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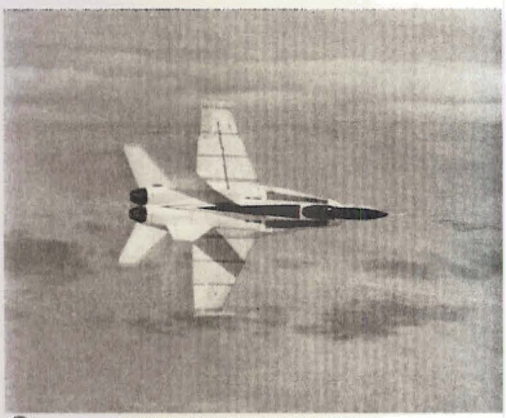

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NASA Dryden's highly-modified Active Aeroelastic Wing F/A-18A shows off its form during a 360-degree aileron roll during a research flight.

Aeronautics Research Mission Directorate
Aviation Safety Program
Integrated Resilient Aircraft Control Project

NASA

Capability Description for NASA's F/A-18 TN 853 as a Testbed for the Integrated Resilient Aircraft Control Project

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EXECUTIVE SUMMARY

The NASA F/A-18 tail number (TN) 853 full-scale Integrated Resilient Aircraft Control (IRAC) testbed has been designed with a full array of capabilities in support of the Aviation Safety Program. Highlights of the system's capabilities include:

- a quad-redundant research flight control system for safely interfacing controls experiments to the aircraft's control surfaces
- a dual-redundant airborne research test system for hosting multi-disciplinary state-of-the-art adaptive control experiments
- a robust reversionary configuration for recovery from unusual attitudes and configurations
- significant research instrumentation, particularly in the area of static loads
- extensive facilities for experiment simulation, data logging, real-time monitoring and post-flight analysis capabilities
- significant growth capability in terms of interfaces and processing power

NOMENCLATURE

1553	Mil-Std-1553 Data Bus
68040	Research Flight Control Computer Processor
701E	Production Flight Control Computer Processor
AAW	Active Aeroelastic Wing
AFSRB	Air Flight Safety Review Board
AirSTAR	Airborne Subscale Transport Aircraft Research
ARTS IV	Airborne Research Test System, 4th Generation
CAT	Choose-A-Test
COTS	Commercial Off-The-Shelf
DAG	Dial-A-Gain
DDI	Digital Display Interface
DFRC	Dryden Flight Research Center
EGI	Embedded Global Positioning and Inertial Navigation System
F/A	Fighter / Attack
FDMS	Flight Deflection Measurement System
FRR	Flight Readiness Review
HIL	Hardware-in-the-Loop
IRAC	Integrated Resilient Aircraft Control
NRA	NASA Research Announcement
NVRAM	Non-Volatile Random Access Memory
NWS	Nose-Wheel Steering
OBES	On-Board Excitation System
PSFCC	Production Support Flight Control System
PVI	Pilot Vehicle Interface
RFCS	Research Flight Control System
SBC	Single Board Computer
SBIR	Small Business Innovative Research
TN	Tail Number

INTRODUCTION

The NASA F/A-18 TN 853 full-scale Integrated Resilient Aircraft Control (IRAC) testbed is an important component of the Aviation Safety Program[1]. In support of IRAC goals, the full-scale testbed is capable of hosting a wide variety of multi-disciplinary, state-of-the-art adaptive control experiments. Classes of potential experiments include, but are not limited to:

- direct and indirect adaptive inner-loop control
- integrated aerodynamic and propulsion flight control
- adaptive mission planning and guidance
- integrated vehicle health-monitoring
- adaptive control with structural constraints (potential future capability)

Full-scale flight testing of these technologies on the F/A-18 IRAC testbed provides the capability for piloted evaluations as well as for the exploration of unanticipated interactions involving non-linear and higher-order effects that are often difficult or impossible to model in simulation. Implementation of these technologies on a real-world platform gives designers the opportunity to explicitly address constraints such as measurement noise, time delays, asynchronous and multi-rate systems, and redundant architectures.

To facilitate testing of experimental adaptive control technologies, the IRAC testbed is capable of simulating a variety of damage and failure conditions. Flight within a limited envelope gives the research systems the capability to fully reconfigure the F/A-18's control surfaces in novel combinations while maintaining adequate structural margin. Direct control of the throttles allows for integrated propulsion control experiments. Special structural instrumentation allows for real-time monitoring of loads and eventually for integration with experimental control laws or integrated vehicle health-monitoring algorithms.

The IRAC testbed system also includes capabilities for experiment development, including dynamics and structural design models, piloted simulation and hardware-in-the-loop test facilities.

