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ADVANCED AVIONICS LABORATORIES

Space Transportation Avionics Technology Symposium
Systems Engineering and Integration
Advanced Avionics Laboratories

Introduction

The simulation, development, and verification of advanced avionics systems for launch vehicles have become increasingly complex and expensive tasks. In the past, launch vehicle manufacturers, subsystem vendors, and customers have independently developed specialized laboratories to support their individual needs. This independent development has resulted in duplication of facilities, equipment, software, and labor, and also has resulted in hardware and software incompatibilities between facilities. As our avionics systems move into the 1990's, the laboratory environments in which they are developed must keep pace with technology while also contributing to system cost reductions. A method for accomplishing these seemingly contradictory goals of flexibility and cost reduction is to implement the following Advanced Avionics Laboratory concepts:

- allow support of differing configurations of avionics for one program or multiple programs at a single laboratory facility
- standardize concepts of operation and interfaces used in laboratories of this type so that hardware, software, and results are compatible and may be shared and compared between labs
- provide a suitable proving ground for potentially cost-saving advanced avionics concepts such as Fault Tolerance, Integrated Vehicle Health Monitoring, and Adaptive Guidance, Navigation, and Control

A capsule description of these concepts for Advanced Avionics Laboratories was presented at the NASA Space Transportation Avionics Technology Symposium (STATS) in Williamsburg, VA on November 7-9, 1989. Representatives from each of the major NASA centers and the major aerospace contractors were in attendance, resulting in an unusual opportunity for interchange on current capabilities and needs for the future.

This white paper will describe the presentation on Advanced Avionics Labs at STATS, present the salient points of the ensuing discussion between attendees, and then focus on the necessary areas of concentration in developing the requirements for laboratories which will implement the advanced concepts described above.

STATS Presentation

The STATS presentation on Advanced Avionics Laboratories was produced with the assistance of the subpanel members and presented in a quad chart format (Figures 1 & 2). The subpanel members contributing to the generation of these charts were: Bud Gates and David Hudson of Martin Marietta, Don Johnson of Boeing, Fred Kuenzel of General Dynamics, and Ron White of NASA-Marshall Space Flight Center. The purpose of this presentation was to identify the current state-of-the-art in Avionics Laboratories and the direction that future Laboratory development should take to support the major NASA Space Transportation programs.

The primary objective of Advanced Avionics Laboratory development as identified in the presentation is to provide a "proving ground" for emerging avionics technologies such as: Fault Tolerance; Adaptive Guidance, Navigation, and Control; and Integrated Vehicle Health Monitoring. In meeting this main objective, other important considerations for new laboratories are to reduce development, validation, and verification costs, to encourage resource and data sharing between programs, and to use flexible design and interface techniques to allow for future growth and technology improvements. One method identified for accomplishing these objectives is to implement a "common core" laboratory concept where a central core area with high-cost items may be shared between a number of separate program development activities. Each program would have its own separate development area adjacent to the central core. The equipment identified for the common area might include precision inertial guidance test equipment, optical test and development equipment, and graphic display equipment for real-time presentations to large groups. The program-specific areas would contain items such as software and hardware development workstations, "hot-bench" areas suitable for standalone static subsystem testing, and flexible microprocessor-based interface electronics to connect to the core area for real-time operations. Standard networking tools such as Ethernet, TCP/IP, NFS, X-Windows, etc. would be implemented for non-time-critical data transmission between lab areas.

A number of technology issues were identified as important to the development of these multi-purpose laboratories including:

- trade-offs between real-time, hardware-in-the-loop capabilities and non-real-time, all software simulations
- development of database technologies to allow data sharing across programs

- providing commonality between the modeling/analysis environment and the real-time simulation environment
- defining hardware and software appropriate for common areas vs. program-specific areas
- providing standalone as well as integrated testing capabilities
- providing easy reconfiguration capabilities to support varying hardware and software requirements

Candidate programs identified as potentially benefitting from Advanced Avionics Laboratories were virtually all major NASA programs including ALS (Advanced Launch System), existing Expendable Launch Vehicle Upgrade Programs, Space Shuttle, Shuttle-C, National Aerospace Plane, Advanced Upper Stages such as the Space Transfer Vehicle, Spacecraft programs including the Advanced X-Ray Astronomic Facility, and the Lunar/Mars Initiative.

