The SPI mode, when selected, presents a map display image so that the latitude/longitude for the system point of interest is depicted in the center of the color display. The map image is displayed in the North Up orientation when the SPI mode is selected. The aircraft symbol, although not centered in the SPI mode, will appear, if the aircraft position is within the area displayed. It will appear in its true position and orientation.

BIT/Self-Test. Self-test is continually performed in the on-line mode. Built-in test (BIT) operates only when commanded. BIT can operate only when the DTMDS is in the off-line mode, and it is used primarily in the aircraft as a GO, NO-GO indication.

SITAN/Mode Select. The SITAN module consists of three major parts: acquisition mode, track mode, and the mode control logic. The mode control logic receives control from the executive at a 3-Hz rate. The actual flow consists of a forced mode and an automatic mode. The automatic mode is SITAN's normal state where flow is passed from acquisition to track and from track to acquisition based on the internal mode control logic. Higher-level logic (or the pilot) can force SITAN into one of three states: off, acquisition, or track. If one of these three states has not been explicitly specified, SITAN remains in the automatic mode. Once turned off, SITAN remains off until either forced into acquisition or track mode, or explicitly returned to the automatic mode by the pilot. On power-up or full reset, if no explicit mode is specified, SITAN will start in the automatic acquisition mode.

General DTMDS Feature Selections

Display of Elevation and Cultural Data. The Defense Mapping Agency (DMA) data are composed of two distinct types of data: elevation data and cultural (or feature) data. These two types of data are mixed together digitally within the DMG to provide a real-time color moving map display. Elevation data can be displayed in one of three formats: elevation shading (shades of gray), sun-angle shading, or terrain above a set altitude. The display format for elevation is user selectable over the 1553B bus.

Elevation Shades of Gray. In the elevation shades of gray format, the intensity of each pixel is a function of the absolute elevation of the terrain being represented. The intensities are grouped into eight distinctive bands. The DTMDS is capable of updating the elevation shades of gray field of each scene memory, by means of the 1553B bus using the following parameters:

1. **Maximum Altitude** - the specific discrete absolute elevation above which the maximum shade of gray value is assigned, and
2. **Band Interval** - the interval at which the shade of gray changes (up to 7 times) below the maximum altitude.

Locations within the memory are accessible by the hardware and are loaded with the maximum shade altitude and the shade interval for the displayed scene memory. The shade values for the displayed scene memory are loaded into the hardware shade table. This is performed within two vertical retrace times (33 milliseconds) from receipt of the command.

Sun-Angle Shading. In the sun-angle shading, display format, the intensity of each pixel on the display is a function of the slope of the terrain represented by the pixel relative to an artificial sun angle. This gives an artificial, three-dimensional appearance to the map. The sun angle is artificially fixed at -45 degrees with respect to the map orientation angle in order to prevent commonly known display illusions. In the sun-angle

display format 16 shade levels are utilized. The DMG automatically adjusts for the display scale factor; thus, no external parameters are required in this mode.

Terrain Above a Set Altitude. The third display format is called terrain above a set altitude. This format is a modification to the standard elevation shading format. The purpose of this mode is to provide the pilot with a display particularly suited to terrain-avoidance flight. In this mode, all areas of the display representing terrain above a set altitude are assigned a distinct color. Other areas of the display are assigned a mid-shade of the elevation shading format. The "set altitude" can be fixed or dynamically controlled by the DMG to correspond to the aircraft altitude plus an externally provided offset. The color chosen is read from the tape at initialization.

Contour Lines. In each of the three basic elevation formats, black contour lines can be added. The contour lines represent lines of constant elevation in the displayed terrain. The contour lines can be selected or deselected by external 1553B bus control. When selected, the lines are generated at a real-time, 60-Hz rate so that they keep up with any aircraft translation or rotation. Two inputs are provided to the DMG via the 1553B bus to define a reference elevation for contour line location (RC) and the interval between subsequent contour lines (IC). The value of RC can be positive or negative. Contour lines will be assigned at the elevation equal to RC and all elevation values above and below RC that are integer multiples of IC. Without specific commands over the 1553B bus, initialization values for the contour lines will be used.

Cultural Data. Feature colors are obtained from DMA cultural data which are composed of area, linear, and point features. Within the DMG, point-feature data are processed with all other symbology in the symbol generator subsystem and are discussed in a later section. Area-feature and linear-feature data are read from the MTL in compressed form and are reconstructed prior to being written into a scene memory. The DMG can process up to 62 different, area-feature types and 64 linear-feature types at one time. Each area-feature and linear-feature type can be individually selected or deselected by means of a preselection memory during the reconstruction process. This preselection memory specifies selection/deselection as a function of display scale as well as of feature type. Thus, detailed feature data can be decluttered when larger, area display scales are desired.

DMG Color Assignments. In general, colors used for DTMDS point and linear features (both topographic and tactical) are highly saturated and of high signal strength. Area topographic features, in contrast, are less saturated. This factor maximizes color contrast of points and lines against the area backgrounds.

Map Display Scales. In order to maintain ground-speed and data-coverage requirements, the DTMDS is capable of reconstructing data compressed from a variety of initial spatial resolutions. Compressed data used by the DTMDS are provided on a one-scale-set per tape basis. A scale set is defined as tape data that contains up to 68 blocks of high-resolution data, and up to 16 blocks of low-resolution data, where the total block count of high- and low-resolution data blocks is less than or equal to 68. Map

scale set identification is provided in the tape directory data portion of the tape initialization data. The DTMDS is able to operate out of any one of three scale sets. Geographic coverage per block in both basic and expanded scale for each scale set is described in Table 3.

Table 3 DTMDS GEOGRAPHIC COVERAGE

MAP SCALE SET 1	
Basic Block Size (Up to 68/Tape) 12.5 x 12.5 KM	Expanded Block Size (Up to 18/Tape) 100 x 100 KM
MAP SCALE SET 2	
Basic Block Size (Up to 68/Tape) 25 x 25 KM	Expanded Block Size (Up to 18/Tape) 200 x 200 KM
MAP SCALE SET 3	
Basic Block Size (Up to 68/Tape) 50 x 50 KM	Expanded Block Size (Up to 18/Tape) 400 x 400 KM

Each Tape Transport Cartridge (TTC) can contain any one of the three scale sets. Any two scale sets can be provided using two TTCs. When using the same scale set for both TTCs, up to twice the area coverage can be provided. When two different scale sets are available, either one is available for display through the DTMDS at one time; however, selection of the other scale set requires reinitialization of the DTMDS.

The DTMDS is capable of operating on tape data that consist totally of basic scale data. In this case, up to 68 blocks of basic scale data can be provided on a single tape. Expanded coverage using two tapes of 136 blocks of basic data may be used. The display scales available per scale set are described in Table 4.

Table 4 DTMDS MAP SCALES

MAP SCALE SET	BASIC (KM)	EXPANDED (KM)
1	3 x 3	24 x 24
	6 x 6	48 x 48
	12 x 12	96 x 96
	24 x 24	192 x 192
2	6 x 6	48 x 48
	12 x 12	96 x 96
	24 x 24	192 x 192
	48 x 48	384 x 384
3	12 x 12	96 x 96
	24 x 24	192 x 192
	48 x 48	384 x 384
	96 x 96	768 x 768

These display scales are provided in a way that ensures real-time readout to the display of either scene memory at aircraft velocities dependent on the following cases:

1. **Primary Display Mode** - When a basic and an expanded scale are in the two scene memories, respectively, real-time video readout of either scene memory is maintained at aircraft velocities up to the maximum velocity indicated in Table 5.

Table 5 DTMDS AIRCRAFT VELOCITY REQUIREMENTS

MAP SCALE SET	BASIC (KM)	EXPANDED (KM)	MAXIMUM VELOCITY (Knots)
1	3 x 3	*	300
	6 x 6	*	400
	12 x 12	*	400
	24 x 24	*	250
2	6 x 6	*	600
	12 x 12	*	800
	24 x 24	*	800
	48 x 48	*	500
3	12 x 12	*	1000
	24 x 24	*	1000
	48 x 48	*	1000
	96 x 96	*	1000

* Velocity is dependent on basic scale selected. Any expanded scale can be selected, and maintain velocity

2. **Alternate Display Mode** - When both scene memories, centered about the aircraft, are reconstructed out of the basic scale set, from Map Scale Set #1, reduced aircraft velocities up to the maximum indicated in Table 6 are maintained.

Table 6 DTMDS ALTERNATE DISPLAY MODE VELOCITY REQUIREMENTS

SCALE SCENE MEMORY A (KM)	SCALE SCENE MEMORY B (KM)	REDUCED MAXIMUM VELOCITY (Knots)
3 x 3	24 x 24	No Requirement
6 x 6	24 x 24	100
12 x 12	24 x 24	100
24 x 24	24 x 24	No Requirement

3. **Look-Ahead Display Mode** - In this mode, the DTMDS is capable of generating and supporting one moving map in one scene memory centered about the aircraft and one moving or static map in the second scene memory. The moving or static map in the second scene memory is capable of being located geographically anywhere in the available, on-line, DTMDS data base (of the same scale set). When operating in this mode, the DTMDS maintains both scene memories with priority given to the aircraft-centered, scene memory.

Symbology

The symbol generator provides a seven-color, symbology palette to overlay on the terrain map or to

present a symbology-only display (electronic flight instrument). The map overlay symbology consists of point features, text, circles, flight-plan lines, cursors and an aircraft symbol. It also includes the bearing to steerpoint arrow.

Typical symbology used with a map display would include flight plans and point features. Point features are defined in the DMA data base as small area features, such as water towers, hospitals, airports, etc. Each is assigned a symbolic representation that has an associated mnemonic. Additional point features may be defined at mission planning time by using existing shape codes or by making a new shape and storing it in RAM reserved for symbol storage. Some are used as steerpoints on the flight plan while others are used as interest areas off of the flight plan. Up to four characters of text may be associated with each point feature. The shape of the symbol provides a generic identification. The text is used to provide additional data as required. The color of the symbol and text may be specified independently. A circle centered on the point feature may be specified to indicate an area of influence surrounding the feature. The radius of the circle may also be specified. To increase the visibility of the point feature when superimposed on the map, an occlusion zone may be specified around the symbol and text. This zone will block out the map data to provide a featureless background for the symbology, greatly enhancing its legibility.

Flight plans are indicated by connecting point features together with straight lines. The symbol generator organization permits the changing of mission-related, point features in real-time. Points may be added to, or deleted from, the flight plan at any time. Commands to edit the list of point features may be received by means of the 1553B bus.

Point Feature Characteristics. There are two general categories of point features supported by the DTMDS - Local Geographic Point Features and Global Point Features. In addition, there are two types of Global Point Features - Flight Plan Points and Interest Points. The DTMDS provides the capability of storing 256 local geographic points for each scene memory. Each subblock on the TTC may contain up to 64 local geographic point features. A total of 96 global point features are provided. To satisfy the need for a permanent record of flight-annotated point features, the DTMDS is able to write these points on tape. The DTMDS has the capability of drawing circles around global point features. The real-world radii that are possible, range from 50 m to 1062 km in 116 discrete steps. The DTMDS provides a means to remove area, linear, and point features from the map in order to prevent overcrowding of the display. Two additional declutter bits supplied to the DTMDS control the point feature symbology. These are the text declutter bit and the circle declutter bit. These bits allow all-point-feature text, and/or all-point-feature circles, to be collectively decluttered.

The DTMDS also provides 25 point features which are dedicated to depiction of the flight plan. Each flight-plan point's shape and color are specified independently. The flight-plan points are initialized from the TTC. Flight-plan points may have an optional circle. The flight-plan consists of line segments joining flight plan

point features. An external command is able to select or inhibit the display of the flight plan. Each TTC has a predefined flight plan. Each flight-plan may contain up to 25 flight-plan point features and up to 25 flight-plan lines.

Five point features are dedicated as markpoints in the AFTI/F-16. These have the same capabilities as flight-plan points, but are used to indicate points of interest beside the flight path such as new threats or potential targets. In addition, two point features are reserved for depicting AFTI/F-16 AMAS bombing routes.