This document describes the current capabilities of the IRAC F/A-18 testbed. It provides a broad functional overview of the experimental capabilities of the IRAC F/A-18 testbed aircraft. It is intended to serve both as a top-level introduction for individuals without specific knowledge of the project and as a guideline to experiment developers and evaluators for assessing the applicability of the aircraft as a testbed for novel technologies.

In addition to the capabilities that are planned for the initial flight phase of this aircraft, there are a number of enhanced capabilities under consideration in support of potential future experiments. These are called out in the appropriate sections.

System Overview

The IRAC F/A-18 full-scale testbed is primarily a flight controls research platform, and as such is largely constructed around the aircraft's flight control computers, as shown in Figure 1. The production flight control computers have been modified with an additional processor in each channel to accommodate a research flight control system (RFCS). In order to provide even greater computational and interface capabilities, the RFCS has been augmented with two identical external airborne research test system (ARTS) computers. Experimental software housed within the RFCS and ARTS computers can exercise full control over the aircraft's flight control surfaces as well as the engine throttle levers.

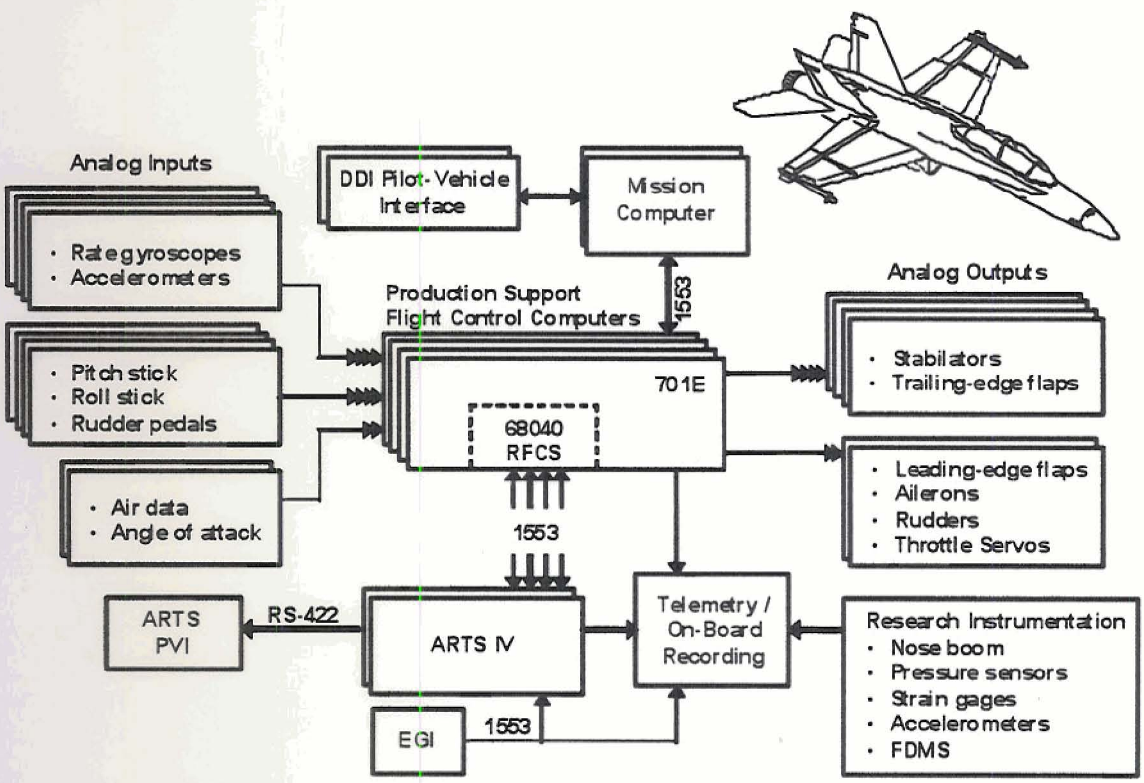

Figure 1 – IRAC F/A-18 Full-Scale Testbed Systems Overview

In addition to its research flight control capabilities, the IRAC testbed has been outfitted with extensive research instrumentation. Loads, dynamics and aerodynamic parameters as well as data from the production flight control systems and on-board experiments is recorded on-board the aircraft and telemetered to the ground for real-time control room monitoring and post-flight data analysis.

Pilot interfaces are provided for situational awareness, experiment selection and configuration and to facilitate transitions between the production and research flight control systems. Flight control authority automatically reverts to the production control system in the event of a system failure or when a flight envelope constraint is violated.

Concept of Operations

Flight test operations will necessarily be tailored to the specific requirements of the experiment(s) being flown. However, flight tests will generally proceed following the same well-established methods as other piloted test programs at the NASA Dryden Flight Research Facility. Additional detail regarding the proposed concept of operations of the IRAC full-scale testbed can be found in reference 2.