A number of past, present, and future milestones in Avionics Laboratory development were identified including the AIPS (Advanced Information Processing System) demos at C.S. Draper Laboratory through October 1989, planned MPRAS (Multi-Path Redundant Avionics Suite) demos in 1990-92, and the ALS Vehicle Avionics Simulation Laboratory at NASA/Marshall planned for 1991.

STATS Discussions

Following the Quad Chart presentation, a spirited fifteen-minute discussion ensued in which the major points of the presentation were debated and amplified. A major point was made and re-emphasized that a common laboratory design was needed among the NASA centers and the contractors in order to improve communication, data sharing, and the validity of comparisons between sites. Currently, isolation of effort between the centers is the norm because of a lack of standardization. This isolation results in duplication of effort and wasted time and talents. It was stated that avionics laboratories are needed most during the development and system integration phases and serious operational problems can arise when attempting to use labs for both development and operations such as validation and verification. Concern was expressed that the common core idea is good in theory, but in reality each program manager will want his own lab dedicated entirely to his program. Cultural changes and efficient design will be necessary in order to ease this concern. One point made repeatedly was that the feasibility of the common laboratory design concept is highly dependent on the development of common software interfaces and models, a difficult technical issue. This issue is particularly a problem with regard to applying standards to programs currently underway such as the Space Shuttle and Space Station. One attendee questioned the value of designing a lab to accommodate future technology advancements if existing technology works and is efficient. The primary thrust of the discussion was that Advanced Avionics Laboratories will be a critical part of the development of avionics for future NASA programs and vehicles and that major changes in the current methods of lab development will be necessary to meet future demands.

Summary of STATS Activity

On the day following the Quad Chart presentations for each subtopic, a summary session was held for the Systems Engineering and Integration subpanel to determine the most useful products of the previous day's discussions. For the Advanced Avionics Laboratories subtopic, it was generally agreed that new, multi-purpose labs providing common hardware and software interfaces will be needed at each NASA avionics center and at each involved contractor. These physically distributed facilities could be connected logically to form a "National Avionics Test Facility" similar to the National Test Bed under development for the Strategic Defense Initiative. Security considerations would be extremely important for such a project but are considered manageable. In order to implement the National Avionics Test Facility, the source of funding would have to be NASA-wide rather than from any one program.

Numerous discussions between participants also took place outside the formal STATS framework regarding Advanced Avionics Laboratories. A number of participants indicated that commonality of operating environments between design, analysis, and lab simulations is highly desirable. Ideally, a flight controls analyst should be able to sit at a workstation, develop a flight control algorithm, run a software simulation against a realistic vehicle model, and then run an actual hardware-in-the-loop simulation for verification without having to change his operating environment for each phase of the process. This type of commonality could greatly reduce time spent and risk incurred due to interchange between groups of analysts, engineers, and programmers all working on different computing platforms and in different environments. Although there is no currently available single operating environment which can encompass all disciplines efficiently, workstation technology is advancing at such a pace that this goal may soon be achievable. The key to implementation of this goal is ensuring that hardware and software interfaces are well-defined and where flight hardware is in the simulation loop the time constraints incurred are not violated.

Although Advanced Avionics Laboratories was a separate subtopic at the Symposium, there were also discussions concerning advanced laboratories during many of the other subtopic presentations. In these other areas the common thread was that advanced laboratory environments are necessary in order to develop and prove advanced avionics concepts. Examples include the Advanced Processors, Advanced Displays and Controls, and Low Cost Avionics subtopics. This widespread recognition of the need for these labs emphasizes the importance of the Advanced Avionics Laboratories concepts previously discussed.

Requirements for Multi-Purpose Laboratories

Cost reduction is the primary factor driving the need for a laboratory supporting multiple avionics development efforts. The high-performance simulation and development environments needed to support state-of-the-art avionics mandate large investments in facilities and high-fidelity test equipment. Development of a "Common Area" housing these high-cost items and sharing these items wherever possible between development efforts can result in tremendous savings.