The DTMDS is capable of accepting updates to flight-plan points while the aircraft is in flight. The updates are received by the DTMDS as 1553 data.

Interest Points. In addition, the DTMDS provides 64, general-purpose, interest points. Each interest point's shape and color is specified independently. The interest points are initialized from the TTC and may have an optional circle. The DTMDS is also capable of accepting updates to interest points while the aircraft is in flight. The updates are received by the DTMDS as 1553 data. Any interest point may have an optional line linking it with another interest point.

Integrated Flight Display. The flight instruments that were displaced as a result of adding the CMFD to the center pedestal were the ADI and HSI. This displacement caused a need for electronic flight instruments on the CMFD. However, there were cases when the pilot needed both ADI and HSI information, such as during a landing approach. This need resulted in the design and implementation of a new flight instrument, one which integrated both the ADI and HSI information. This flight instrument is called an Integrated Flight Display (IFD). The integrated flight display combines the information contained in an attitude direction indicator, a horizontal situation indicator, an altimeter, and a velocity scale into a single-display format for presentation on the Color Multifunction Display (CMFD).

FUNCTIONAL GROWTH OF THE DTMDS

Mention has already been made of the fact that the DTMDS has been designed for additional growth in functional capability. This growth is accommodated in three ways: (1) provision of additional spare processor card slots in the basic DMG (the digital map processor) unit to allow for more processing capacity; (2) substitution of higher-capacity, data storage devices to achieve a greater geographic area coverage; (3) preparation of the appropriate software to implement the additional processing functions. This section will cover the above growth capabilities in more detail and will address projected future functions of the DTMDS.

Increase in Processing Capacity

The design of the DMG unit is based on an efficient, global bus concept in which the multiple microprocessors communicate with each other through a shared, global memory. The bus itself is pre-wired to three spare card slots in the unit, into which standard processor cards may be inserted to increase processing capacity. In the AFTI/F-16 application, one of these three cards is already used by the SITAN processor, leaving two more slots available for other functions. In addition, the

SITAN processor itself is not heavily loaded, and, therefore, can also provide support for other processing operations.

There is a set of additional functions currently being considered for implementation in the DMG unit. These are briefly summarized in Table 7 and will be discussed later in more detail. Table 7 illustrates the comparative processing load of the current AFTI/F-16 configuration and the future growth capability with additional processor cards in place (columns SP1 and SP2 in the table). It can be seen that the overall processor loading is quite reasonable.

Table 7 DMG PROCESSOR LOADING SUMMARY

PROCESSOR	TC	SP0	SP1	SP2	SP1	SP2
CURRENT FUNCTIONS	-BT SELF TEST -DATA CONTROL -IN MAINTENANCE -IN MAINTENANCE	-BT SELF TEST -MAP MOTION -MODE -NAVIGATION -DATA BASE -IN MAINTENANCE -IN MAINTENANCE -BT DISPLAY	-BT SELF TEST -MAP DISPLAY -FLIGHT PLAN -INTEREST POINTS	-BT SELF TEST -BT	N/A	N/A
LOADING	20%	20%	SP1 40% SP2 40%	10%	N/A	N/A
ADDITIONAL FUNCTIONS	-ADAPTIVE -INTERFACE	-CORE PROCESSING -RANGE TO BT -TARGET -ELEVATION OF -CHERRYBT	-HD HD -CORE BITTER -LABELLED -INTERVIEWABILITY -DISPLAY	-SYSTEM ALTITUDE -SAFE ZONE -SURVIVANCE -OTHER	-BT SELF TEST -INTERVIEWABILITY -OTHER	-BT SELF TEST -OTHER
TOTAL LOADING	20%	40%	SP1 40% SP2 40%	10%	20%	MODERATE/HEAVY

Higher Capacity Data Storage Devices

Because of their availability and a background of performance in military applications, a tape cassette is the current storage medium. Two cassettes, each having a capacity of 25 megabits, are used in the AFTI/F-16. This somewhat-limited capacity necessitates the compression of the stored data to achieve reasonable coverage of the geographical area of interest.

Higher-capacity storage could allow at least two options to be considered: (1) an expansion of the area covered, with retention of the data compression, and (2) an elimination of data compression, yielding a simplification of the processing hardware and software. Performance of a digital terrain system is largely dependent on the type of storage media used, and for the present time, the only reasonable data storage is magnetic tape. When higher-density media become available and qualified for aircraft applications, they will also be considered for the AFTI/F-16.

At the present time, the most promising storage device is the optical disk, although smaller, magnetic-disk systems could certainly become available as well. For limited-area coverage, no better device could be used than a solid-state memory. The optical disk, however, offers the possibility of large area coverage and of storage for other data such as charts, photos, and approach plates - all without the necessity for data compression.

Additional Processing Functions

We have briefly explained how the DTMDS has the capability for expansion to include additional processing

functions. We will now summarize several representative processing operations that are being considered for the enhancement of weapons system performance.

Incorporation of Display Generator Functions

The mechanization of the pilot interface in the AFTI/F-16 is made possible through a color display with typical pushbutton function selection. This display generator feeds commands to the DMG, requiring additional hardware and software. By adding a processor card to the DMG, it is possible to simplify the pilot interface, eliminate one LRU from the avionics system, and process all display functions. This capability includes all of the currently implemented functions of the present, display generator except stroke writing on the CRT; the DMG would generate all display outputs in a pure raster format. It has been found that the stroke capability lends very little to the system function, and moreover, its effectiveness becomes severely limited when complex displays are required. Raster, on the other hand, has no such limitations. However, brightness considerations must be addressed before a change to an all-raster system is made.

All that is needed to provide the capability of replacing the current display generator is to add the processor card, and to write the appropriate software for symbol generation and switch panel translation. This is a modest effort that could pay huge dividends in the reduction of avionics hardware.

Safe Ground Avoidance

With the DLMS data base on board, the capability of enhancing the ground avoidance function exists. The projected improvement uses the terrain data in conjunction with the radar data and includes a projection of aircraft flight path. Any time the combination of aircraft altitude, attitude, or flight dynamics indicates an impending ground collision, one of two things will occur: either (1) the pilot will receive a warning, or (2) an automated control function will maneuver the aircraft to a safe flight envelope.

All of these functions may be calculated or processed in the DMG unit by the use of currently available aircraft position and control data. The blending of the radar data and the DLMS terrain data, along with the necessary processing of control commands, represents a minimal processor load in the DMG.

Range to Sensor/Tracker Target

A reasonably simple calculation is all that is needed to determine the range to a target, given its location on the ground, or given the angle of the IR sensor/tracker system. This will allow more rapid sensor focusing, laser-designator motion compensation, or other weapon-delivery calculations at a time when fractions of a second can be significant. Table 7 illustrates how the DMG's processing capability can handle these calculations.

Elevation of a Selected Point

The cursor function of the DTMDS can be implemented to allow the readout of the elevation at the

point of the cursor's location. This data can be used to enhance mission planning or weapon delivery.

Integrated Flight Display (IFD)

Using the available data in the avionics system and overlaying a flight director template, a completely integrated electronic flight display can be generated on the color CRT. Because the IFD is under software control, there is an unlimited number of variations achievable in the visual presentation.

Intervisibility Calculations

The elevation data base, when combined with aircraft position and altitude, also offers the possibility of calculating whether or not the aircraft can be seen from a point on the ground or vice versa. With the symbol generator in the DMG, a pattern can be plotted to show safe areas for flight. This calculation can be performed in real time, allowing the pilot to make inflight adjustments of his route for maximum survivability. Also, line-of-sight determination to target will exist, thus allowing a minimum exposure profile during target designation. The most frequent use of this capability, however, would normally be in mission planning, where the pilot can plot his course based on known threats and their envelopes at his planned altitude. He can adjust his planned altitude or his flight path, or both, and observe the effect on resulting intervisibility patterns.

CONCLUSION

The technology brought about by the Digital Terrain Management and Display System will be the next major advance in avionics with the on-board data base being the key that unlocks the door to numerous applications. Because this newly emerging technology has not yet been available for testing and evaluation, its full usefulness has not been determined. However, any self-contained/autonomous terrain-data base which correlates with other on-board systems will enhance the present positional accuracy scheme. Additionally, as display evolution moves towards an all-encompassing information distribution system, a Tactical Situation Display (TSD), which spatially depicts friendly and unfriendly forces overlaid on topographic features, will be incorporated into future fighter aircraft. The pilots of future, tactical fighter aircraft cannot be expected to continue to function in their traditional role of primary systems operator and information integrator. The AFTI/F-16 is attempting to transition the pilot to the not-yet-fully-defined role of systems manager.

The AFTI/F-16 demonstrates the ability to integrate aircraft systems for improved pilot performance. As aircraft systems increase in complexity, the pilot/manager must maintain situational awareness, or risk reduced survivability. It is evident from the functions presented herein that the digital map provides the necessary information to ensure that pilot survivability is enhanced.

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AFTI/F-16 Gravity-Induced Loss-of-Consciousness and Spatial
Disorientation Auto-Recovery System

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**AFTI/F-16 Gravity-Induced
Loss-of-Consciousness and Spatial Disorientation Auto-Recovery System**

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ABSTRACT

A G-induced loss-of-consciousness (GLOC) and spatial disorientation auto-recovery system has been developed and tested on the Advanced Fighter Technology Integration (AFTI)/F-16 aircraft. The pilot controls the operation of this system by entering an MSL altitude and manually arming the system. Engagement conditions of the auto-recovery maneuver are controlled by aircraft speed, altitude, attitude, and the set recovery altitude and do not depend upon any determination of pilot physiological condition. Initiation of the recovery maneuver is preceded by visual and aural warnings which continue until the pilot resumes control. The pilot always has the capability to override or disengage the auto-recovery maneuver. This system, as developed on the AFTI/F-16, is directly and quickly applicable to other analog or digital flight control systems such as found in the F-16 or F-18. This system provides the pilot protection from ground collision in most air-to-air training environments.

INTRODUCTION

With a simple application of current technology we have the capability of preventing most fighter accidents attributed to spatial disorientation and gravity-induced loss-of-consciousness (GLOC). This can be done with an autopilot recovery system, such as the GLOC and spatial disorientation auto-recovery system currently in use on the Advanced Fighter Technology Integration (AFTI)/F-16 advanced development aircraft.

In the last 15 years, there have been more than 50 spatial disorientation mishaps resulting in the loss of USAF fighter aircraft and aircrews. In more recent years, as aircraft performance capabilities have increased, pilot incapacitation due to GLOC has also been identified as a serious hazard. In the last four years alone, 10 aircraft and aircrews were lost because of GLOC.

These are grim statistics that we can nearly eliminate in the future. In the 9 months between June 1985 and February 1986, a GLOC and spatial disorientation auto-recovery system was designed, tested, and put into operation on the AFTI/F-16. In a similar short period of time, we could begin incorporating this system on current fighter aircraft. Further delay increasingly shows the need for such a system. As an example, during the period we used to develop and test the AFTI/F-16

auto-recovery system, two Air Force pilots were killed in F-16's because of unrecognized spatial disorientation. In both of these accidents, the pilots were on routine air combat training missions. They lost awareness of altitude while looking back behind their aircraft and hit the ground without realizing they were in danger. Had the AFTI/F-16 auto-recovery system been incorporated on their aircraft, these pilots would be alive today. With simple modifications, this auto-recovery system is directly and quickly applicable to analog or digital flight control systems (such as in the F-16 or F-18) or to other aircraft with autopilot systems (such as the F-15).

In this paper, we'll take a brief look at the AFTI/F-16 program and how the requirements for the auto-recovery system evolved. With this in mind, we'll present the alternate approaches we examined, the auto-recovery system design and testing, and improvements planned for the future.

AFTI/F-16 PROGRAM

The AFTI/F-16 Advanced Development Program is a joint US Air Force, NASA, US Navy, and General Dynamics Corporation program. The overall program is managed by the Advanced Development Program Office at the US Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio. Systems development takes place at General Dynamics, Fort Worth, Texas with flight testing at the US Air Force Flight Test Center, Edwards AFB, California.

