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SYSTEM OVERVIEW OF THE NASA DRYDEN INTEGRATED TEST FACILITY

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Abstract

The Integrated Test Facility, built at the NASA Dryden Flight Research Facility, provides new real-time test capabilities for emerging research aircraft. This paper is an overview of the test facility and the real-time systems developed to operate this unique facility. The facility will reduce flight test risk by minimizing the difference between the flight and ground test environments. This ground test environment is provided by combining real-time flight simulation with the actual aircraft. A brief introduction to the facility is followed by a discussion of the generic capabilities of its real-time systems. The simulation system with flight hardware and the remotely augmented vehicle system is described. An overview of many hardware systems developed for the facility follows. The benefits of applying simulation to hardware-in-the-loop testing on the X-31A flight research program concludes the paper.

Nomenclature

ASCII	American Standard Code for Information Interchange
CAST	computer-aided system test
CIU	cockpit interface unit
CL	control law
HiMAT	highly maneuverable aircraft technology
ITF	Integrated Test Facility
NASA	National Aeronautics and Space Administration
PCM	pulse code modulation
RAV	remotely augmented vehicle
SES	simulation electric stick
SID	simulation interface device
STC	system test console
UMN	Universal Memory Network
Vac	volts, alternating current
Vdc	volts, direct current
VME	Versa-Module Eurocard

Introduction

The Integrated Test Facility (ITF), built at the NASA Dryden Flight Research Facility, provides new real-time test capabilities for emerging research aircraft. The ITF (fig. 1) will reduce flight test risk by minimizing the difference between the flight and ground test environments for advanced research aircraft.[1] Characterized by the integration of flight control, propulsion, structures, and aerodynamics, these aircraft rely on embedded digital control systems. Exhaustive ground testing of the embedded control systems is required to ensure aircraft safety and the efficient use of flight test missions. The ITF addresses the ground test needs of aircraft with integrated systems through the application of advanced real-time capabilities.[2]

Figure 2 shows a cutaway view of the ITF. The facility contains three separate test bay areas. This hangar space will accommodate six fighter-size or fewer larger-size aircraft. Each area can be configured to support classified projects. The research and test staff is located in the front section of the building. The aircraft technicians and maintenance staff are on the first floor of the central section. The second floor of the center section of the building houses the flight simulation systems, placing them in proximity to all six test bays. Proximity provides the short connection distances between the aircraft and simulation systems needed for closed-loop simulation with the flight vehicle.

Aircraft services, such as electrical power, hydraulic supplies, and cooling air, are provided to support aircraft-in-the-loop simulations. All aircraft services can be monitored in real time when performing tests with the aircraft.

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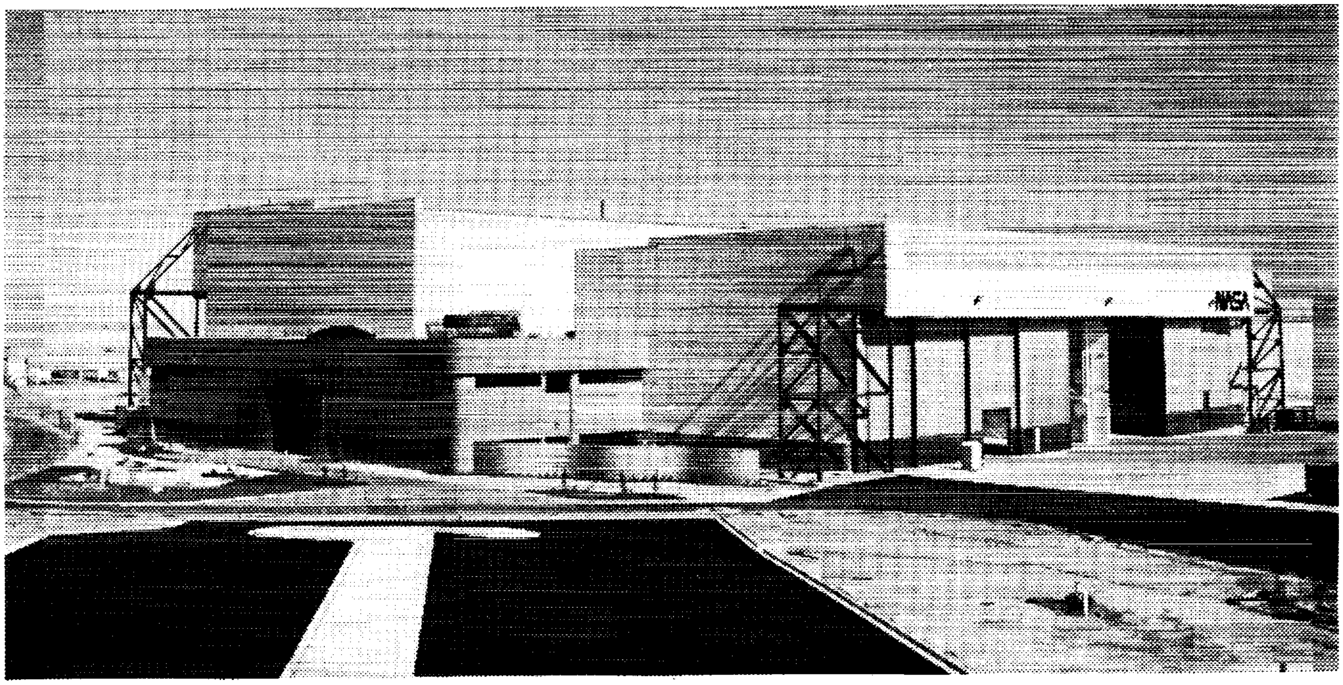

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Fig. 1 The Integrated Test Facility.