When considering the concept of a laboratory to be used for multiple development activities, certain trade-offs must be made in order to determine the functions best suited for a common area. One of these trade-offs involves determining when dynamic simulations with flight or breadboard hardware in the loop are appropriate. Certain operations will require hardware-in-the-loop for fidelity during simulations, particularly inertial measurement unit and optical sensor calibration, characterization, and evaluation operations. In order to provide a high-fidelity test environment for these systems, a seismically stable environment must be provided, generally implemented using massive concrete piers isolated from the laboratory structure. To provide a dynamic, flight-like environment for the sensors, a three-axis inertial test table is required. Coordinating table movement profiles with the sensor data in real time during simulations requires a real-time oriented processor with fast input/output capabilities. All of these items are quite expensive and large savings can be realized by providing the proper interfacing to allow multiple programs to use them on a time-sharing basis. Other operations such as standalone subsystem testing and fully software based simulations are more user-specific and require smaller investments in equipment and facilities. These program-specific areas could be located adjacent to the common core and contain flexible microprocessor-based interface electronics to tie them in to the hardware under test in the core. High-cost items necessary for modeling, characterization, and hardware-in-the-loop simulation of avionics components include:

- Seismically quiet environments for IMU evaluation and testing
- Three-axis inertial test tables and indexing heads for IMU evaluation and testing
- Real-time hardware-in-the-loop oriented simulation host computers
- Graphic display systems to aid data interpretation
- Optical testing environments for star trackers, star scanners, etc.
- Analysis equipment including spectrum analyzers, signal analyzers, etc.

Each of these items could be candidates for location in a central core area accessible on a time-sharing basis to multiple development efforts. The use of a common core labor force able to support hardware-in-the-loop simulations for multiple programs can also result in large labor savings. To date, the tasks of configuring a simulation system for real-time runs, managing databases, operating the system, and acquiring and reducing data have required large staffs, duplicated for each laboratory. Advances in technology will allow reductions in the size of this labor force, and a common area implementation will allow sharing of the labor cost between programs. An example of a laboratory configuration which could support multiple development efforts is shown in Figure 3.

Benefits From Commonality

Another factor supporting the development of multi-purpose laboratories is the potential benefit from sharing data between related avionics development efforts. Typically, avionics laboratories produce tremendous quantities of raw data from simulation, and use a large number of personnel to reduce that data and draw results. Providing the data and results in a form usable by multiple development activities can also result in less duplicated effort. The key component necessary to allow this data sharing activity is commonality of software models, databases, and operating environments. In addition, common data transfer formats and media between facilities must be provided to permit timely data transfers between geographically separated laboratories.

The real-time control and simulation requirements for particular programs and particular disciplines within programs may vary greatly with regard to the hardware interfaces to flight-type equipment. For example, a simulation laboratory for an advanced expendable launch vehicle may require relatively slow loop rates in the 10-100 Hz range for vehicle guidance and control functions, but may require rates of 100-1000 Hz for high-speed engine control and monitor functions. A flexible, expandable real-time interfacing architecture is a must for an advanced, multi-purpose avionics laboratory. The real-time operating environment should be standardized across geographically separate laboratories to maximize the validity of data sharing and comparisons between sites.

Flexibility and Expandability

In order to provide maximum flexibility and minimize costs due to interface incompatibilities, standard hardware and software should be used wherever possible. Examples of current standards which may be applicable to the Advanced Avionics Laboratory architecture include FDDI, Ethernet, NFS, and TCPIP for networking, X-Windows and PHIGS for graphics software, UNIX for workstation operating systems, Ada for software development, VMEBus, Multibus, and Futurebus for microcomputer backplanes, and the Mil-Std-1553B avionics bus.

The hardware and software architecture must be modularized to the greatest extent possible to provide expandability and adaptation to future changes in requirements. The central host computer, graphics workstations, and interface electronics must all have a modular design in order to accommodate anticipated changes in requirements for the number and types of processors, number and types of hardware interfaces, Input/Output bandwidth and communications bandwidth. To provide true flexibility of operations, each program's facility and the subsystems within must be able to operate independently of the others. To meet this goal, each facility must contain a certain amount of development capability as well as the operational interfaces to connect it to the Common Core Area. The software architecture for the labs must also be modularized with the goal of providing rapid prototyping capabilities. Easy transitions from software simulations to simulations with various configurations of flight-type hardware will greatly enhance the efficiency and productivity of the laboratory.

Special Considerations

Certain special considerations are necessary when defining the electronics for a real-time simulation facility which will contain hardware in the control loops and will be used to support multiple development efforts. These special considerations have a great deal of impact on the overall system architecture, particularly with regard to inter-computer communications and connections from computer-based controllers to simulated flight hardware, breadboards or actual flight articles.