The overall AFTI/F-16 program objectives are to develop and evaluate new technologies and to provide flight-validated technologies for future applications. The primary technology under development during Phase I flight test (June 1982 to July 1983) was a triplex digital flight control system (DFCS) with eight task-tailored control laws incorporating six decoupled (six degree-of-freedom) control options. Phase II testing (July 1984 to present) includes integration of sensors, avionics, and flight controls into an Automated Maneuvering Attack System (AMAS) for both air-to-air and air-to-surface automated attack. Included in AMAS are a conformally-mounted forward-looking infrared tracker and laser ranger, voice interactive avionics, digital terrain map, and helmet mounted sight. The integration of avionics and sensors with flight control in this type of system has required the development of a System Wide Integrity Management (SWIM) system to provide artificial redundancy and added safety. SWIM monitors all system components for integrity and provides ground collision avoidance and automatic air-to-air

breakaway. Development of an auto-recovery system for GLOC and spatial disorientation was an outgrowth of this SWIM system.

AUTO-RECOVERY SYSTEM REQUIREMENTS

Initially, the requirements for the auto-recovery system on the AFTI/F-16 were limited. As has been typical of the experimental nature of the AFTI/F-16 program, during system development it became apparent that a broader set of system requirements could be accommodated. To a great extent, this was the result of the simple system design chosen. In general, the requirements for the design evolved to the following:

Rqmt #1: Protection from GLOC - This was initially the only requirement for the system: provide protection for the pilot in the event of G-induced loss-of-consciousness. The automated maneuvering system being developed on the AFTI/F-16 aircraft for air-to-air has full flight control authority which includes up to 9 g's at high onset rates. GLOC, with this automatic air-to-air system, is considered a hazard since the pilot is not flying the aircraft and therefore not completely anticipating aircraft accelerations. The automated maneuvering system for air-to-surface, on the other hand, is limited to 5 g's of authority. As a result, GLOC is not considered likely with the air-to-surface system. The requirement for GLOC protection was, therefore, restricted to the air-to-air (medium to high altitude) environment. As it turns out, although there has been at least one incident of GLOC in the F-16A at low altitude, almost all GLOC incidents have been in the air-to-air environment. Consequently, this system has wide applicability as a protection from GLOC.

Rqmt #2: Simplicity - In the development of the auto-recovery system, simplicity became an additional requirement. We were constrained to develop the auto-recovery system within the capabilities of the current AFTI/F-16 system. This was actually of benefit because it forced us to develop a system simple enough that it had wide applicability to other aircraft and other safety problems. This naturally led to our final requirement.

Rqmt #3: Wide Applicability - In the initial development, the AFTI/F-16 auto-recovery system was planned to be applicable to GLOC in both the AFTI/F-16 and the basic F-16. The system as developed, however, is also applicable not only to other modern aircraft, such as the F-18, but also to spatial disorientation--a potentially wider application than GLOC.

ALTERNATIVE APPROACHES

During the design of the AFTI/F-16 auto-recovery system, several approaches involving numerous design issues were considered. The issues can generally be grouped into two areas. First, we had to determine what we would use to initiate the auto-recovery maneuver; and second, we needed to establish the proper flight path for the auto-recovery itself.

Initial discussions centered around attempting to make some determination of pilot condition in order to trigger the auto-recovery. Consideration was given to using physiological sensors to

determine whether the pilot was conscious. Possible physiological sensing methods included comparison of the Fourier transform of pilot brainwave patterns (EEG), determination of retinal blood flow or pupillary reflexes with infrared lasers directed at the eye, or the use of an infrared laser directed through the skull to sense blood flow to the brain. A variation of the physiological sensing methods was to use a stick force sensor to initiate autorecovery after some sequence of aircraft accelerations that ended with the pilot letting go of the stick. The advantage of such systems is that if the reaction of the system is quick enough, it would be good at any altitude and require no radiating sensors, such as a radar altimeter.

Systems using stick force or physiological sensors, however, have the disadvantage that the design and implementation are complicated, requiring extensive redundancy and sophistication in order to prevent inadvertent engagements. They also use complex unproven technology currently only in the early stages of development. The initiation of the recovery maneuver would also not be keyed off actual aircraft flight path or altitude; and because there is significant time anticipated between the actual GLOC and the recognition of GLOC by the recovery system, the aircraft could end up in a condition where recovery is not possible when the auto-recovery is initiated. The most serious disadvantage, however, is that these types of systems can only be used for GLOC and are not useful for spatial disorientation. Because of these reasons, determination of pilot physiological condition in order to initiate recovery was not chosen for the auto-recovery system.

The alternative to the use of physiological or stick force sensors was to have the recovery initiated by aircraft attitude, airspeed, and altitude compared to some set minimum altitude. Ideally such a system would use above-the-ground (AGL) altitude in order to cover all possible causes of GLOC or spatial disorientation, and perhaps have a combat application. This type of system would require the use of an external AGL sensor such as a terrain-following radar or the use of a digital terrain data base in combination with a digital map, global positioning system, or other sophisticated determination of AGL altitude. This would have required a major development program with significant aircraft modifications. This was not within the scope of the current AFTI/F-16 test program and would also have resulted in a system with limited applicability to current aircraft.

We chose instead to use a pilot selected mean-sea-level (MSL) altitude as the set minimum altitude. The advantages of this approach are that it is simple and easy, requires no external AGL or other sophisticated sensor, and that it is usable for both GLOC and spatial disorientation. The primary disadvantage is that it is not usable at very low AGL altitudes and relies upon pilot judgement of the safe MSL recovery altitude. Such a system, however, has wide applicability and simplicity--providing protection in the training environment where most GLOC and spatial disorientation incidents have occurred.

When we designed the auto-recovery system, the SWIM ground collision avoidance system had already

been proven in flight test for use with the automated attack system. It was apparent that a similar arrangement would provide the necessary auto-recovery maneuver. The first issue, however, was the amount of acceleration the auto-recovery system should use. The easiest choice was to use 5 g's because that was already proven in the SWIM system. Using more than 5 g's was not justified for the training environment, would have dissipated energy required to maintain level flight after the recovery, and could possibly aggravate a GLOC situation. Five g's was therefore chosen for higher speeds, with a limit of 15 degrees angle of attack (AOA) for low speed.

The SWIM ground collision avoidance recovery results in a ballistic flight path that requires the pilot to immediately resume aircraft control. We ruled this out for the auto-recovery system because the pilot would be incapacitated after GLOC. We considered, instead, three alternative flight paths: a level or climbing turn, a wings-level climb, or wings-level altitude hold. We decided among these flight paths based on how long the auto-recovery system would have to protect the pilot.

Studies of GLOC episodes in flight and centrifuge testing showed that the duration of incapacitation from GLOC is from 9 to 21 seconds with an absolute maximum of 30 seconds. The duration of unrecognized spatial disorientation should only be momentary, indicating that the maximum time before the pilot should resume aircraft control after an auto-recovery is 30 seconds. Since we did not intend this system to be applied to a more serious pilot incapacitation, a longer safe recovery time than 30 seconds was not required.

For this short period of time, we decided against leaving the aircraft in a level or climbing low g turn. The increase in complexity did not justify the small increase in safety. Centrifuge tests conducted at the US Air Force School of Aerospace Medicine (USAFSAM) showed no increase in incapacitation time when the pilot was left at 2 g's, instead of 1 g after GLOC. The aircraft does not, however, travel forward a significantly shorter distance when in a low g turn. For example, as shown in Figure 1, an aircraft in a 2 g turn at 600 knots true airspeed (KTAS) travels forward 3 miles in 30 seconds. In wings level flight the aircraft would go only 2 miles further. We wouldn't gain very much, therefore, by having the aircraft in a turn.

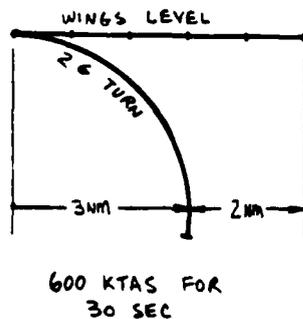


Figure 1 Distance Traveled in 30 Seconds

Although a wings level climb for a final flight path does show clear advantages, such a climb would be at the expense of aircraft energy. This requires the angle of climb to be a function of airspeed and the angle of climb to decrease if airspeed is decreasing. We elected to take a more simple approach which was to leave the aircraft in wings level altitude hold. A system that would climb was left for possible future development.

Another design consideration was whether the system would be automatic or require pilot action to engage or arm. Ideally, the operation would be automatic. This is not feasible, however, in a system where recovery is initiated with reference to a set MSL altitude because a significant portion of a normal flight would be flown below that altitude. We, therefore, made system operation pilot selectable. A future system using AGL altitude could be automatic.

Warnings of impending auto-recovery were deemed an essential part of the system. We intended these warnings to allow the pilot to disengage the auto-recovery system before an impending auto-recovery maneuver. This feature would be used in the event of unrecognized spatial disorientation or when the system was inadvertently left on during an intentional descent below the set minimum altitude. The visual warnings in the HUD and MFDs developed and tested from SWIM ground collision avoidance were appropriate for the auto-recovery system. Based on centrifuge tests at USAFSAM, aural warnings were expanded for use in the auto-recovery system. These studies have shown that pilot incapacitation time can be decreased by the use of tones and lights. An even more significant decrease, however, can be gained by actually talking to the pilot. We therefore use a combination of lights, tones, and voice synthesis to generate warnings.

Some capability for the pilot to override the auto-recovery was seen to be a necessary part of the auto-recovery system. In the AFTI/F-16 system, we gave the pilot full aircraft control capability to override the auto-recovery outside a set stick force breakout. In addition, full pitch stick (either direction) and a paddle switch on the stick are methods the pilot can use to disengage the auto-recovery maneuver once it begins. Prior to the actual auto-recovery, a paddle switch on the stick can also be used to turn the system off and prevent the auto-recovery. In another aircraft, a different arrangement would probably be appropriate.

The last issue was the choice of an appropriate altitude source. The most accurate source of altitude is available from the inertial navigation system (INS). This system, although reliable, is not redundant and inaccuracies are not necessarily detectable to the pilot. We chose instead to use the Central Air Data Computer (CADC) for altitude because the necessary interfaces with the flight controls were already established for other uses and required few changes. The CADC outputs can also be compared with inputs taken directly from the pitot-static instruments. The disadvantage of this approach is the need to compensate for altimeter lag which is significant at steep dive angles and high mach. A possible future improvement would be to use INS altitude compared with CADC and

pitot-static outputs. We did use the INS to determine aircraft attitude which we deemed acceptable because this INS failure is indicated to the pilot.

SYSTEM OPERATION

In flight, the auto-recovery system is in one of four states: Off, Standby, Armed, or Engaged. In the "Off" state, all system functions are inoperative and none of the calculations for the auto-recovery are performed. The auto-recovery system is considered on if the state is "Standby" or "Armed". If the appropriate conditions are met when the system is in the "Armed" state, the state changes to "Engaged" which means the auto-recovery maneuver is being performed.

At startup, the auto-recovery state is "Off". The pilot requests the system to be on ("Standby" or "Armed") through the cockpit multifunction displays (MPDs). The system will remain "Off," however, if the inertial navigation system (INS) is inoperative, the landing gear or flaps are extended, there is a dual failure of the flight control system, or the pilot has not set a minimum altitude (floor). This last requirement was included to ensure the pilot has set a floor appropriate to the terrain on that flight. Since the auto-recovery system uses MSL altitude, it is not appropriate to use a standard startup value or a value set on a previous flight, either of which might not be a safe value for the planned flight terrain. The floor, therefore, is set to zero at startup, and the system cannot be turned on if the floor remains zero. In addition, we do not want an auto-recovery maneuver to occur at or shortly after the time the system is turned on. The system remains "Off" if when the pilot requests the system to be turned on, the aircraft is at or below the floor plus 500 feet or within 5 seconds of an auto-recovery. Once the system is turned on, a failure of the INS, dual failure in the flight controls, or extending the landing gear or flaps causes the auto-recovery system to revert to the "Off" state.