Prior to flight, all planned flight test maneuvers are evaluated by the pilot in the simulation, if possible. Predicted results are recorded and critical parameters are identified for real-time monitoring. The planned maneuvers and mission rules are reviewed by the entire test team at a pre-flight crew briefing.

Research missions are always flown with control room monitoring and a chase support aircraft. The test aircraft will takeoff and land under production control laws. Upon reaching the test condition, the pilot will configure the RFCS and the experiments within the ARTS via the digital display interface (DDI)[3]. Although only one experiment can directly control the aircraft at a time, additional experiments can interact with the controlling experiment or operate as independent monitoring (non-controlling) experiments.

Once the system has been configured and verified by the control room, the pilot will arm the RFCS via the DDI and engage using the nose-wheel steering (NWS) switch. RFCS and ARTS status information is displayed to the pilot on the DDI and the ARTS pilot-vehicle interface (PVI)[4]. Flight test maneuvers are then performed as required and data is transmitted to the control room and recorded for post-flight analysis. Between test points, the system can be disengaged and the same experiment can be configured differently, or a different experiment can be selected as the controlling experiment. A goal of the IRAC testbed is to provide the maximum amount of in-flight experiment flexibility as is practical.

Following landing, a post-flight briefing is conducted to review initial results, pilot comments and any anomalies that occurred during the flight. Plans for the next flight test mission are discussed.

Experiment Life Cycle

Experiments to be flown on the IRAC full-scale testbed will be selected from a pool of ongoing NRAs, SBIRs and internal NASA proposals. Experiments are selected for flight following a thorough review by researchers at the NASA Ames, Dryden, Glenn and Langley aeronautics research centers. When appropriate, experiments may also be selected for flight on the NASA Langley AirSTAR subscale transport testbed[5], either as a risk-reduction effort or as a parallel test path focused on complementary objectives.

Once an experiment is selected, a review will be conducted to ensure that implementation requirements are well understood and agreed upon by the researchers and the test team. It is anticipated that most experiments will be auto-coded from Matlab Simulink following guidelines outlined in the ARTS experimenter's handbook (currently in development).

Configuration control of all flight software and related documentation, including hazard reports, discrepancy reports and change requests, is maintained by the Dryden Flight Research Center (DFRC) project manager for TN 853. The DFRC air flight safety review board (AFSRB) process will be used to ensure flight safety and maximize the potential for mission success. The process to obtain approval to proceed to flight depends upon the criticality of the experiment, but may include a flight readiness review (FRR). Technical briefings are conducted as required during the flight program to address any issues that arise. System safety working groups are held periodically to identify experiment hazards.

Flight qualification testing will be conducted using the Dryden hardware-in-the-loop (HIL) test bench and piloted simulation. Controlling experiments will generally be tested to level-B, or mission-critical, standards. Non-controlling experiments may be treated as either level-B or level-C (non-mission critical) software. In the event that software changes are required during the test program to correct anomalies or improve performance, regression testing will also be accomplished using the HIL. Aircraft integration tests will be conducted using ground test mode capabilities programmed into the RFCS and ARTS computers.

F/A-18 Airframe Capabilities

NASA F/A-18 TN 853 is a modified single-seat A-model F/A-18 aircraft. It served as flight test vehicle for the Active Aeroelastic Wing (AAW) project from 1996 - 2005[6]. The original wings have been replaced with pre-production F/A-18 wings for increased torsional flexibility. Wing modifications do not restrict the experimental envelope. Certain military functions have been removed from the aircraft, including systems for weapons and countermeasures, radar and the wing fold mechanism. Carrier operations are prohibited.

The normal test configuration for this aircraft is internal fuel capacity only, although the plane is capable of employing an external centerline fuel tank. The capability for external wing fuel tanks has been disabled. Aerial refueling using the Navy-style probe and drogue system is supported. At typical test conditions (see class-B envelope description below), internal fuel quantities provide approximately 1 hour of flight test time.

The F/A-18 has well-characterized pre- and post-departure characteristics and a robust capability to recover from unusual attitudes and departures. The production F/A-18 control laws are used for takeoff, landing, and up and away flight between test points. They also provide a safe reversion mode.

The F/A-18 IRAC full-scale testbed experiment envelope[7] is shown in Figure 2. For certain experiments which do not exercise command of the aircraft's control effectors and which require minimal real-time configuration by the pilot, the entire aircraft envelope is available for experiment flight planning and execution. Due to modifications to the aircraft's pitot-static system, flight within visible moisture is prohibited.