Software-Based Simulations

Full software simulations of complex electromechanical control systems are possible using the quickly evolving high speed families of desktop workstations. These stations can perform extremely high definition simulations and have become the workhorses for Computer Assisted Design/Computer Assisted Engineering (CAD/CAE) applications. The operating system of choice on most high performance workstations is UNIX, providing a high degree of portability for applications. UNIX is flexible, powerful, and capable of handling the most difficult simulation problems. The drawback to using a UNIX-based engine for simulation is its inability to operate in real-time and control actual hardware. This however is generally not a problem during the initial system, component, and algorithm development stages. High definition graphics output, coupled with the workstations' power to solve complex math-intensive problems, allows the control systems designer to see the results of changing control algorithms, plant dynamics, and other control critical parameters without having to deal with cumbersome pieces of hardware and test equipment.

Hardware-In-The-Loop

When simulations are performed completely in software without hardware stimulation and response, synchronization of the various parts of the simulation is not a time-critical concern and the phase relationship between various operations may be controlled with relative ease. The introduction of hardware into a control system simulator brings with it a whole new family of problems. Hardware-in-the-loop simulations are generally time and phase critical and must be closely synchronized to the digital control processors used to close the loops. Deterministic control algorithms must be designed to insure that timing errors such as control frame overruns can not occur. The hardware must be designed to minimize latency of responses to external events and to insure that no undefined timing jitter will be added by the interfaces. Any timing uncertainties induced by algorithms or hardware will result in undesirable phase errors and time aliasing creeping into the control loops. These types of errors will result in the inability to time correlate multiple control loops and will cause unreliable test results and output data.

Embedded Controllers

The design of true real-time control system hardware requires the design of dedicated interface electronics with embedded microprocessor controllers. These dedicated interfaces provide the wide I/O bandwidths and high-speed mathematics necessary to close robust precision servo loops. Hardware-In-The-Loop Simulations require very high bandwidth local control loops to ensure sufficient phase margins for an unconditionally stable system. These types of local loops generally require embedded controllers running at control loop frequencies 10 to 100 times faster than the host computer loop frequencies. The embedded controllers are typically responsible for the mathematics required to compensate local control loops, such as State Variable Control and Proportional, Integrator, Differentiator (PID) types of compensators. Wide bandwidth dedicated buses are used to ensure that data is always available to the processors and to the actuators at the same time in each frame. This guarantees that there will be no timing inconsistencies to cause loop overrun errors or time aliasing. Fast interprocessor communications are required for concurrent algorithm processing. Intermediate control variables to be passed from controller to controller or to the data logger interface are passed on this type of interface.

Analog Interfaces

In order to provide extremely accurate and reliable control of sensor and actuator interfaces, precise and noise-free analog interfaces must be implemented. To provide the maximum noise immunity for analog signals, a low impedance balanced differential signal path must be used and the physical distance between drivers and receivers must be minimized. When these guidelines are followed, accuracies of up to 15 bits during D/A and A/D conversions may be attained. This level of accuracy will allow precise control of actuators and minimize jitter due to quantization noise. The sampling and command rates for all servo hardware must be completely synchronous and phase-locked. A flexible scheme of distributing a hardware synchronization pulse to the remote analog and digital data acquisition electronics and the controlling computer systems must be implemented. The hardware synchronization system should be capable of providing phase-locked synchronization pulses throughout the system at frequencies varying from 10 Hz to 10 KHz. Where possible, sensors should be sampled at a rate ten times the command frequency in order to maximize the phase margin for each control loop. Anti-aliasing filters must be implemented for each sensor input and data smoothing filters for each actuator output to eliminate aliasing errors and undesired high-frequency signal components. Power for the hardware under test should be isolated as much as possible from the electrically noisy computer environment in order to provide maximum noise immunity. This may be accomplished by means of fiber optic data links and opto-isolators at critical interfaces. As stated above, distribution of analog signals should be by means of differential amplifiers and receivers wherever possible.

Host Computer

Typically, a real-time simulation laboratory will require the use of a modern high speed, multiple processor, concurrent algorithm computer. This computer will handle the high level mathematics, simulation control, and man-machine interfaces for the entire laboratory complex. The real-time frame rate for the host machine will generally be from 10 to 100 times slower than the rate for the the local control processors. The host will be required to handle most of the mathematics associated with the equations of motion and will be required to solve math intensive problems including rigid and flexible body mechanics. The host computer must be capable of very wide I/O and interprocessor backplane bandwidths. Data must be passed to and from local control processors quickly in order to avoid an adverse impact on the processing time available to the local controllers. Data and intermediate control variables must also be passed between CPUs inside of the host computer system to allow for interaction between concurrently operating servos and algorithms.