Once the auto-recovery system is on, the auto-recovery state is "Standby" or "Armed" depending on the position of the air refueling door. An inadvertent auto-recovery during air refueling would be catastrophic and therefore, the auto-recovery system reverts to "Standby" when the air refueling door is opened. In the "Standby" state as in the "Off" state, all system functions are inoperative. When the air refueling door is closed, the auto-recovery state automatically changes back to "Armed" without any additional pilot action. The exception to this occurs when the aircraft is below the floor plus 500 feet or within 5 seconds of an auto-recovery. In this case, the system goes to "Off" instead of "Armed" from the "Standby" state.

The actual auto-recovery maneuver is keyed off the time-to-go to auto-recovery, t_{ar} . This time is only calculated when the auto-recovery state is "Armed." When t_{ar} goes to zero, the auto-recovery state changes to "Engaged" and the aircraft rolls wings level at a rate proportional to the bank angle (maximum of 180 degrees/second). At bank angle greater than +120 degrees, the load factor is commanded to cosine of the pitch attitude times cosine of the bank angle (which will be -1 g for

level flight inverted). As bank angle decreases below +120 degrees, the load factor command increases until it is 5 g's when the bank angle is less than +90 degrees. This 5 g command continues until V_z is greater than zero. This results in a climbing flight path as the maneuver transitions to altitude hold. The aircraft levels off and holds 500 feet above the floor. Using this altitude instead of the floor itself makes the recovery maneuver smoother (the flyup portion already results in a climb) and helps prevent an inadvertent second flyup. If the aircraft speed decreases to 15 degrees angle of attack (AOA), the recovery load factor is reduced; and if level flight cannot be maintained at 15 degrees AOA, the aircraft will descend.

If the INS fails during the auto-recovery maneuver, the auto-recovery is terminated when flight path is +3 degrees or higher and the bank angle less than +15 degrees based on flight control system estimated attitudes. No altitude hold feature is included.

Time-to-go to auto-recovery (t_{ar}) is computed whenever the auto-recovery system is "Armed" and the vertical velocity (V_z) is less than zero. If t_{ar} is not being computed, it is set to 10 seconds. When t_{ar} is being computed, it is found from the following:

$$t_{ar} = \frac{H_{MSL} - H_{FLOOR} - \Delta H}{V_z} \quad \text{for } V_z < 0$$

where H_{MSL} = selected MSL altitude
 H_{FLOOR} = set recovery altitude (floor)
 ΔH = altitude required for recovery
 V_z = INS vertical velocity

If t_{ar} is less than zero using the above formula, t_{ar} is set equal to zero in order for HUD symbology to be displayed properly (see the next section).

Selected MSL altitude (H_{MSL}) is the current aircraft barometric altitude reduced by an amount proportional to the vertical velocity:

$$H_{MSL} = H_{CADC} + K * V_z$$

Using these formulas, t_{ar} decreases as vertical velocity increases (at the same barometric altitude) which is a compensation for altimeter lag errors. The CADC supplies the auto-recovery system with barometric altitude compensated for non-standard day. If the CADC data is bad, the current aircraft altitude is determined from the static pressure ratio with direct inputs to the flight control system from the pitot-static system. H_{MSL} is then reduced by 1000 feet to compensate for possible errors on a nonstandard day:

$$H_{MSL} = H_{Ps/Po} + V_z - 1000$$

The altitude required for recovery (ΔH) is calculated based upon the flight-tested SWIM ground collision avoidance algorithm. This algorithm was derived from data gathered during real time simulation of flyup maneuvers. The SWIM altitude

required for ground collision avoidance (ΔZ) is found from the following empirical formula:

$$\Delta Z = \Delta Z_1 + \Delta Z_2 + \Delta Z_3$$

where ΔZ_1 = altitude required for wings level non-rolling flyup

ΔZ_2 = additional altitude required for roll angle or roll rate

ΔZ_3 = additional altitude required for initial load factor (g)

This approach has proven effective within the airspeed limits it was designed for (260-580 KCAS). The auto-recovery system, however, is designed with no airspeed limits and an additional factor, ΔZ_4 , is added at low speed to compensate for the smaller load factor that is available at lower speeds. In addition, we assumed the auto-recovery would most likely be initiated when the aircraft is in a steep, high speed dive (the most likely GLOC scenario). In such a dive, the additional altitude required because of roll attitude, roll rate, and initial load factor becomes less significant. Penetrations of the floor by several hundred feet were also not considered significant in a system using an MSL altitude floor, which would be set several thousand feet above the ground. As a result, we simplified the calculation of the altitude required for auto-recovery to:

$$H = \Delta Z_1 + \Delta Z_4$$

Figure 2 shows the MSL altitude that the auto-recovery system will engage with the floor set at 10,000 feet MSL for various dive angles and airspeeds.

PILOT VEHICLE INTERFACE

The pilot controls the auto-recovery system through switches on the MFDs and the control stick. Visual and aural warnings are provided through the MFDs, the head-up display (HUD), and the voice synthesis system.

The minimum altitude (floor) is set through the MFD flight control page. Altitudes, entered to the nearest 10 feet, will be rejected if not between 0 and 20,000 feet. Once entered, the current floor value is sent continuously from the flight control system for display to the nearest foot on the MFD flight control page. The pilot turns the system on using one of the buttons on the MFD when the flight control page is displayed. The MFD shows OFF, STBY, or ARM depending on the system state. If t_{ar} is less than 1 second, the MFDs will all show a flashing "Break X" overlaid across the current display. The flight control MFD page also shows the following fault messages when required:

Fault	Meaning
OMR GLOC FLYUP	auto-recovery engaged
OMR ALT	auto-recovery "armed" request was rejected because the floor was zero or the aircraft was below the set floor plus 500 feet or within 5 seconds of flyup

OMR FCS

auto-recovery system was forced "Off" because the landing gear or flaps were extended

FAIL FCS

auto-recovery system was forced "Off" because there was a dual flight control failure

FAIL INU DATA

auto-recovery system was forced "Off" because the INS failed

NORM SWITCH

auto-recovery system was turned "Off" by the pilot through the switch on the MFD flight control page or the upper paddle switch on the stick

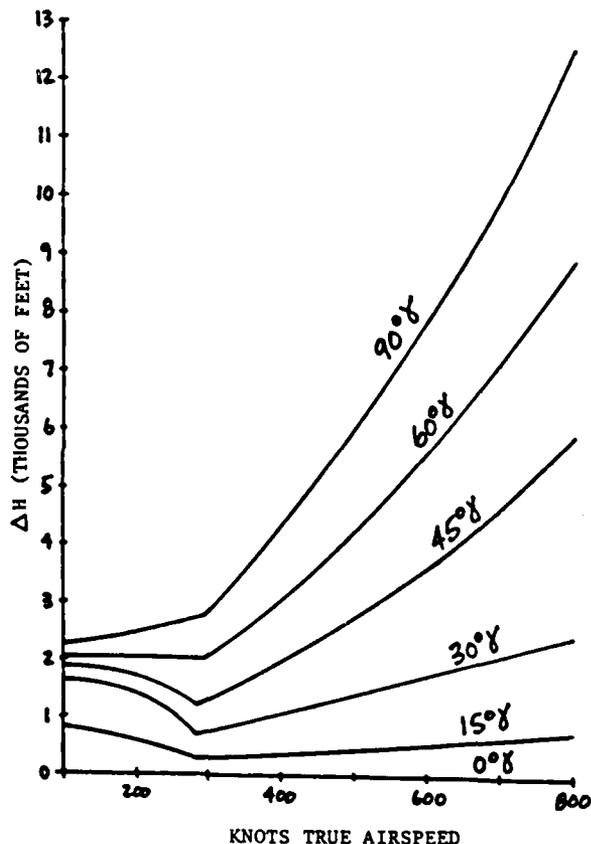


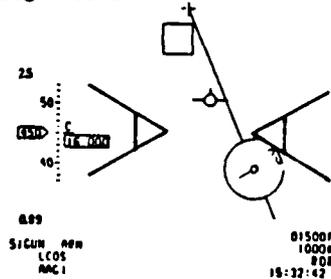
Figure 2 Recovery Initiation Altitude Above Floor

The APTI/F-16 side stick controller has an upper and lower paddle switch used to control numerous functions related to operation of the automated maneuvering system being tested on the aircraft. Because of this, we were limited in using these switches to control the auto-recovery system. When the time-to-go to auto-recovery (t_{ar}) is less than 5 seconds, the upper paddle switch can be used to turn the auto-recovery system off. When the auto-recovery is actually taking place (engaged), the lower paddle switch can be used to discontinue the auto-recovery maneuver, but the system remains armed. In addition, 90 percent of maximum stick force up or down also terminates the auto-recovery maneuver with the system remaining

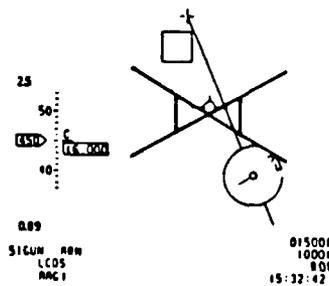
armed. This is not an ideal arrangement for a production system. In a production system only one switch on the stick would be appropriate. This switch would interrupt operation of the system when it was depressed and held but would not turn it off. This way the pilot could prevent an auto-recovery when it was not desired with the system remaining armed. In addition to hands-on controls to terminate an auto-recovery, the pilot can override or blend with the auto-recovery system by using greater than 6 percent of maximum stick force in pitch or 40 percent in roll.

When any of the fault messages (listed above) are sent by the auto-recovery system for display on the MFDs, a 250 Hz tone of 0.25 or 1.5 seconds (depending on the fault) is generated. In addition, a red integrated fire and flight controls (IFFC) warning light to the right of the HUD is illuminated for 3 or 5 seconds (depending on the fault). At 5 seconds to flyup, the voice synthesis system announces "pullup, pullup". A minimum of 5 seconds is required before this message can be repeated in the event the pilot is flying in and out of 5 seconds to auto-recovery. At auto-recovery, the IFFC warning light illuminates and the tone is generated for 1.5 seconds. This is followed by "flyup, flyup" from the voice system. "Pullup, pullup" is then repeated every 5 seconds with the IFFC warning light continuously on until the auto-recovery system is disengaged by the pilot.

When time-to-go to auto-recovery (t_{ar}) is less than 5 seconds, chevrons are displayed on the HUD at a distance apart corresponding to t_{ar} (see Figure 3). At t_{ar} equals zero the chevrons come together to form a "Break X" in the HUD. The mnemonic BKWY (breakaway) is then also displayed in the lower right of the HUD.



a) $t_{ar} = 5 \text{ sec}$



b) $t_{ar} = 0 \text{ sec}$

Figure 3 HUD Display

SYSTEM REDUNDANCY

Auto-recovery system redundancy is not considered an important requirement. As long as the pilot is made aware of system failures through a built-in test (BIT) system, the auto-recovery system does not need to be redundant. For example, modifying the existing aircraft's autopilot with the auto-recovery system was considered a viable option. The flight control system on the AFTI/F-16, however, is a triplex digital control system. Changing this software was the easiest way to incorporate the auto-recovery system. As a result, the AFTI/F-16 auto-recovery system became part of the flight control computers themselves. Interfaces with other aircraft systems are through the aircraft multiplex bus system. Such an arrangement on another aircraft, requiring changes to the flight control system itself, may not be necessary or desirable.

The AFTI/F-16 auto-recovery system is designed to be "first fail operate". All single failures of the flight controls (no matter how many there are), failure of the fire control computer, or the CADC have no effect on auto-recovery system operation. Total failures of the INS, stores management set, or multiplex bus do prevent engagement, although an auto-recovery would continue with these failures if already engaged. Loss of the HUD, MFDs, or Voice do not effect system operation, except for the loss of displays or warnings.