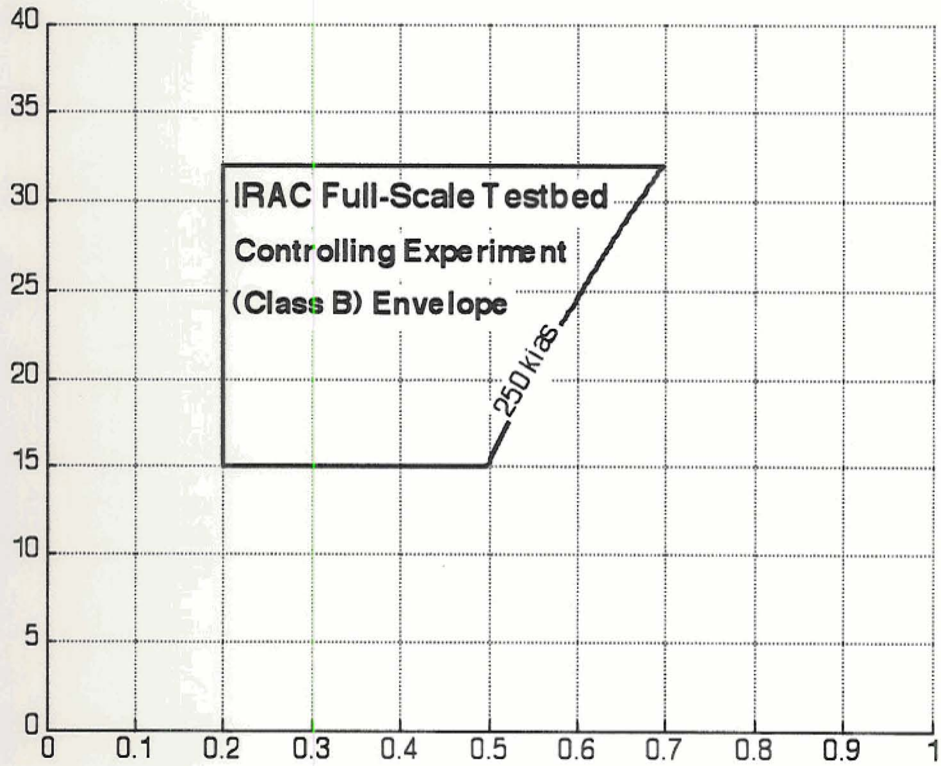

Figure 2 – F/A-18 IRAC Full-Scale Testbed Experiment Envelope

A *class B envelope* has been defined for TN 853 for the purposes of protecting against generic faults within the experimental software. The term class B refers to the Dryden flight qualification level of software that is *mission critical* but not *safety critical*. For test points within the class B envelope, hard-over commands of the aircraft control surfaces are predicted to produce transients that do not exceed aircraft load limits. Software qualified to level-B rather than level-A standards follow a simplified development process and undergoes a reduced level of testing. This allows for the project to get experiments to flight more quickly and facilitates software changes between flights.

In addition to airspeed and altitude constraints, the experimental envelope includes maneuvering constraints. The RFCS will disconnect the experimental software from control of the aircraft surfaces in the event that a constraint, or disengage limit, is violated. The entire set of RFCS disengage limits is listed in Table 1.

Table 1 – RFCS Class B Envelope Disengage Limits

parameter	lower limit	upper limit	units
static pressure	608.8	1200.3	psf
impact pressure	0.0	227.5	psf
Mach number	0.2	0.7	--
normal load factor	-1.5	+4.0	g's
lateral acceleration	-1.0	+1.0	g's
body axis pitch rate	-20	+30	deg / sec
body axis roll rate	-200	+200	deg / sec
body axis yaw rate	-25	+25	deg / sec

The RFCS limits are implemented to level-A standards and are therefore considered an important component of ensuring flight safety. For this reason the limits are fixed and not configurable. Experiment-specific limits can be set within the ARTS provided they are more restrictive than the RFCS disengage limits. Because the ARTS is normally programmed with level-B software, these limits are restricted to constraints critical to mission success and not to flight safety. ARTS limits can be easily reconfigured between flights.

Potential Future Capability :	**Fail-op capability for experiments involving takeoff, landing or flight outside the class B envelope.**

Experimental System Capabilities

The experimental system capabilities onboard the TN 853 are designed to allow flexible yet safe flight test evaluation of state-of-the-art adaptive control technologies. The experimental system is comprised primarily of the research flight control system (RFCS), the airborne research test system (ARTS) and research instrumentation.

PSFCC / RFCS

Experimental flight control capability on TN 853 is centered about the *production support flight control computers*, or PSFCCs[8]. The PSFCCs consist of quad-redundant production (701E) flight control computers and software augmented with a 68040 research processor and software in each channel. A diagram of the PSFCC architecture is shown in Figure 3.