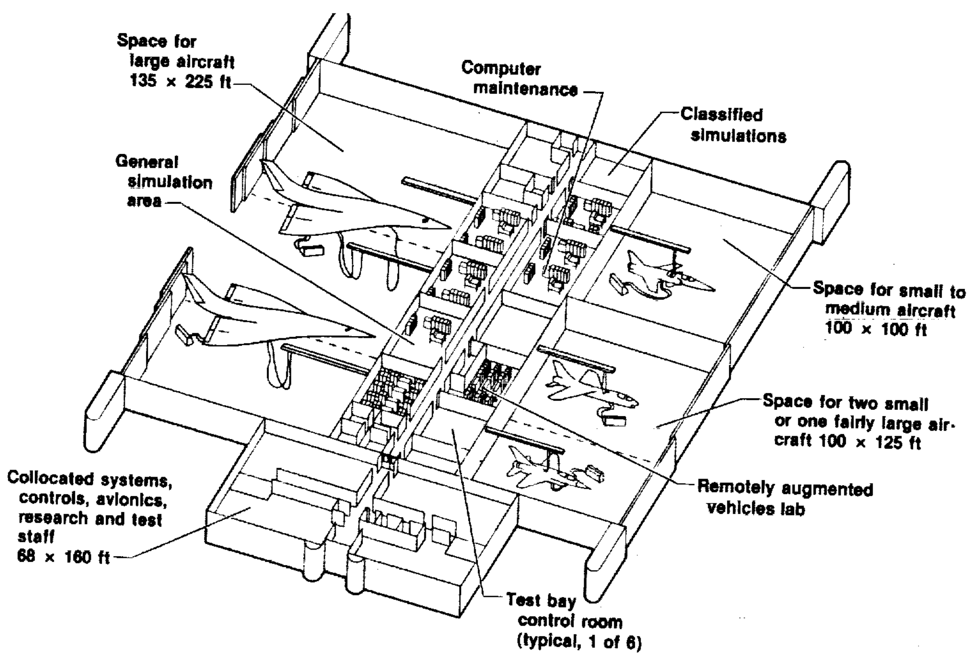

Fig. 2 Cutaway view of the Integrated Test Facility.

The electrical power includes 277/480 Vac and 120/208 Vac, three-phase, 60 Hz; 120/208 Vac, three-phase, 400 Hz; and 28 Vdc. The hydraulic systems for the six test bays are independent, allowing different pressures and fluids to be used. The initial hydraulic system has three pumps providing 35 gal/min at 5000 lb/in^2 pressure. The flow per pump can be increased to 50 gal/min at a pressure of 3500 lb/in^2. The aircraft cooling system provides each test bay with 4000 ft^3/min of airflow. Exit air temperature is 40 °F, provided through two 14-in. supply ducts.

This paper begins with a description of generic real-time capabilities of test systems, including simulation with flight hardware and remotely augmented vehicle capabilities. Next, support systems for real-time capabilities are examined, including those systems which support flight projects (real-time data recording and monitoring) and hardware support systems (simulation electric stick, simulation interface device, and cockpit interface unit). The final section before concluding remarks describes an application of the ITF real-time systems to the X-31A research aircraft.

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Generic Real-Time Capabilities of Test Systems

The simulation system is the core of the real-time capabilities; it provides high-fidelity modeling of the atmosphere, aircraft rigid body dynamics, and if required, the flight control system. All ITF simulation systems can be controlled by a computer-aided test system, allowing the test engineer to automatically run test cases from a computer workstation console. The remotely augmented vehicle (RAV) laboratory provides ground-based control of aircraft systems from the ITF.

Simulation With Flight Hardware

The simulation capability is an integral part of the ITF. Simulations are important engineering tools used through all phases of flight research.[3] The simulations are used to do various tests: time response, frequency response, redundancy management, failure modes and effects testing, and pilot evaluation. Proposed modifications are tested using the simulation in the ITF before installation on the aircraft.

To accommodate diverse projects, the ITF provides multiple simulation configurations with varying levels of aircraft hardware included. These configurations range from simple batch versions, which use only the computer and a user terminal, to complex aircraft-in-the-loop versions, which may use any of the actual flight systems including the entire aircraft. This diversity allows the project team to easily select the level of hardware needed to support test activities. The resulting flexibility permits quick comparisons between software models and flight hardware.