The auto-recovery system is also designed to be "dual fail safe". A dual failure of any part of the flight control system immediately disarms the auto-recovery system. This prevents an abnormal or inadvertent auto-recovery due to flight control failures.

FLIGHT TEST RESULTS

The complete auto-recovery system was released for simulator verification and validation testing in the AFTI/F-16 simulator at Fort Worth on February 3, 1986. Flight testing began at Edwards AFB on February 20, 1986. The basic auto-recovery system, including displays and warnings, operated correctly from the beginning of flight test. At most dive angles and airspeeds the auto-recovery maneuver was satisfactory. Some improvements, however, will be made at steep dive angles where the system is too conservative when upright, and results in some penetrations of the floor when inverted.

As a result of flight tests, the auto-recovery system is operational on the AFTI/F-16 providing protection to the pilot when required. Flight testing of the auto-recovery system will continue through Spring 1986 as changes are made to improve system performance.

FUTURE IMPROVEMENTS

A limited AGL capability is planned for Spring 1986 as an improvement for the current auto-recovery system. When AGL data is valid from the radar altimeter on the AFTI/F-16, an auto-recovery will be keyed off either the set MSL floor or an AGL minimum descent altitude (MDA) set separately by the pilot (whichever will be reached first).

This extra capability is meant for protection in such environments as visual low-level navigation or in the instrument approach pattern prior to final. This system would be intended for shallow dive angles and will require a more accurate determination of the altitude required for recovery, ΔH . Such a system has already been proven on the AFTI/F-16 for ground collision avoidance (SWIM) and will use the following formula for H:

$$\Delta H = \Delta Z_1 + \Delta Z_2 + \Delta Z_3 + \Delta Z_4$$

where each of the terms are defined in the System Operation section above. To support this capability, the AFTI/F-16 system will also be made available in all flight control modes.

Improvements are also planned to refine the calculations of pull-up altitude when using the MSL altitude based auto-recovery. The auto-recovery system will be made less conservative during steep dives at upright attitudes and more conservative when inverted. The intention will be to have the minimum altitude for most auto-recovery maneuvers between the floor and 500 feet above the floor.

Two additional improvements are being investigated for the current system. The first is to incorporate a climb capability for the auto-recovery to be used instead of altitude hold at higher throttle settings or airspeeds. The second is to use the INS as the primary source of altitude with the CADC and pitot-static inputs to the flight controls as backups.

APPLICATION OF AUTO-RECOVERY SYSTEM TO OTHER AIRCRAFT

Adding the AFTI/F-16 auto-recovery system to existing tactical aircraft should require only simple modifications. Each type aircraft will have a unique arrangement. Three general components will be required:

1. Computer - The purpose of the computer will be to take inputs from various aircraft components (altitude, attitude, airspeed), calculate when an auto-recovery is required, and send the auto-recovery command to the aircraft component that will fly the auto-recovery. This computer must have the necessary interfaces with other systems and indicate to the pilot when it is not in operation through some built-in-test feature. An example of aircraft computers that could be used are the F-15 central computer, or the F-16 Electronic Component Assembly.

2. Autopilot - The autopilot portion of the system will fly the maneuver once it is commanded by the computer. This autopilot must be capable of commanding up to 5 g's which may require increasing the authority of existing autopilots.

3. Pilot Vehicle Interface - The capability to enter the floor altitude, arm the auto-recovery system, and blend with or disengage the auto-recovery will be required. In addition, each aircraft will have its unique method to give audio and visual indications of system operation.

PHASE II SYSTEM

Plans for a follow-on to the current AMAS program on the AFTI/F-16 include development of a fully integrated terrain following and terrain avoidance (TF/TA) system. The TF/TA system will use active AGL sensors in combination with a digital terrain data base and digital map for accurate positioning in three dimensions. This will allow the auto-recovery system to incorporate a true AGL capability and include automatic operation with the gear up, and altitude warnings with the gear down. An increased command authority will also be given allowing recoveries at 7 or even 9 g's.

CONCLUSIONS

Unlike programs being pursued to find a suitable physiological sensor of loss-of-consciousness, an auto-recovery system based upon aircraft altitude, attitude, and airspeed in relation to a set recovery altitude is applicable to most cases of spatial disorientation and loss-of-consciousness. The AFTI/F-16 auto-recovery system is based upon a pilot-selected MSL altitude floor and is operational today. This system should be incorporated into current tactical aircraft as soon as possible.

As long as system operation is indicated to the pilot, the auto-recovery system need not be redundant or require extensive aircraft modifications. When incorporated on a tactical aircraft, the system will use a computer to determine when the auto-recovery is required, an autopilot to fly the recovery, and an appropriate pilot vehicle interface.

Future auto-recovery systems should be developed to use AGL altitude which will provide automatic operation, increased authority, and combat capabilities.

**AFTI/F-16 Automated Maneuvering Attack System -
Operational and Technological Implications**

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AFTI/F-16 AUTOMATED MANEUVERING ATTACK SYSTEM

OPERATIONAL AND TECHNOLOGICAL IMPLICATIONS

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ABSTRACT

The AFTI/F-16 testbed is being used as a systems prototype for the Automated Maneuvering Attack System (AMAS) and associated technology relevant to combat automation. The developments have focused on improving terminal weapon delivery and survivability in a low-cost, operationally suitable configuration. Realistic flight demonstration is a critical element in the process of accelerating the maturation of advanced, high-risk, fighter technology. The testbed aircraft is currently demonstrating the advanced combat capabilities that a highly automated and integrated weapon system can provide. By testing in an operationally relevant flight envelope, this integrated systems demonstration stresses all aspects of technologies being evaluated, including important functional, packaging and safety-related issues not addressed in analytical or simulation evaluations. The interim results of the flight test program are examined in terms of their operational and technological implications. Lessons learned and their meaning to other advanced development programs and the technology transfer process to operational weapon systems are discussed.

INTRODUCTION

The AFTI/F-16 Program was conceived to move advanced technology from the laboratory to the operational Air Force. Systems prototyping was viewed as an effective means for flight demonstrating the transition potential of high-risk, high pay-off technology and concepts. That viewpoint is shared by the recent Packard Blue Ribbon Commission (Reference 1):

"A high priority should be given to building and testing prototype systems and subsystems before proceeding with full-scale development....It should demonstrate that the new technology under test can substantially improve military capability, and should, as well, provide a basis for making realistic cost estimates prior to a full-scale development decision."

The AFTI/F-16 testbed has provided simultaneous focus on the multiple objectives of systems prototyping, discipline oriented subsystem technology development, and integration as a technology. Prototype hardware, together with working software, provides conclusive demonstration of technology readiness to meet operational system requirements. Such readiness was demonstrated during the first phase of the program, the Digital Flight Control System (DFCS) Phase. A fault tolerant, task-tailored flight control system, designed to support the flight research objectives of that phase (advanced control laws and decoupled flight-path control), was matured and most of the technology transitioned into the F-16 C/D production digital flight control system. Full Scale Development (FSD) is proceeding at half the cost of the prototype AFTI/F-16 systems directly due to transitionable hardware and software technology.

The DFCS development has also provided the core technology for providing the flight-path control needed in this second program phase, the Automated Maneuvering Attack System Phase. The flight test program over 250 AFTI/F-16 missions have produced a DFCS baseline that, when combined with a D-1553 distributed avionics suite, permits the implementation of a variety of automated functions. The AMAS Phase demonstrates new weapon delivery capabilities enabled by extensive system integration of the flight, engine and weapon control functions (Figure 1). Specific operational goals include: (1) air-to-surface, low-altitude, curvilinear bombing (opens the attack arena to lateral, high-g maneuvers), and (2) air-to-air, all-aspect gunnery (opens the attack arena to front-quarter and high, angle-off geometries).

BASIS FOR FORECAST

Inherent fighter agility, combined with the flexibility and precision control of a digital flight-control system, allows for new dimensions of maneuverability for engaging and destroying the enemy. By taking advantage of the digital system processing of the modern fighter,

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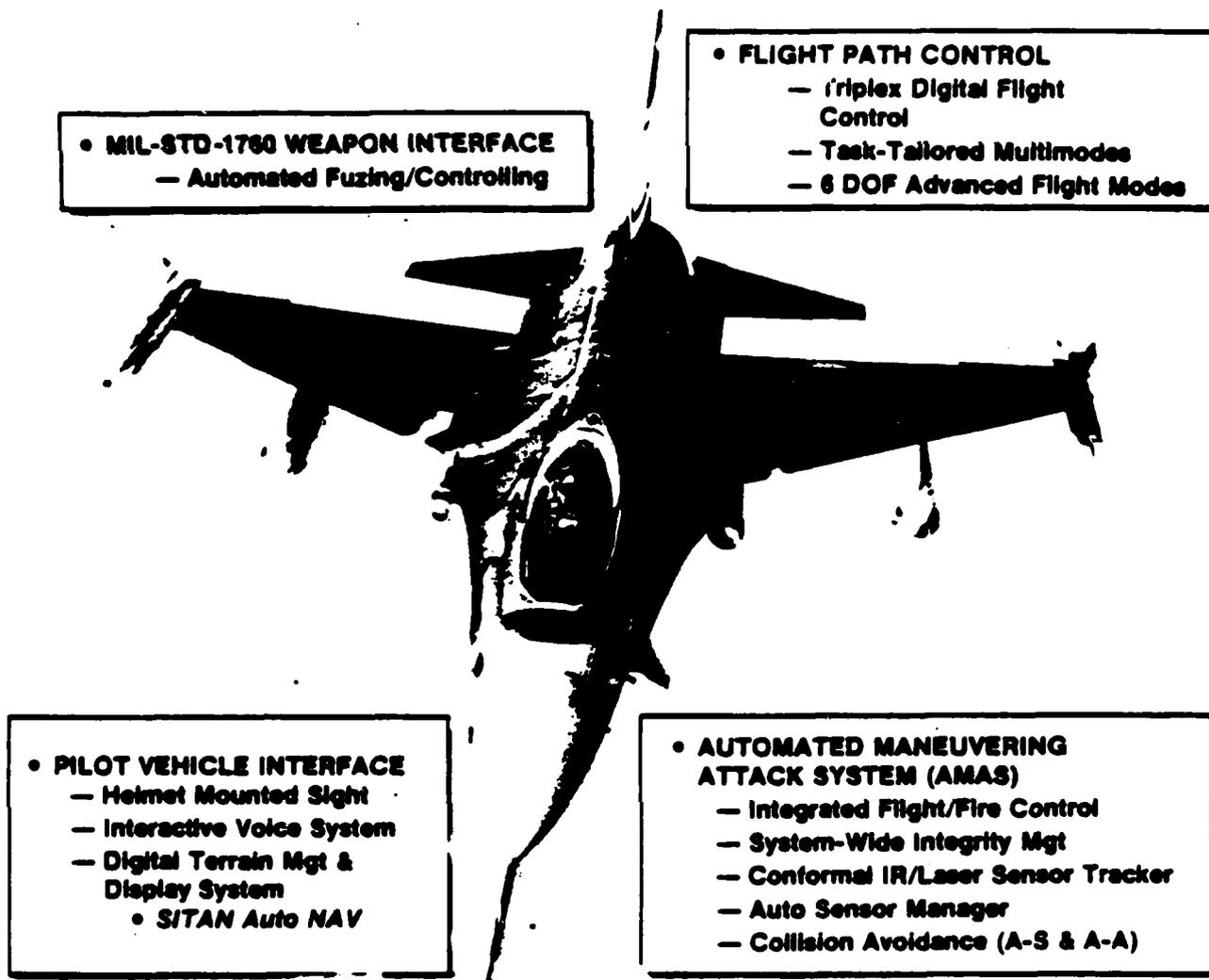


Figure 1 AFTI/F-16 Technology Integration

the opportunity now exists to enable high-gain, automated control tasks that have previously been impractical to implement, such as the AMAS low-altitude curvilinear bombing and all-aspect, air-to-air gunnery.