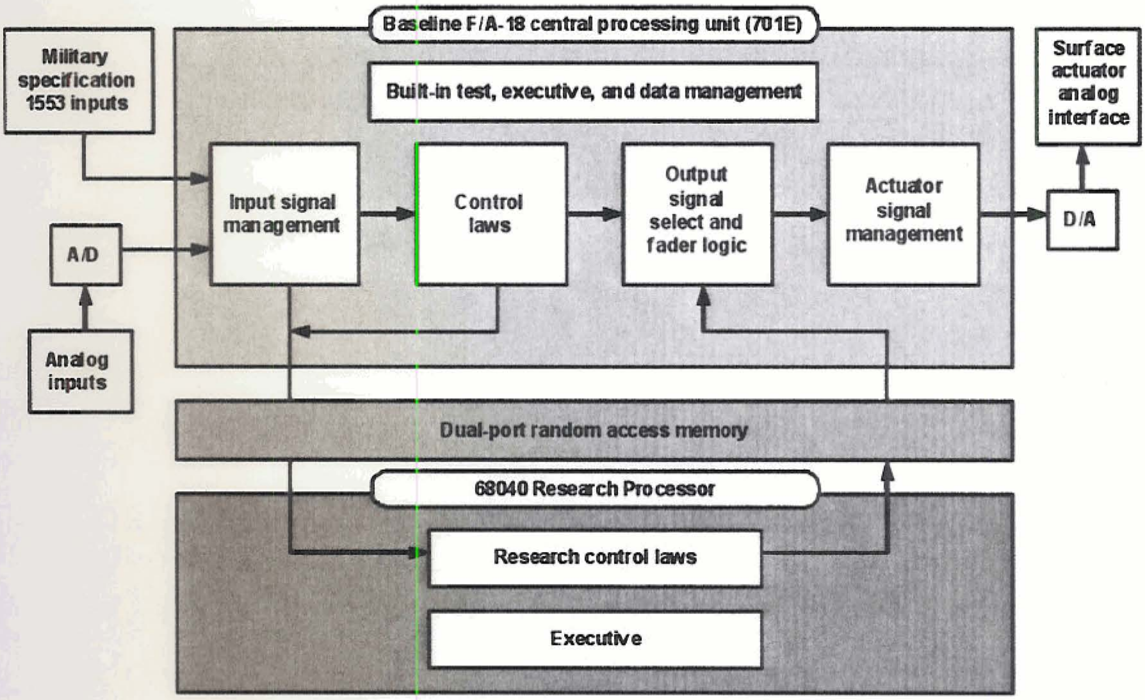

Figure 3 – PSFCC Architecture

Special software modifications to the 701E software, together with the 68040 processor and its associated software are collectively referred to as the *research flight control system*, or RFCS. The RFCS provides the following on-board functionality:

- performs fading to and from experimental control laws
- monitors RFCS disengage limits (see Table 1)
- passes aircraft state data, pilot inputs and other system parameters to the ARTS
- receives and applies commands from the ARTS
- executes a replication of the production F/A-18 flight control laws
- provides actuator commands and RFCS status for output to instrumentation

<u>States</u>

The RFCS has three states of operation. When the system is *disengaged*, the 701E processor has complete control over the flight control system. The pilot can put the system into an *armed* state in which the 701E is still the primary flight control system, but the 68040 processor also begins computing its replication control laws. The pilot can then transition the system to an *engaged* state, in which command of the aircraft control surfaces is given to the RFCS. This three-state concept enhances flight safety by requiring two proactive pilot actions to transition control to the RFCS. The pilot can disengage the system at any time.

Modes

A ground test mode is available when the aircraft is weight-on-wheels[9]. The ground test mode disables the RFCS disengage limit checks to allow the system to be armed and engaged on the ground for systems testing. With weight on wheels, control of the throttles by the RFCS is not available and the input to the pitch axis forward-loop integrator is zeroed.