High-fidelity modeling of the aircraft and its systems is of key importance in the ITF. This high-fidelity modeling provides aircraft hardware with a realistic flight environment while remaining in ground test. The success of this modeling becomes increasingly important as aircraft systems become more integrated.

The simulation interfaces give users fingertip control of the simulation. The simulations can be controlled by buttons and switches in the cockpit or from a menu of display pages on an American Standard Code for Information Interchange (ASCII) terminal; or the entire control mechanism can be run from the computer-aided system test (CAST) workstations. The user generates simulation command files to automate the process of running tests. This approach uses a mouse-driven menu interface and eliminates the need to enter the simulation commands through the terminal.

Remotely Augmented Vehicles

The ITF provides RAV capabilities to enhance research missions by providing ground-based computers interfaced to the aircraft in flight through telemetry and radio uplinks.[4] These components allow the ground-based computers to provide closed-loop control of vehicles or to drive aircraft displays that aid the pilot in performing complex maneuvers.

The control law (CL) computer and the pulse code modulation (PCM) computer are ground based. The CL computer augments the aircraft onboard control systems and is programmed in a high-level language. It uses telemetry downlink data and software-coded control laws to generate aircraft commands. The PCM computer shares memory with the CL computer and is the interface with the aircraft telemetry stream. For data downlink operations, the PCM computer converts scaled integers used in the telemetry stream to engineering units used by the CL computer. These operations are reversed for data uplink.

A computer identical with the CL computer is paired with each simulation computer for verification and validation of the RAV ground-based software. The simulations interface to this computer in the same manner as the PCM computer. Timing relationships are preserved to model accurately the flight system. Figure 3 shows the relationship between the CL computer and the PCM computer in the RAV laboratory and in the simulation lab. The RAV configurations are divided

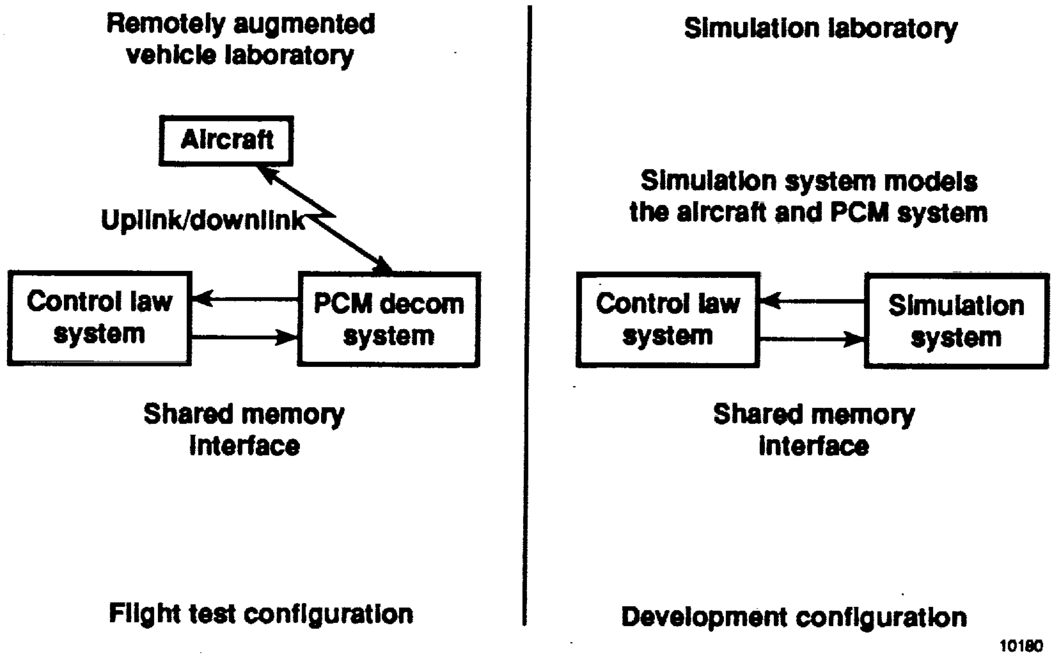


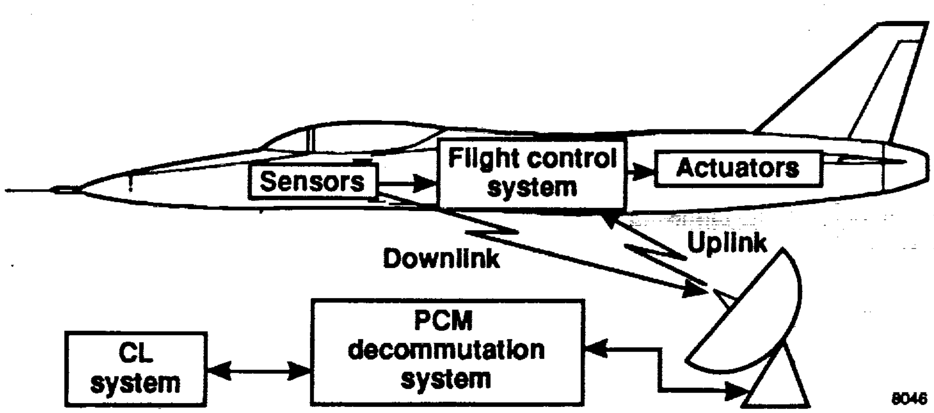
Fig. 3 Control law system configuration for flight and development.