The design premise of the AFTI/F-16 AMAS is that flight-path control, with attendant safety functions, is central to the accomplishment of the tactical mission, and that system integration and automation should propagate from this central task. The attack geometries provided by this high level of system integration provide the flexibility that is essential for sustaining a tactical advantage for our future fighters. Our observation is corroborated in Reference 2:

"Computer technology makes it possible to develop dynamic, integrated, and comprehensive automated systems for future combat aircraft. A systems approach,

emphasizing the core function of flight trajectory and attitude control, is a logical and necessary starting point."

AMAS flight-path control not only opens new, attack geometries otherwise unachievable within the bandwidth of pilot-in-the-loop flight-path control, but it is a continuous and central function, which when automated, can enhance safe mission accomplishment. The weapon-delivery timeline, as shown in Figure 2, has both discrete and continuous tasks. As the cockpit task transitions from target acquisition to weapon delivery, the intensity of flight-path control increases, requiring increased pilot attention, competing with essential pilot tasks associated with the operation of attack sensors, weapons, and threat countermeasures. The automation of the flight-path control provides a means for reducing workload, thus freeing the pilot to devote more time to attack execution and threat management tasks.

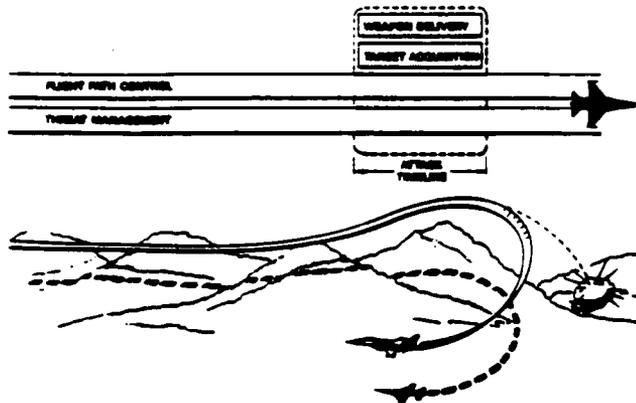


Figure 2 Critical Functions of the Attack Phase

IMPLEMENTATION

The AMAS program has focused on developing and flight validating a design that is practical in terms of performance, cost, and operability, particularly safety. The AMAS configuration includes a prototype low-cost sensor/tracker system (FLIR/laser) specifically developed for the AMAS demonstration. The remainder of the basic AMAS functions are in Operational Flight Programs (OFFPs) resident in F-16, Block 25 processors integrated with the Phase I DFCS. Ancillary program objectives include the evaluation of the digital-terrain system, the interactive voice system, and automated weapon fuzing.

The AMAS capabilities are primarily software-driven within the distributed, asynchronously operated MIL-STD-1553 network of processors. Major software functions include guidance and control, the sensor manager, and the System-Wide Integrity Management. Through a system-integration approach, functional redundancy provides the safety needed for demonstrating AMAS operation in the chosen attack arenas without resorting to a duplication of avionics processors.

The AFTI/F-16 systems engineering has clearly weighed the integrated systems objectives against the compromise of the airframe performance. While developing the technology that allows the pilot to engage the enemy more freely in three dimensions, the equipments required to enable the new attack functions were designed for minimum impact to the operational speed and range of the basic F-16. At the same time, the DFCS provides a more agile control system than the baseline F-16, and the AMAS opens attack geometries not possible without closed-loop control provided through the attack sensor.

The AMAS research has emphasized operationally relevant flight envelopes in both the air-to-surface and air-to-air fighter arenas. The low-altitude bombing system was developed to operate at 3.5 g's as low as 200-ft AGL with level, dive, and loft options unconstrained to any one plane. Air-to-air gunnery was designed to operate to 9g and to Mach 1.2, within an all-aspect attack envelope, including head-on closure. This emphasis on operational envelope realism ensured that the practi-

cality of coupled weapon deliveries were examined in terms that would increase the transition potential by addressing issues of safety and pilot acceptability.

Operational relevance is being measured in the ability to deliver conventional, unguided ordnance that is prevalent in today's tactical operations. Delivery of these weapons, which requires precision trajectory control, presents the most restrictive requirement; technical solutions to this challenge are readily applied to other trajectory control tasks requiring lesser precision. But a more overriding consideration for using unguided ordnance stems from the reality that our tactical forces have large inventories of these low-cost conventional weapons. Improvements to the delivery of these weapons would have very significant benefits to combat readiness and mission effectiveness.

The single-seat configuration was chosen for several reasons. First, this is the cockpit configuration where higher payoffs could result from automation, and specification of this configuration would steer the design process to single-seat workload issues. Second, the post-Vietnam trend in fighters is clearly toward the single-seat fighter, driven primarily by a force strength consideration to lower personnel and training costs. Additionally, weapon system cost reduction and airframe performance benefits can be gained by eliminating the second seat. Though a second cockpit was considered for safety reasons, it was ruled out due to the potential corruption to single-seat automation goals.

The approach that has been taken in the AMAS cockpit development is to leave the pilot acquisition task as a semi-automated function, but provide workload alleviation via automated flight-path control. Although research continues in the field of automatic target acquisition methods, progression or break-throughs are not apparent to indicate that significant workload reduction can be achieved through this automation approach in the foreseeable future. It is our contention that the target acquisition task in the tactical fighter will likely always rely heavily on the perceptual and interpretive skills of the pilot, due to the variability and changing nature of the tactical battlefield.

Similarly, the AMAS demonstration has made no attempt to integrate active threat management or automatic evasion into the system. In the low altitude attack profile, a passive approach has been taken, that is, to avoid and evade threats by using a turning weapon delivery to defeat threat acquisition and tracking, as well as to provide standoff from the target. The flight control system and trajectory control algorithms are designed to allow pilot blending for jinking and evasive maneuvers, if needed.

KEY RESULTS

The AMAS flight testing is now producing the desired results in air-to-surface operations, demonstrating attack capabilities that have significant implications to future fighter operations. These include new capabilities and enhancements associated with weapon delivery, target acquisition, weapon integration, situational awareness, and safety.

Weapon Delivery - Curvilinear Bombing

Today's weapon delivery methods are designed for a wings-level release (level, dive, loft) in a vertical plane. Most methods require a linear flight path during final delivery that presents a predictable flight path to the enemy threat systems. Sight depression angles needed for accurate radar ranging for visual delivery require close-in delivery methods. The combination of these factors pose a very severe threat to the survivability of our fighters when attacking a well defended target.

The AMAS bombing system, which allows precision weapon delivery while maneuvering at 4 to 5 g's at very low altitude, provides substantial survivability benefits. First, the system's high degree of maneuvering freedom greatly decreases vulnerability to terminal gun threats by eliminating linear flight-path segments. Second, the sensor/tracker system provides precision target-state measurements at very low-grazing angles, allowing low-drag weapons to be accurately delivered from lower altitudes and greater standoff ranges. This combination of maneuverability and standoff allows the pilot to avoid target over-flight, turning inside the target's point defenses and the bomb fragmentation envelope. This feature is also key to the ability to deliver low-drag weapons under low ceilings, another significant payoff of curvilinear bombing.

End-to-end fully automatic system operation has been demonstrated at 500-ft AGL. The remaining tasks are the weapon accuracy and tactical evaluations, which include a demonstration at 200-ft AGL. Given the anticipated success, the AMAS curvilinear bombing technology is judged ready for transition. The sensor/tracker, fire-control guidance, and flight controls will have been demonstrated in a very relevant operational flight envelope. Although the AMAS was designed for the flat-earth test environment, the curvilinear bombing capability could be implemented using a selectable minimum descent altitude based on the local terrain.

The AFTI/F-16 sensor/tracker system offers a very versatile design for follow-on development, either in its current multifunctional configuration or to other electro-optical applications requiring precision tracking. Two design requirements have resulted in an attractive baseline design: (1) the low-drag requirement to minimize aerodynamic penalty, and (2) the multirole tracker requirement. The combination of these factors has resulted in a successful design that is efficiently packaged and optimally integrated, with growth potential to operational systems that are flexible, maintainable, and low-cost. Test results indicate that the overall design is sound, particularly in the turret stabilization and laser boresight. The common aperture, coaxial laser output provides for better spot-aiming and stabilization on the target. The wing-strake position is also advantageous because it allows for much latitude in maneuvering during target designation. While performance has been adequate for basic AMAS bombing guidance, the video imaging and tracking performance was less than our specification goals. Areas of emphasis indicated for full-scale development would be optimization of the optical train, FLIR detector, and digital scan converter.

Target Acquisition

Target acquisition consists of three tasks: detection (sensing) of possible targets, selection of a probable target from the candidates, and designation of this target to the fire-control system. The task must be completed quickly, under the stress of enemy threats, while making sense of available, and unavailable information. In the multisensor aircraft, this is an extremely complex task that requires mental agility and manual dexterity as the pilot operates and switches between sensors, each with its unique operation and frame of reference. At the same time, the tasks of flight-path control, attack planning, and threat management compete with target acquisition. The proximity to the earth (Pk=100%) in the low-altitude arena places significant demands on the pilot for flight-path control.

While the AMAS implements several automated target-acquisition features, the pilot is viewed as the key integrating factor for the target-acquisition task. The pilot's vision comes into play in two ways: (1) in the direct out-of-the-canopy target acquisition, and (2) in the scanning and interpretation of the cockpit displays. The AMAS-configuration incorporates a baseline sensor suite typical of the modern fighter: the fire-control radar, the inertial navigation system, a targeting sensor (FLIR), and head-up display. A sensor manager is implemented to assist in sensor cueing and switching. For the air-to-air task, the sensor-manager function introduces the fusion of radar and sensor/tracker data. For air-to-surface operation, the sensor manager cues to inertial locations. The inertial estimate of the aircraft's present position is refined by the Sandia Inertial Terrain-Aided Navigation (SITAN) mechanization in the digital-terrain system. This enables target acquisition with the sensor/tracker without a position update via radar or visual fixpoint overflight.

The AMAS cockpit configuration also incorporates a helmet-mounted sight and an interactive voice system to assist the pilot in target acquisition. The helmet-mounted sight is incorporated to provide rapid off-axis cueing of attack sensors, and the voice system is integrated with the sensors and displays to evaluate its utility during target acquisition. The testing of these two subsystems has not progressed to the evaluation phase; test results are preliminary or unavailable and do not support any further discussion or conclusions at this time.

In the air-to-surface environment, the AMAS cockpit design has thus far not resulted in any workload reduction during sensor operation. The high workload can be attributed to cockpit mechanization immaturity, marginal sensor/tracker video, tracker operation, and system interface problems associated with working at low altitudes and low-grazing angles. However, our flight tests have proven an extremely important point. With the availability of a fail-safe, low-altitude autopilot and automated steering to the target, the AFTI/F-16 pilots have had the time to focus most of their attention on the high-workload, target-acquisition task. Because of this flight-path automation, with its fault-tolerant, triplex-redundant, collision avoidance function, the net effect is a higher probability of success in acquiring the target.

Weapon Integration - Automated Weapon Fuzing

The AMAS configuration includes a MIL-STD-1760 digital interface that provides a real-time (15 Hz) communication from the fire-control computer to the prototype Standard Avionics Integrated Fuze (SAIF). This fuze is installed on a Tactical Munition Dispenser (TMD), a canister-type weapon loaded with inert submunitions for the AMAS demonstrations. The test objective is to demonstrate the capability to accurately deliver a two-stage ballistic weapon, such as the TMD, while the aircraft is free to maneuver and change delivery airspeed. Currently, such weapons must be delivered from fixed airspeed/altitudes, or be equipped with a more expensive proximity fuze, in order to obtain proper pattern control.

The SAIF integration with the AFTI/F-16 has been demonstrated in the simulator. Four TMD weapon deliveries are scheduled during the AMAS bombing demonstrations. Given a successful demonstration, the fuze is scheduled to enter full-scale development. For aircraft equipped with a MIL-STD-1760 weapon interface, the TMD/SAIF can be delivered using any of the currently operational fire-control/weapon delivery methods programmed with two-stage ballistic algorithms.