In flight, there are three operational modes that affect the way in which commands from the RFCS replication control laws are combined with commands from ARTS. The three modes, shown functionally in Figure 4, are defined as:

1. RFCS Primary – commands from the ARTS are ignored
2. RFCS / ARTS – commands from the ARTS are combined with those from RFCS
3. ARTS Primary – commands from the RFCS are replaced by those from the ARTS

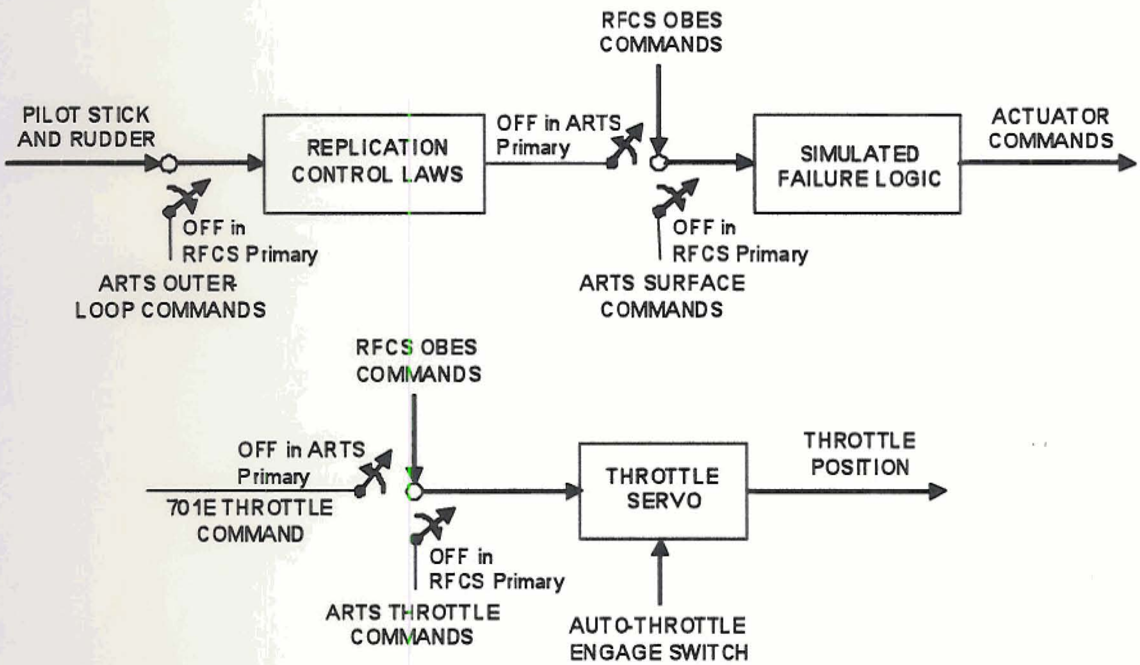

Figure 4 – RFCS Mode-Dependent Command Source Selection

In all three modes, the RFCS provides throttle commands to the 701E. Prior to engaging RFCS, the pilot has the option of engaging *auto-throttles* by selecting the velocity hold autopilot mode. With auto-throttles engaged, the throttle levers are positioned by a servo that is driven by commands from the flight control computers. If RFCS is engaged in conjunction with auto-throttles, the 701E throttle servo commands are replaced by those of the RFCS.

Experiment software within the RFCS and within the ARTS is configured by the pilot through the selection of dial-a-gain (DAG) and choose-a-test (CAT) entries on the cockpit DDI[3]. There are 27 DAG and 27 CAT selections from which to choose. DAG entries configure the RFCS into one of its three modes according to Table 2. They are also sent to the ARTS for use in configuring its software.

Table 2 – Operating Mode Selection

DAG Range	Operating Mode
0	RFCS Primary
1 – 13	RFCS / ARTS
14 – 26	ARTS Primary

Sixteen of the CAT entries are used to select simulated failures and on-board excitation system inputs within the RFCS. These are discussed in the sections below. The remaining eleven CAT entries are reserved for use by the experimental software within the ARTS. In addition, the nose-wheel steering button can be used by the pilot to trigger discrete events within the ARTS experiments.

Simulated Failures

Simulated failure capabilities have been programmed within the F/A-18 research systems to provide challenging scenarios for use in evaluating new adaptive control technologies[10]. These failure modes, listed in Table 3, include single and multiple control surface failures as well as a series of "damaged wing" scenarios. Additional simulated failures can also be programmed within the ARTS, if required.

Table 3 – RFCS Simulated Failures

DAG	CAT	Description
any	0	no OBES and no simulated failure
any	1	right stab, left and right ailerons failed at 0° offset
any	2	left and right stab failed at 0° offset
any	3	left and right stab, left and right ailerons failed at 0° offset
any	4	left and right stabs, left and right ailerons, left and right rudders and differential leading- and trailing-edge flaps all failed at 0° offset
any	5	collective leading- and trailing edge flap schedule multiplier of 1.0, right leading- and trailing-edge flaps failed at 0° absolute
any	6	collective leading- and trailing edge flap schedule multiplier of 2.0, right leading- and trailing-edge flaps failed at 0° absolute
any	7	collective leading- and trailing edge flap schedule multiplier of 4.0, right leading- and trailing-edge flaps failed at 0° absolute
any	8	collective leading- and trailing edge flap schedule multiplier of 8.0, right leading- and trailing-edge flaps failed at 0° absolute
any	9	right stab failed at 0° absolute

OBES Inputs

Table 4 lists on-board excitation system inputs that have been implemented within the RFCS to aid in in-flight parameter identification[11]. Additional OBES inputs can be programmed into the ARTS software.