into three categories as described below and shown in figure 4:

1. The RAVs use the ground computer to augment the aircraft onboard control system (fig. 4(a)). This capability can be used to test alternative control laws, to insert sophisticated autopilots to fly precise research maneuvers, or to generate pulses or frequency sweeps for data analysis. A pilot is on board the aircraft during these test procedures. Besides automatic safety systems, the RAV system may be easily disengaged at any time during flight by either the pilot or flight test engineer. The X-29A airplane is an example of a research aircraft currently using RAV operation.

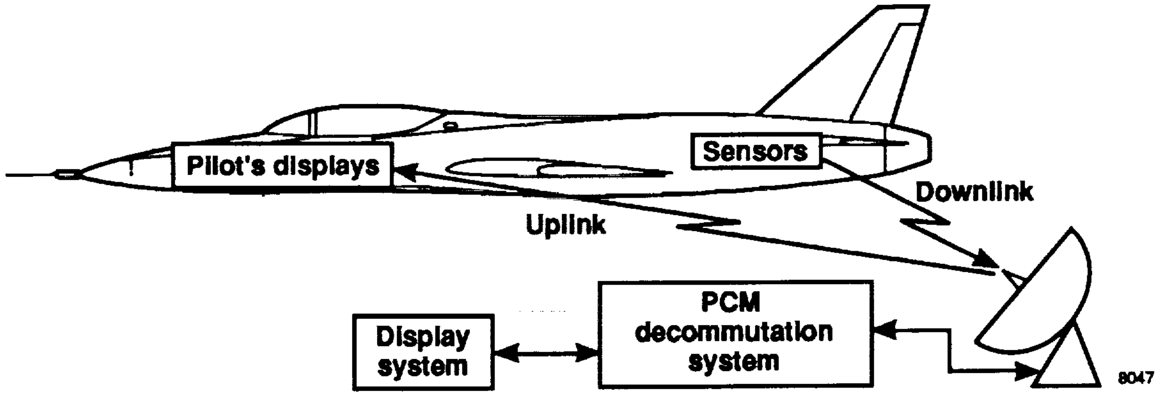
2. Remotely computed displays help to guide the pilot in flying a precise maneuver (fig. 4(b)). The CL computer uses downlinked data to calculate the fly-to signals sent to the aircraft display. This capability is used extensively by flight research projects.

3. Remotely piloted research vehicles are flown from a ground-based cockpit (fig. 4(c)). The vehicle control laws are coded in a high-level programming language and executed in the CL computer. Remotely piloted research vehicles that have been flown at NASA Dryden range from the subscale highly maneuverable aircraft technology (HiMAT)

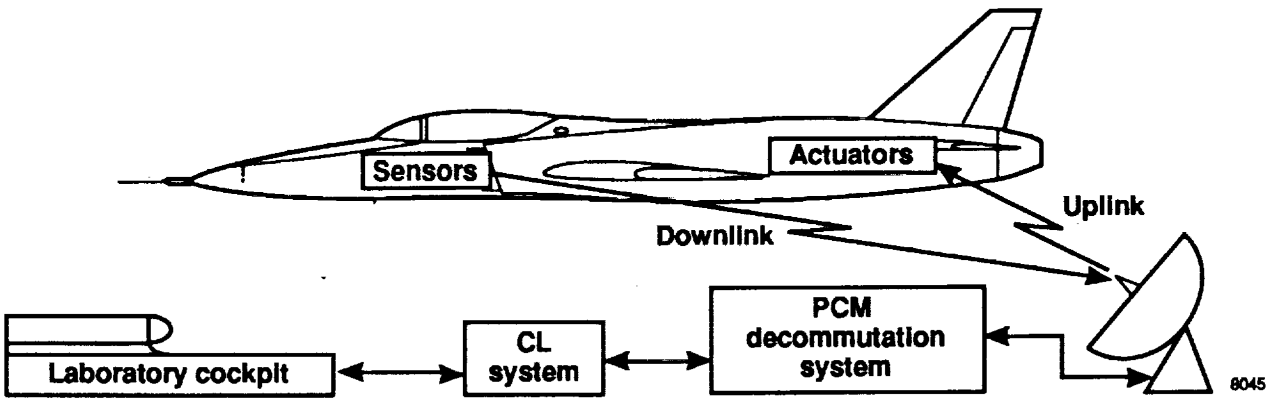


(a) Remotely augmented vehicle.

Fig. 4 RAV configurations.



(b) Remotely computed display.



(c) Remotely piloted vehicle.