One payoff complementary to the AMAS bombing fire-control guidance is the ability to accurately deliver the TMD/SAIF by using any of the available attack profiles, giving increased survivability during the attack. For example, AMAS can be used to deliver a TMD/SAIF in a turning, loft maneuver. A second capability is that of changing the desired submunition impact patterns from the cockpit rather than being stuck with preset parameters. As part of the AMAS demonstration, optimal pattern control will be changed during the attack using the voice interface to identify the target type, e.g., "tanks", "trucks", or "troops." A third, very pervasive capability enabled by the TMD/SAIF and digital-terrain system is a "blind" weapon delivery using passive ranging. Using the SITAN for accurate position updates, and an algorithm for automatic system altitude calibration, the weapon could be delivered on known target locations (pre-planned or data-linked) without the aid of any active target sensor.

Situational Awareness

No precise definition of "situational awareness" exists, but in essence this refers to the availability and assimilation of information or data needed by the pilot to conduct the mission and constantly assess alternative actions. The availability of data on the target(s), threat, terrain, own-state, and friendly forces is very critical. Modern fighters, typically, are limited in the availability of needed data, and data that are available tend to be uncorrelated. Much of the data consist of manually prepared products, and inflight updates are generally accomplished through voice communications. The advent of dense digital storage media and data links are starting to correct this deficiency.

The AFTI/F-16 digital-terrain system development marks a major aviation advancement by providing a means for storing massive data that is displayed in a correlated manner in three-dimensional terrain scenes.

The availability of a real-time, color moving-terrain map allows instantaneous situational awareness of the pilot's own-state position relative to terrain, targets, threats, surface features, control zones, and other tactical descriptors.

The digital-terrain system has been functionally demonstrated in the flight environment. Tactical evaluations are planned, but are on hold pending the installation of a brighter color tube in the cockpit display. In simulator demonstrations, the utility of the terrain display has been demonstrated for terrain and threat avoidance. Threat locations and status are displayed on the Tactical Situation Display (TSD) in a planform navigation scene. Variable sized circles can indicate the approximate threat radius of lethality. Terrain at or above the aircraft altitude can be highlighted, which is useful for threat avoidance and evasion. This capability provides a first-order approximation of threat intervisibility displays of the future.

Safety

The program goal to operate the AMAS system as low as 200-ft AGL presented significant design challenges with respect to safety. An integration concept labeled System-Wide Integrity Management (SWIM), evolved to provide a "safety net under the system." Using redundant, logical processing embedded in the digital flight-control system, a combination of single-thread, computation monitoring, sensor comparison monitoring, and redundant computation of imminent ground collision has been mechanized to run as a background, flight-control task during automated attack. This pioneering effort in the extension of flight-control safety engineering to avionic processing is a direct result of interdisciplinary functional integration of flight control and avionic design technology. The protection afforded by flight-control redundancy can be deeply propagated in an integrated, networked system. For the current AMAS system, SWIM is mechanized to provide protection against ground collision while operating over flat terrain; however, the concepts are extensible to operation in rough terrain through integration with the digital-terrain system.

One key result of our testing has been the pilots' confidence in the safety features of the AMAS. During high-workload tasks associated with sensor management during target acquisition, the pilots had sufficient confidence in the low-altitude autopilot and ground-collision-avoidance systems to accomplish the weapon deliveries under totally automatic flight-path control. The flight-path control fully compensated for the level of cognitive tasks during acquisition. During weapon delivery, the time when the task load increases with manual control, the AMAS has demonstrated reduced workload. We believe that this same degree of workload will be experienced in the combat environment, and that our flight tests are demonstrating that automated, flight-path control, combined with the other AMAS features, will permit the single-seat pilot to effectively accomplish his mission in a high-threat environment.

OPERATIONAL IMPLICATIONS

The flight test results of the AFTI/F-16 AMAS Phase clearly validate that the flight-path control func-

tion can provide the core building block for comprehensive system integration and automation. Today's fighters are integrated around the manual flying task, placing a high premium on the simultaneous accomplishment of flight-path control, target acquisition, weapon delivery, and threat management. AMAS, the antithesis to this traditional approach, flies the aircraft to a precision weapon release, giving the pilot more time to effectively work the target acquisition and threat-management tasks. The test results have demonstrated that the AMAS combat automation is technologically ready for transition today and provides a real-world capability usable by the pilot. While no forum exists to define automation policy, our results define the basis for substantial change in tactical fighter, combat automation.

The introduction of new automation into combat aircraft has generally required that two factors be satisfied: (1) overcoming senior management concern about increased cost and complexity of automation, and the potential for its unreliability, and (2) gaining operator acceptance, often in the face of "show me" and "white scarf" attitudes. The AMAS combat automation demonstration has provided the opportunity to look at these issues.

The AMAS flight validation has provided an extremely important cost and reliability baseline for future weapon system modifications or developments. The experience gained in implementing the APTI/F-16 with emphasis both to operability and safety, is not unlike that of an PSD development. Because of the functional redundancy approach that was the network of embedded, single-thread avionics, the system development was complex, leading to a higher-than-expected, non-recurring development cost. However, the task was accomplished, and the technical approach has been very successful in producing a reliable, software-intensive configuration that avoids recurring hardware costs and airframe penalties associated with hardware redundancy. A functioning software-support environment has been defined, and all safety-of-flight test goals have been met in an aggressive flight-demonstration program.

The AMAS demonstration has also provided a critical, operationally relevant evaluation by the operators, and the pilots, that is essential to fielding such automation concepts. There is precedence for the acceptance of the automation of functions that humans cannot perform, that compete with critical tasks, or that can be more reliably performed through automation. The AMAS testing has clearly demonstrated the benefits that flight-path automation provides to mission accomplishment, survivability, and safety during target acquisition and weapon delivery. We are confident that the AMAS demonstration has provided the key to this critical acceptance.

There is no doubt that AMAS capabilities signal a changing pilot role in the cockpit. These capabilities have not been effected with any thought of displacing the human pilot from the cockpit. In fact, quite the opposite is true. The implication of AMAS technology is that the effectiveness of the pilot is enhanced through flight-path automation and will sustain the viability of piloted aircraft in the tactical missions of the future. The flight-path automation that brings these new dimensions to attack maneuverability also can be used to allow the

pilot to devote attention to tasks that are dependent on the human operator. This is especially important for successful mission accomplishment using a single-seat, multisensor configuration designed to operate around-the-clock and in marginal weather conditions. The authors contend that the human pilot's perceptual and interpretive skills are better utilized for target acquisition and threat management. Although a number of advanced development programs are working to automate these functions, the technology and integration that supports full automation of these largely cognitive tasks has not emerged.

Given the acceptance of automated weapon delivery, this has important implications to the operational sensor and weapon configurations. The performance of the AMAS bombing system depends critically on the proper system integration of the three enabling subsystems: the conformal sensor/tracker system (measurement of target state), the fire-control computer (guidance command), and the flight-control system (closed-loop flight-path control). However, with the sensor/tracker now directly controlling the aircraft, the systems integration must be approached from a "built-in" rather than a "bolted-on" engineering frame of mind. The implication is that the overall weapon system integration would proceed from a functional design, with the sensor/tracker integrally designed into the system.

Perhaps the most important consideration for implementing the AMAS bombing system is the sensor airframe installation. It is absolutely essential that the sensor installation allow uplook to the target while maneuvering at bank angles of 90 degrees or more. This was the primary consideration in the selection of the wing-strake position for the APTI/F-16 (other considerations were low, aerodynamic drag and structural rigidity). Belly, inlet, and missile-well mounted sensors all tend to limit the bank that is achievable due to fuselage interference to the target line-of-sight; hence, these sensor restrictions severely limit the maneuver envelope during the attack phase.

The AMAS-SAIF integration has provided an important look at the payoffs achievable by complementary, advanced, aircraft and weapon integration. During the course of the AMAS program, we have also studied a number of other promising integrated weapon concepts. The availability of a communications link between the weapons and the aircraft avionics provides the ability to initialize a weapon before launch with a variety of readily available aircraft data. This MIL-STD-1760 interface can enable "smart" aircraft/"smart" weapon combinations that greatly increase weapon-system effectiveness. The potential also exists for significant weapon cost savings by taking advantage of the availability of aircraft data and eliminating unnecessary functional duplication in the weapons-of-state data that can be shipped at weapon release rather than autonomous sensing or estimation in the weapon guidance and warhead packages.

The importance of the on-board, digital-terrain data base for system integration, as well as situational awareness displays, cannot be overstated. Every aspect of the low-altitude, mission flight-path control, target acquisition, weapon delivery, threat avoidance - is affected by the topography of the area. The availability of an on-board, digital-terrain data base provides a

picture of the world not available through any combination of sensors. Furthermore, this data base provides the physical baseline for the registration of target, threat, geographical, and tactical data. Because of the revolutionary capabilities that the digital-terrain data base can provide, our recommended roadmap for this technology is singled-out in the final section of this paper.

TECHNOLOGICAL IMPLICATIONS

Integration is emerging as the key technology in systems prototyping. Currently, AFTI/F-16 AMAS is the largest-scale, aircraft integration completed by the Air Force Wright Aeronautical Laboratories. Most of the AFTI/F-16 integration is resident in software. In the accomplishment of the AMAS system integration, General Dynamics has matured in excess of 85,000 lines of object code (not including vendor subsystem software), which resides in five major subsystems. The scale of this activity has been comparable to that of a production program; yet, has been accomplished within the resources and philosophical context of a research program. Some of the lessons learned and the developments implemented, as a result of these experiences, are the subject of this discussion.

Software production has been a limiting factor in the development of new capabilities and engineering changes in the AMAS program. After the initial release of an OPP, problem disclosure has been accomplished in three stages: (1) code-oriented test, Computer Program Test & Evaluation (CPT&E), (2) stand-alone test, and (3) integrated system test. The process has been frustrated at each stage by a combination of slow-turnaround for changes and insufficient data for problem diagnostics. As a basis for formulating a new change approach, we have used, as a referee model, the development of software by the use of commercial software tools and test equipment. Our goal is to provide an integrated, system-development environment which reflects the commercial state-of-the-art.

- (1) Production of Code - The scale of change and available processors have dictated a combination of assembly (Z8001, MIL-STD-1750 and BDX-930) and Higher-Order Language (HOL) (JOVIAL J73 to Z8001 and MIL-STD-1750) programming. Early in the program, the lack of vertically integrated tools, (i.e., a compiler, assembler, linker and emulator) hosted in an interactive and accessible facility, greatly retarded the development for the HOL-implemented software. In fact, assembly-programmed patches dominated the repair process due to the lack of efficient code development facilities. The introduction of a vertically integrated tool set, which includes a symbolic debugger developed at General Dynamics, hosted on a MicroVAX II, raised the code development process to the efficiency limits of the tools. While we achieved a significant turnaround improvement, the preparation of a load module may still require as much as three hours, which precludes interactive debugging. Even at the current status of the tools, the efficiency of the vertically integrated, HOL-based development is significant, both in programmer productivity and in error reduction. Super-microcomputer technology has reduced the

capital requirements for embedded software development by more than an order of magnitude. We are currently performing this development in small teams, which are fully facilitated with vertically integrated tool sets.

The introduction of the Ada language is a significant step in enabling transportable code, but unless the attendant downstream link, load and test interfaces are simultaneously developed, a key element of the development chain will remain frustrating.

- (2) Stand-alone Test - It is not difficult to justify the development of custom, test facilities for production systems due to the amortization of the non-recurring costs over a significant production run. For the AMAS system avionic prototypes, we could not justify cloning cost, let alone the development cost of the required facility. This brutal fact forced us to sandwich into production facility schedules, adapt test procedure designed for qualification, not prototyping, and subsequently spend an inordinate amount of time in the stand-alone test process.

Until recently, commercial test equipment for custom, bit-slice processor MIL-STD-1750 computers did not exist. Our perception is that the small military market, coupled with the technologically outpaced MIL-STD-1750 processor, has delayed the availability of low-cost, test equipment. That equipment, now available even for custom, bit-slice computers has enabled a re-thinking of test station configurations. We have integrated a Tektronix 8540 with the Delco M372 fire-control computer to provide a low-cost, efficient debugging interface. Definition has begun on a super-microcomputer and commercial-interface-based, stand-alone, test facility; however, it is work-in-progress.