Table 4 – RFCS OBES Inputs

DAG	CAT	Description
any	10	OBES frequency command to differential (toe in/out) rudder
any	11	OBES frequency command to differential trailing edge flap
any	12	OBES frequency command to collective throttle
any	13	OBES frequency command to differential throttle
any	14	OBES doublet commands to collective surfaces
any	15	OBES doublet commands to differential surfaces

ARTS IV

The fourth-generation airborne research test system (ARTS IV) provides a flexible and configurable capability for hosting IRAC experiments. It utilizes an open architecture and development environment for rapid transition from algorithms to mission-critical (level-B) flight software. The ARTS provides a robust capability augmentation to the RFCS for external I/O, internal memory and processing power.

Hardware

The ARTS is a system of two ruggedized, fully dual-redundant COTS hardware boxes running customized software. Each ARTS box contains 3 single board computers (SBC), one for executive functions and two for hosting experiments. Table 5 lists specifications for the ARTS.

Table 5 – ARTS Specification

Specification	Value
processor clock speed	1.0 GHz
memory	512 MB RAM 16 GB NVRAM
operating system	VxWorks 5.5
minor frame rate	160 Hz
experiment execution window	~2.5 ms

Figure 5 shows the ARTS hardware configuration. Each box is configured identically. Potential future capabilities that are currently unused include a slot for a third research processor and spare analog, discrete, Ethernet and USB interfaces.

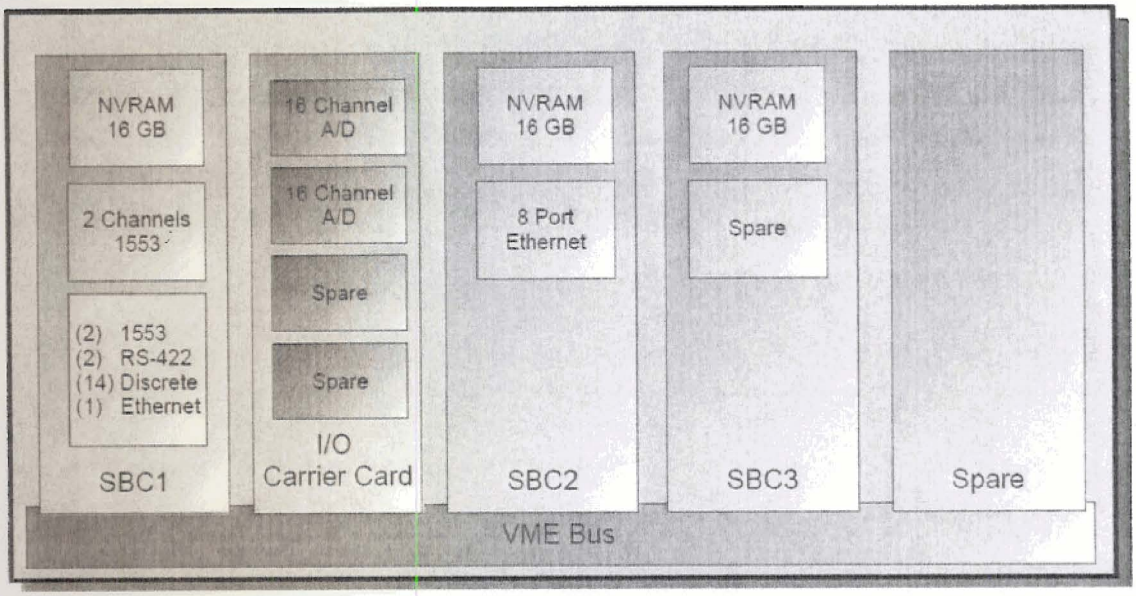

Figure 5 – Hardware Configuration of Each ARTS Box

Software

The software configuration of the two boxes must be identical. Each of the two research SBCs in a box can host up to four experiments, for a total of eight running at any one time. Only one of these, selected via the pilot DAG entry, can be a controlling experiment in the sense that its commands are sent to the RFCS. However, the experiments can communicate between themselves, so that non-controlling experiments can provide inputs (adaptive augmentation, for example) to the controlling experiment (a non-adaptive controller, for example).