Fig. 4 Concluded.

vehicles to the joint Federal Aviation Administration/NASA Controlled Impact Demonstration using a Boeing 720B (Boeing Company, Seattle, Washington).[5]

Support Systems for Real-Time Capabilities

The ITF real-time capabilities require various hardware and software systems to support project operations. The systems were developed to meet the needs of advanced research aircraft. They provide a simulation environment for pilot training, verifying and validating flight software, and mission planning. The following sections describe the design, capabilities, and implementation of some systems that make up the ITF real-time systems. These systems are classified as either flight-research project support systems or ITF hardware support systems.

Flight-Project Support Systems

The following sections describe the design and capabilities of some flight-project support equipment that was developed for the ITF. These systems provide the flight test engineer with capabilities to collect, display, analyze, and store data quickly and easily.

Real-Time Data Recording

Essential to any flight test environment is the ability to record all the data needed to verify the correct response to a test and to analyze anomalies. This is especially true when testing complex integrated digital systems. Such recording is perhaps the most demanding task faced by the ITF. When an anomaly occurred in the past, the detailed data needed to resolve the problem were often not recorded. The test would then be rerun with the proper instrumentation, but the anomaly often would not repeat itself. By recording all possible aircraft and simulation data during a run, the ability to resolve a problem without repeat runs is greatly increased.

The ITF real-time system records data from the simulation, the aircraft flight control analog interfaces and digital busses, the telemetry system, and the ITF services (hydraulics and electrical power). The data from these sources are supplied to the data recording system through an interprocessor communication link. This link connects the different computers at memory access speeds over long distances. The approximate quantity of data recorded for the F-18 High Alpha Research Vehicle research program is shown in the following table. The data recording system records up to 500,000 parameters/sec. These data sources are time tagged to provide exact correlation of events that occur at different data sources.

Source	Number of parameters	Rate, Hz	Samples/sec
Simulation	50	100	5,000
Aircraft			
flight control	300	100	30,000
Digital busses	1500	100	150,000
Telemetry	100	100	10,000
ITF services	20	10	200
Total	1970	N/A	195,200

The hardware implementation of the recording system currently consists of an Encore 32-67 (Encore Computer Corporation, Fort Lauderdale, Florida) mainframe computer with a large, high-speed, hard-disk array for storage of the recorded parameters. The Universal Memory Network™ (UMN) (Computer Sciences Corporation, El Segundo, California) provides the required, high-speed interprocessor communication link to and from the recording system.

The UMN provides the backbone of the real-time data communications among the various ITF computer systems. The UMN is a high-speed, reflective memory network that allows interprocessor communication at computer memory speeds. The unique architecture of this system interconnects a heterogeneous network of computer subsystems. These subsystems include the Encore 32-series, Sun Workstations®, IRIS™ workstations (Silicon Graphics, Inc., Mountain View, California), and Versa-Module Eurocard (VME) based real-time controllers. The controllers run OS-9/68000™ (Microware Systems Corp., Des Moines, Iowa) and VxWorks™ (Wind River Systems, Inc., Alameda, California) operating systems.

Real-Time Data Monitoring

The normal operating mode of a flight test project conducted in the ITF allows the flight test engineer to control an entire test from a workstation console. It is important for the engineer to observe the tests as they progress. The ITF real-time data monitoring system provides this capability.

The system allows the flight test engineer to select from available simulation and MIL-STD-1553B bus parameters and to monitor them in real time. The data are also recorded and may be plotted using a workstation console immediately following the test run. The test engineer gets immediate feedback of the results of the simulation or flight test. The data may then be stored, analyzed, and plotted to a PostScript® device for archival purposes.

The current implementation of the data monitoring system includes an Encore 32-series mainframe to collect and distribute data parameters through the UMN. Data are displayed using X Window System™ (Massachusetts Institute of Technology, Cambridge, Massachusetts) based programs running on various Unix workstations and X terminals.

Hardware Support Systems

The following sections describe the design and capabilities of some ITF hardware support equipment that has been developed. These systems provide some basic hardware platforms upon which the various ITF test systems are built. They provide aircraft hardware connections and the human interface to the equipment. This equipment supports the operations of pilot training, system evaluation, and system test operations.

Simulation Electric Stick

Piloted simulations that support the flight research projects are an important tool for mission planning and pilot training. To provide an accurate representation of the cockpit in a ground test, NASA has developed the simulation electric stick (SES). This device simulates the dynamic characteristics of the control stick of the aircraft and gives the pilot proper tactile feedback.

The SES operation is under the direct control of the host simulation computer. The forces on the stick, including apparent force, stick mass, force gradient, force breakout, force balance, damping, stops, trim rate, and trim limits are all directly controlled from the simulation. Data on stick position, velocity, acceleration, trim position, deflection from trim, force out, and various switch positions are transmitted to the simulation computer.

The SES uses electric motors operating on 110 Vac instead of hydraulics to provide the forces on the stick. This design provides a more simple, compact, and cleaner system than a hydraulic design would provide. The design approach increases system reliability and greatly reduces maintenance requirements.

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Each axis motor is directly controlled using signals provided by the simulation computer. An analog control circuit implements a force feedback loop to provide the individual motor control signals. This analog control circuit may be replaced using a model-follower feedback loop to provide different stick characteristics.