- (3) Integrated System Test - The AFTI/F-16 hotbench simulator facility has become the primary, system-level debug, verification and validation tool. It is in this facility that we are currently demonstrating the larger methodology change.

The hotbench has two development-evaluation modes: first, simulation models executed on mini-computers, and second, hotbench operation using target processors. The mini-computer step was necessitated by the long turnaround cycle for trial, target computer software. Development facilities, which are compartmented in small, vertically integrated "nests", are now networked to the simulation facility. On-line debug interfaces are available at the target processor. With the addition of a commercial multiplex bus analyzer, the system is simultaneously observable at the target processor(s), bus and functional system level. This facility has been called an "instrumented hotbench".

Because of near-term standardization on Ada as both an embedded software and a simulation language, the role of the mini-computer as an embedded software modeling device is being challenged. A facility as defined in Figure 3, combined with a rapidly executing, development,

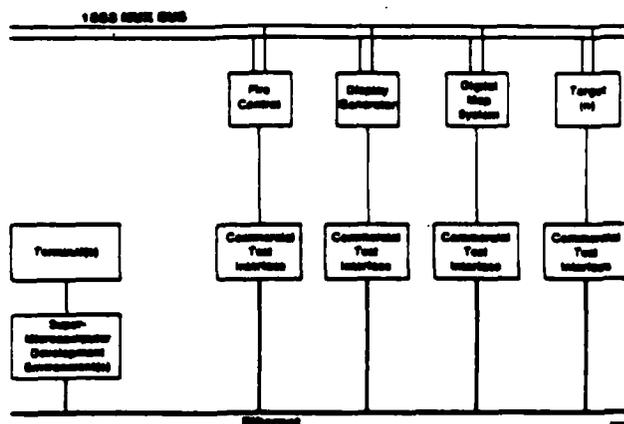


Figure 3 Instrumented Hotbench Development Systems

tool set can become a system-level, interactive debug facility. Automated, stand-alone facilities are embedded and, in some cases, could provide stand-alone results in concert with the operation of targets. A facility prototype exists, and extension is underway.

The fact that the "instrumented hotbench" is nearly electrically and functionally identical to the testbed aircraft could justify the migration of test procedures to the testbed. At this time, the lack of flight-line interfaces to the airborne targets precludes this step.

The viability of the adaptation of commercial, test equipment to the systems prototype process has led us to another parallel - what about commercial microprocessors? The fundamental health of the private sector has led to the recent introduction of five, 32-bit super-microcomputers with military application potential. Commercial microprocessors combined with transportable Ada code should solve many tool and test availability problems. These chip sets are fabricated to VHSIC Phase I line rules and are supported with commercial test interfaces. One VHSIC application studied for the Digital Terrain Management and Display System (DTMDS), symbol-generator, an upgrade to a VHSIC MIL-STD-1750 offered no payoff, not because of VHSIC, but because of 16-bit addressing in the MIL-STD-1750A processor.

The authors contend that implementation of the Packard Commission findings could profitably begin with computers: "rather than relying on excessively rigid, military specifications, DoD should make much greater use of components, systems, and services available 'off-the-shelf.'" It should develop new or custom-made items only when it has been established that those readily available are clearly inadequate to meet military requirements".

Our integration efforts have almost paralleled subsystem developments, and a pattern of critical, subsystem development/integration has emerged. The payoff derivable from further integration on the testbed is currently at the highest level since the program began, because of the presence of the onboard, digital-terrain data base. That potential direction is the subject of the next section.

RECOMMENDED R&D ROADMAP

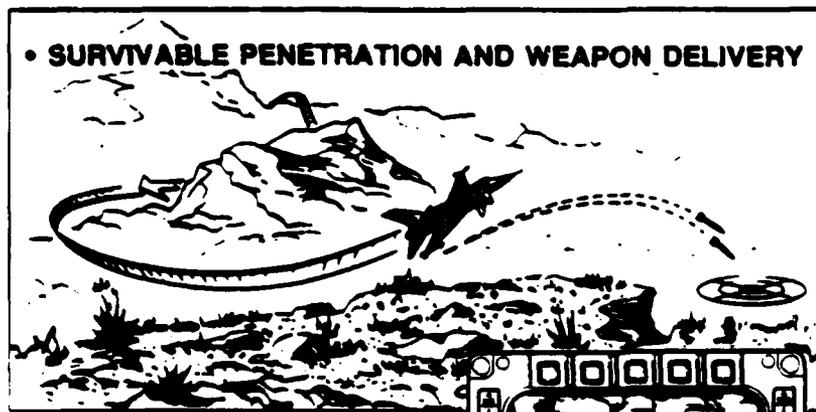
The most pervasive follow-on to the AFTI/P-16 AMAS research is the extension of the air-to-surface capabilities to generalized topography to take advantage of terrain masking during weapon delivery. This would allow the pilot to stay lower by ingressing, engaging the target, and egressing below the localized, minimum, enroute altitude. The current AMAS system can be employed in hilly or mountainous terrain only by ensuring that the weapon delivery is initiated with parameters that would result in a flight path that clears terrain in the sector approaching the target. However, this tactic does not take advantage of the terrain for masking from threats, and also places a burden on the pilot for careful attack planning to ensure timely target acquisition, a clear weapon trajectory, and ground-collision avoidance.

Research would include these developments: methods to determine target intervisibility for ensuring unobstructed line-of-sight for target acquisition, designation, and weapon delivery; a generalized ground-collision-avoidance system by considering terrain surrounding the projected ground track; optimal trajectory control algorithms based on knowledge of target(s), terrain, and threats; and pilot situational displays.

The central thrust to our recommended follow-on research would be oriented toward providing the same maneuverability and safety of the AMAS system in the presence of terrain. The key performance characteristics are illustrated in Figure 4. Because it is necessary to see beyond the local horizon, to see the hill behind the hill, a digital-terrain data base is absolutely essential to enable the proposed capabilities. Integration of the attack radar and the digital-terrain system will be required to provide the ground-collision-avoidance function in a robust manner. Two very significant challenges would be the development of (1) a generalized, weapon-delivery guidance algorithm and (2) an all-terrain, ground-collision-avoidance system.

A generalized, curvilinear, weapon-delivery algorithm must account for terrain in two ways. First, it must guarantee a terrain-free flight path of the weapon to the target. Second, if target designation is required, as is usually the case, then the sensor must have a terrain-free line-of-sight to the target for some finite time before weapon release. This second constraint can be very limiting to the attack geometry since targets tend to be located along valley floors. This suggests that an all-terrain, weapon-delivery algorithm must have the ability to "snake", that is, to allow turn reversals and variable g command to keep line-of-sight to the target without having to climb too high. Other factors which should be considered in the guidance algorithm include time-over-target constraints, weapon effectiveness, post-release constraints, threat avoidance, etc.

The attack planning will likely depend heavily on pilot judgment; therefore, the guidance algorithms must be adaptive to an iterative planning process so that the pilot can make the trade-offs between weapon effectiveness and survivability. A very important, operational requirement that should be considered is the ability to coordinate the attack of multiple ships to concentrate firepower, permitting simultaneous attacks from multiple directions, saturating and confusing enemy defenses. To permit coordinated attack, the maneuvering attack



• DATA BASE DRIVEN PILOT CONFIDENCE DISPLAYS



• TACTICAL SITUATION DISPLAY

- ✓ Attack Planning
- ✓ Interactive Route Planning
- ✓ Threat Management

- ✓ Integrated Flight/Fire/Weapon Control System
- ✓ On-Board Terrain Data Base and Display System

PLANNED FEATURES

- ALL-TERRAIN TACTICS
- 5-g MANEUVERABILITY
- TERRAIN/RADAR DATA FUSION
- LOW PROBABILITY INTERCEPT OPERATION
- AUTONOMOUS PRECISION NAVIGATION
- BLIND TARGETING
- NIGHT/WEATHER OPERATION

Figure 4 Digital Terrain System Integration Thrust

algorithms would have to lend themselves to deconfliction of flight paths and weapon fragmentation patterns. All these factors require guidance algorithms that are predictable so that tactics can be planned and rehearsed in a mission-planning station using a data base common to the aircraft system.

The development of a prototype mission-planning station is viewed as an integral research objective to develop a support concept for the generation, distribution, and flight-preparation of the DMA DLMS data bases and other operational data bases (ops plan, frag, intelligence, weather, etc.). The results of the AMAS DTMDS development have demonstrated that such data bases can be stored, processed, and displayed in a fighter aircraft. The remaining hurdle is to develop the procedures and protocols for the logistics of the data base. The planning at the squadron level is absolutely critical to the success of the low-altitude mission. Pilots must have the tools readily available for target study, attack planning, route planning, mission rehearsal, etc., and it is essential that these tools be as close to the aircraft system configuration as possible.

Fail-safe operation is obviously paramount to any practical application of the above. A major part of the development would be the extension of the AMAS System-Wide Integrity Management program to generalized topography. A predictive algorithm must constantly

monitor a projected flight path, as well as possible escape paths. The availability of a digital-terrain data base provides the capability to see around corners and eliminate the maneuver restrictions of current terrain-following/terrain-avoidance approaches.

The digital-terrain system must be properly integrated with the flight control and avionics sensors to provide fail-safe, fault-tolerant capability. Of foremost importance is the registration of the aircraft position within the data base. Two independent position and altitude correlation techniques are required. In addition to the SITAN historical position correlation, a forward-looking, terrain correlation technique is indicated using radar measurement. Other considerations that will require a forward-looking radar are the height measurement of terrain cells in the near-field for vertical clearance, as well as for searching for unregistered obstacles.

Pilot acceptability is mandatory to the successful implementation of an all-terrain, maneuvering attack system. The pilot must have confidence in the performance of the system and be able to anticipate maneuvers. This requires that the algorithms be predictable, and that the flight path be suitably portrayed in relationship to the terrain. A vital part of our recommended research is the integration of flight path, attitude control, and terrain data into comprehensible cockpit displays. One very

promising display format that may enhance head-down situational awareness is a real-time, space-stabilized, pilot-perspective display.

The availability of a digital-terrain data base also suggests new opportunities for weapon integration. The passive ranging for delivery of an auto-fused weapon dispenser is being demonstrated in the current AMAS Phase. Several extensions of this concept are possible. For standoff weapons that must navigate to a target area, and then search a footprint for the target, weapon initialization release with the best available target and aircraft-state information would provide benefits in weapon performance and reduced guidance and seeker costs. In addition to state information, a navigation patch with terrain data could also be shipped to the weapon navigation computer. The weapon navigation autopilot could use vertical terrain profiles for terrain following, allowing launch under "blind" (masked) conditions and target acquisition under low-ceilings. For longer-range standoff weapons, like cruise missiles, terrain data can be shipped for terrain-correlation navigation. On-board data also provides the flexibility for retargeting.

CONCLUSIONS

The AFTI/F-16 systems prototype effort is nearly concluded and the results are now being measured directly. The transition of the DFCS Phase technology is understood and documented. The positive results are directly correlated to original program groundrules which include:

- (1) A realistic test environment afforded by an advanced technology fighter testbed
- (2) A concentration on the solution of fundamental, chronic, operational problems

- (3) The simultaneous stressing of functional and packaging technology.

Adjunct to the systems-level prototyping, was the development of subsystems technology, which can be measured in terms of aviation firsts:

- (1) First digital fly-by-wire system flown on a statically unstable aircraft
- (2) First airborne application of voice command
- (3) First fully autopilot-driven, precision-delivery of an unguided bomb
- (4) First tactical fighter application of DLMS-driven map system.

Today's technology makes the systems of prototype as viable as the airframe prototypes of the past. Hardware and software advances that are currently emerging make the extension of combat automation to a wider span of functions immediately available. Integration at a scale previously reserved for FSD development is accessible for prototypes.

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