Various constants within each ARTS experiment can be specified using configuration files rather than being fixed at compile time. Multiple configuration files are available for each experiment on a given flight, and different sets of files can be loaded between flights. Experiments within the ARTS can select their configuration files using either pilot DAG or CAT entries, as appropriate. Following engagement, the nose-wheel steering switch and DDI buttons can also be used by the pilot to configure the experiment.

Inputs and Outputs

The ARTS is time synchronized with the RFCS and designed to minimize time delays in the control paths. One additional RFCS frame of latency will be incurred, which equates to 12.5 ms for stabilators, ailerons and flaps and 25 ms for rudders. The RFCS passes along to the ARTS all of the critical input data that it receives from the 701E production flight control computer. This input data includes, but is not limited to, the following:

- pilot control inputs, switch settings, etc.
- 701E and RFCS flight control commands
- actuator position feedbacks

- body axis rotational rates
- normal and lateral accelerations
- euler angles
- airspeed, altitude, angle of attack
- static and impact pressures
- system status information

In the RFCS Primary mode of operation, all communication from the ARTS is ignored. Therefore, there is no designated controlling experiment. Non-controlling experiments can execute in any of the three modes.

In the RFCS / ARTS mode, the ARTS can send increments to be summed with the pilot inputs to the RFCS replication control laws. The pilot inputs are pitch stick, roll stick and rudder pedals. Increments can also be provided to the trim left and right throttle settings. These capabilities enable a number of classes of experiments, including:

- autopilot, guidance and mission management
- retrofit adaptive flight controls
- pre-canned pilot inputs and on-board excitation

A second option is available when the system is in RFCS / ARTS mode. The ARTS can send control surface commands to be combined with commands from the RFCS replication control laws. In this case the ARTS commands could represent, for example, persistent excitation signals, OBES inputs or retrofit adaptive flight control augmentation. Control surface commands are also sent by the ARTS in the ARTS primary mode. In this mode, the ARTS is the primary flight controller. Within the class B envelope, the ARTS controlling experiment then has the capability to command novel combinations of the F/A-18's suite of control effectors:

- stabilators
- ailerons
- rudders
- leading- and trailing-edge flaps
- engines, controlled individually via throttle servos

To aid in situational awareness, the ARTS drives a small pilot display. The current ARTS mode and status as well as the selected DAG and CAT are displayed.

Potential Future Capability :	**Additional instrumentation inputs to the ARTS, such as loads measurements or embedded GPS/INS data.**

Instrumentation

Most instrumentation data is available via telemetry for real-time data monitoring and is also recorded on-board the aircraft. Both telemetered and on-board recorded data are processed for post-flight analysis. In total, there are over 1600 instrumented parameters on the airplane[12-13]. Currently most research instrumentation is unavailable to the ARTS, but may be included as a future capability.

Aerodynamics

A nose boom is installed on the aircraft and provides measurements of angle of attack, angle of sideslip, total pressure and static pressure. A total of 40 pressure sensors are installed on the upper and lower surfaces of both wings, as well as on the right leading-edge flap and the left aileron. Data is also available from the F/A-18's production air data computer.

Flight Dynamics

Signal selected data from the quad-redundant rate gyroscopes and accelerometers used by the flight control system is passed to the instrumentation system. Inertial data from the aircraft's production inertial navigation system (INS) is available along with global positioning system (GPS) data.

Loads

Real-time loads measurements are available from nearly 200 strain gages on the two wings. A flight deflection measurement system (FDMS) measures deflection of the left wing during flight for post-flight analysis. Real-time video of the left wing deflection can be transmitted to the control room. Over 50 accelerometers are installed in the wing, fuselage and empennage in support of structural dynamics research.

Other

Real-time video of the heads-up display can be transmitted from the aircraft to the control room. Individual fuel tank quantities are telemetered for accurate mass property calculations.

FLIGHT TEST SUPPORT CAPABILITIES

A real-time piloted simulation exists at DFRC to support advanced analysis of experiments, including flight planning and piloted evaluations. The piloted simulation includes software models of the RFCS and ARTS subsystems.

Flight qualification testing of experiments will be conducted using the DFRC F/A-18 hardware-in-the-loop (HIL) test bench. The HIL bench provides researchers with the capability to evaluate verification techniques of embedded software for adaptive systems. The HIL exhibits many of the same difficult-to-model constraints that are encountered on the aircraft, including timing issues and system noise. The HIL bench also provides the capability to rapidly advance experiments to flight, and to make quick turn-arounds between flights (updates and regression testing).

During flight experiments, data is telemetered from the aircraft to the ground to support real-time monitoring and analysis in the control room. Critical disciplines present in the control room will generally include loads, flight controls, flight systems and operations. Depending upon the experiment, aerodynamics, propulsion and structural dynamics personnel may also be required. Data is also recorded for post-flight analysis.

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