The SES system circuitry monitors for error conditions and shuts down its stick motion operations when any error conditions occur. Some of these conditions are internal hardware failures, excessive thermal conditions, improper stick movements, and erroneous simulation motion commands.

The SES analog circuitry is controlled by a VME-based system. The system connects to the simulation computer using a high-speed digital interface that performs all data communications. It performs all required data preprocessing for the SES and uses the native data storage format of the host simulation computer, reducing the host computation overhead costs.

Simulation Interface Device

A unique capability of the ITF simulation systems is the integration of different types of aircraft flight hardware, including actual aircraft, into the simulation and test system environment. To interface flight hardware with the simulation systems requires many signals with a variety of signal types. Some flight and simulation hardware is unique in its design, and it may be difficult or impossible to replace failed components. A safe and flexible simulation interface is required to provide a mechanism for test and evaluation and to protect the aircraft equipment and the simulation computer equipment from hardware failures or human operator errors. The simulation interface device (SID) provides this interface capability.

The SID contains the necessary, protected, real-time data connections between the flight hardware and the simulation computers. It provides electrical protection for both the aircraft hardware and the simulation computers using electrical isolation. Figure 5 shows an example installation of the SID.

The SID enables the flight test engineer to perform the following functions in real time on the aircraft hardware under test:

- Passive signal monitoring
- Active signal insertion
- Signal error insertion
- Signal failure insertion

The SID uses both passive and active analog electrical components to provide interface and protection capability. The protection capability uses a combination of optical isolation and thermal-sensitive resistance.

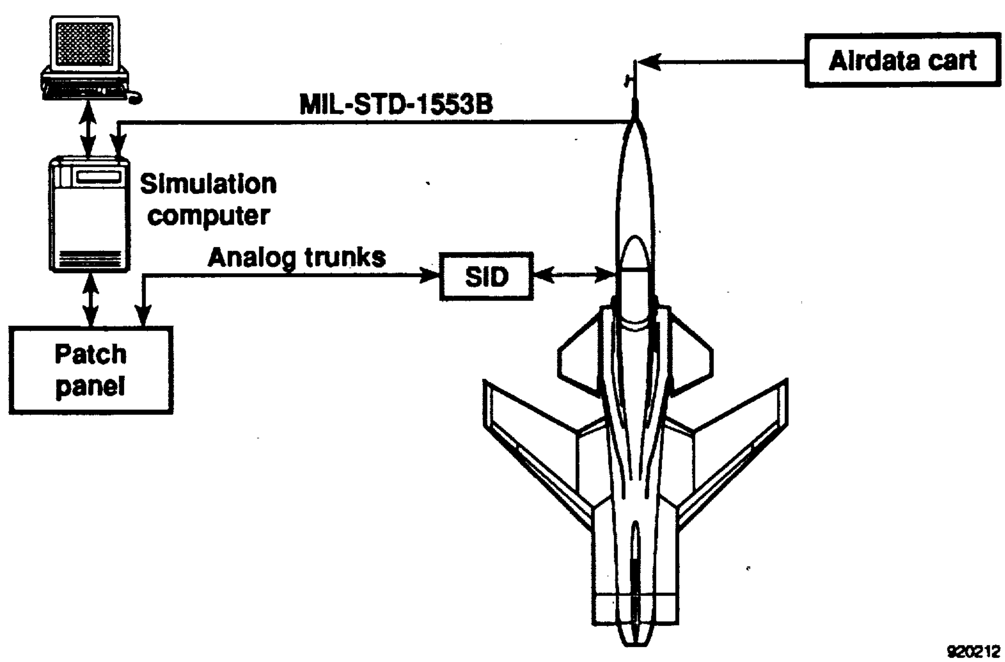

Fig. 5 X-29A aircraft-in-the-loop using a SID.

Cockpit Interface Unit

The variety of flight research simulations supported in the ITF requires many types of cockpit equipment for the project simulations. The cockpit equipment includes several types of analog instrumentation, switches, lamps, real-time digital data busses, and simulation computer hardware. Various data storage formats are also required. A partial list of the required data formats includes 1's complement binary, 2's complement binary, single- and double-precision IEEE-754 floating point, single- and double-precision excess-64 floating point, and packed and unpacked discretes.

The cockpit interface unit (CIU) provides a flexible digital input-output front-end processor between the simulation computers and cockpit instrumentation hardware. It also powers all cockpit instrumentation. The primary CIU task performs all cockpit data collection and preprocessing tasks for the host simulation computer. All data are transferred in the native data storage format of the simulation computer. This eliminates the need for the simulation computer to preprocess data and increases the time available for simulation modeling.

The CIU is a VME-based system with associated input-output processing and is assembled from many off-the-shelf boards. Data are passed to and from the simulation computer using a high-speed, real-time data communication link. The cockpit data are converted to and from the required voltage levels off-line from the simulation host computer.

Figure 6 shows a typical CIU installation. The CIU currently supports host computers including the Encore 32-series mainframes, IBM® RS/6000 series™ workstations, Sun SPARC® series workstations, and IRIS workstations. Supported host communication links include MIL-STD-1553B, UMN, SBus™ (Sun Microsystems), SCRAM-Net™ (Systran Corporation, Dayton, Ohio), and EtherNet®. Supported input-output signals include ±10-V linear analog channels, sine-cosine channels, synchro channels, transistor-transistor logic level input-output discretes, 28-V lamps, and 28-V switches. Additional support for other signal requirements is possible through simple in-house system upgrades.

Example Application to a Flight Project

The most recent project using the ITF is the X-31A enhanced fighter maneuverability research program. The X-31A project support team includes members from

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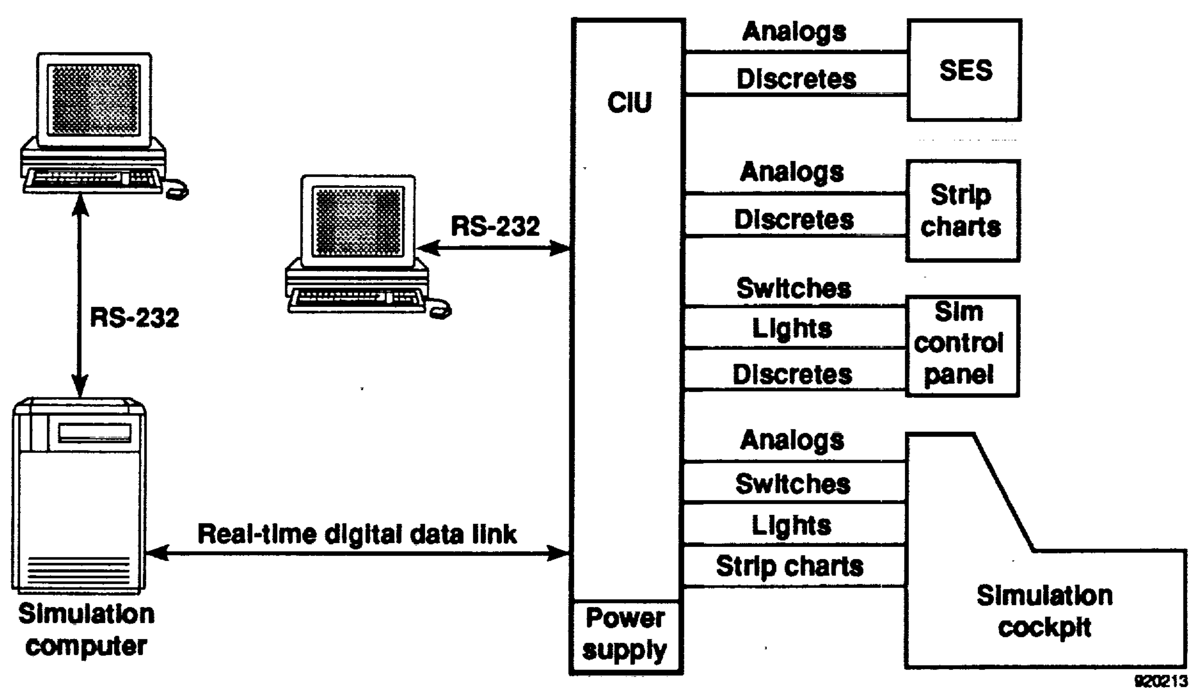

Fig. 6 Typical CIU installation in simulation.

NASA Dryden, U.S. Air Force, U.S. Navy, German government, Rockwell International Corporation, and Messerschmitt-Bolkow-Blohm.

The following sections describe how real-time systems were applied to the X-31A program. The first section describes the simulation requirements for the X-31A; the second section describes how various ITF systems supported the program.

Simulation Requirements

The X-31A simulation requirements include those to support project requirements, such as flight control software verification and validation using a flight control system hardware-in-the-loop simulation configuration. The project requires that the simulation support pilot training, planning of flight test points, and engineering analysis for various disciplines. The simulation requirements that satisfy these fall into three main areas: cockpit layout, simulation model fidelity, and visual displays.

Flight control verification and validation require batch, real-time all-digital, and hardware-in-the-loop simulations. Hardware-in-the-loop simulation requires real-time, low-latency interfaces with the flight control system computers to ensure the stability and control responses with the simulation match the responses of the aircraft in flight.

Simulation Design Approach

The X-31A simulation system was rapidly developed using the ITF support systems described in a previous section.[6] Using the system components previously developed to support other projects and adapting them to the unique requirements of the X-31A simulation reduced the development time to a 9-month schedule. Figure 7 shows the X-31A hardware-in-the-loop system implementation, which consists of seven key elements:

- A simulation host computer
- A simulation cockpit
- A simulation electric stick
- A cockpit interface unit
- A real-time data recording system

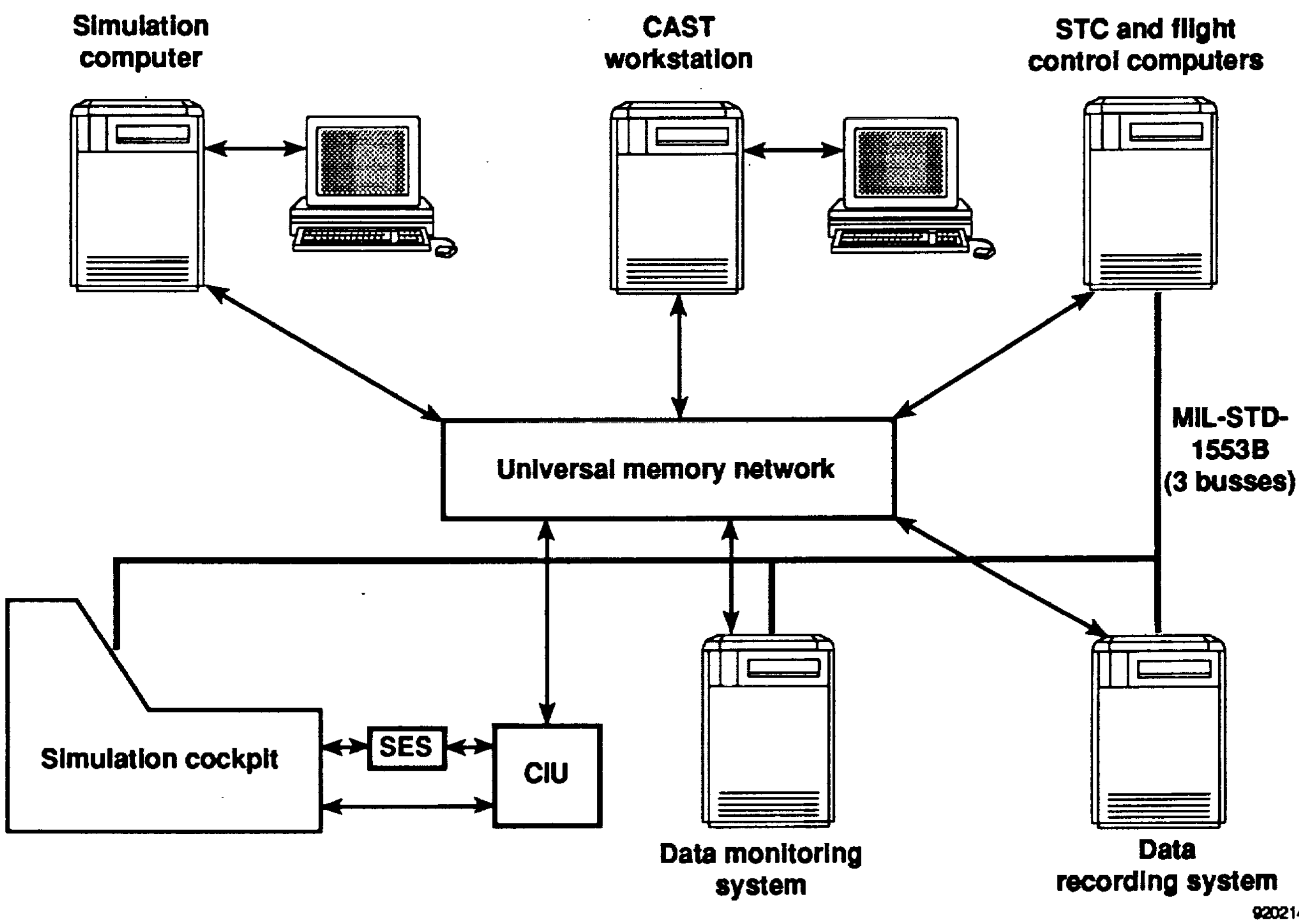

Fig. 7 X-31A simulation hardware architecture.

- A real-time data monitoring system
- Aircraft flight hardware

The architecture for the X-31A simulation is based on a distributed set of high-performance Unix workstations and VME systems connected through shared memory. The simulation and visual system computers are Silicon Graphics Power Series 4D-440 computers with the VGX graphics options. The host simulation computer runs the real-time X-31A simulation software at 100 Hz. Flight visuals include out-the-window scenes for takeoffs and landings, a simulated heads-up display, and a special three-dimensional model for visualizing high-angle-of-attack maneuvers.

The aircraft flight hardware in this system can be interfaced with using the X-31A system test console provided by Rockwell International. The console provides all analog and digital interfaces to the flight control system hardware and uses the UMN to interface with the ITF simulation system.

Concluding Remarks

The Integrated Test Facility at NASA Dryden provides capabilities that are crucial to the next generation of flight research aircraft. Routinely interfacing aircraft with facility systems will reduce the risk posed by actual flight test by creating the flight test environment on the ground. The simulation systems have provided the X-31A project engineers with the capabilities to perform flight tests with a high degree of confidence, and have reduced the simulation time required before a flight. The Integrated Test Facility brings to the flight test community the capabilities needed to maintain a leading role in aeronautics and to provide safe, efficient flight testing.

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