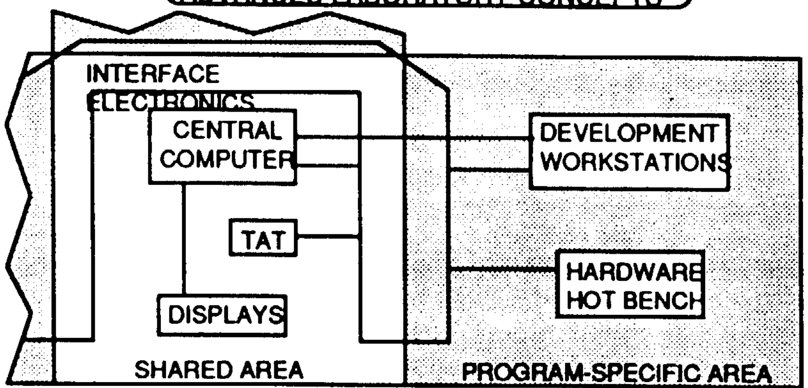
Summary

In order to develop the new generation of avionics which will be necessary for upcoming programs such as the Lunar/Mars Initiative, Advanced Launch System, and the National Aerospace Plane, new Advanced Avionics Laboratories are required. To minimize costs and maximize benefits, these laboratories should be capable of supporting multiple avionics development efforts at a single location, and should be of a common design to support and encourage data sharing. Recent technological advances provide the capability of letting the designer or analyst perform simulations and testing in an environment similar to his engineering environment and these features should be incorporated into the new laboratories. Existing and emerging hardware and software standards must be incorporated wherever possible to provide additional cost savings and compatibility. Special care must be taken to design the laboratories such that real-time hardware-in-the-loop performance is not sacrificed in the pursuit of these goals. A special program-independent funding source should be identified for the development of Advanced Avionics Laboratories as resources supporting a wide range of upcoming NASA programs.

SPACE TRANSPORTATION AVIONICS TECHNOLOGY SYMPOSIUM
SYSTEMS ENGINEERING AND INTEGRATION
ADVANCED AVIONICS LABORATORIES
FIGURE 1

NOVEMBER 1989

ADVANCED LABORATORY CONCEPTS



SHARED AREA
- IMU Cal, test, and eval
- HWIL Simulation
- Data acquisition, logging, and display

PROGRAM-SPECIFIC AREA
- Software development
- Subsystem development and simulation
- "Hot Bench"

MAJOR OBJECTIVES

- Provide a proving ground for advanced avionics concepts (Fault Tolerance, AGN&C, advanced sensors, integrated VHM)
- Reduce development and V&V costs via:
  - common hardware and facilities
  - commonality of software models and database structures
  - reduced manpower requirements for operational support
  - more efficient operations
- Provide a common development environment to encourage data sharing between programs
- Provide growth path for adaptation to new technologies

KEY CONTACTS AND FACILITIES

Contacts
Chuck Meissner, Felix Pitts/LaRC
Ken Cox/JSC
Ray Bortner/WRDC
Whit Brantley, Ron White/MSFC
Don Johnson/Boeing
Fred Kuenzel/GD
Crane Simmons/MDAC
Bud Gates/MMAG
Leon Shockley/RIC
Jay Lala/CSDL

Government Facilities
AIRLAB - LaRC
WRDC labs
MSFC labs - APC, SSME lab
JSC labs - SAIL

Contractor Facilities
ELV Labs at MMAG, GD, MDAC
Shuttle labs at RIC
Boeing System Integration Labs
CSDL Labs

MAJOR MILESTONES

- AIPS demos at CSDL - Oct 89
- MPRAS Demos
  - Key Concepts Mar 90
  - Subsystems Jul 91
  - Full Architecture May 92
- Shuttle-C Avionics Lab (MSFC)
  - S/W only capability Aug 90
- ALS Vehicle Avionics Simulation Laboratory (MSFC)
  - IOC Oct 91
  - Operational Aug 93

SPACE TRANSPORTATION AVIONICS TECHNOLOGY SYMPOSIUM
SYSTEMS ENGINEERING AND INTEGRATION
ADVANCED AVIONICS LABORATORIES
FIGURE 2

NOVEMBER 1989

TECHNOLOGY ISSUES

- Cultural changes necessary for acceptance of advanced avionics concepts
- Real-time hardware-in-the-loop simulation vs. all software approach
- Common database technology for multiple programs
- Providing easy transition from modeling/analysis environment to HWIL simulations
- Defining hardware and software appropriate for common areas
- Providing standalone as well as integrated testing
- Ease of reconfigurability

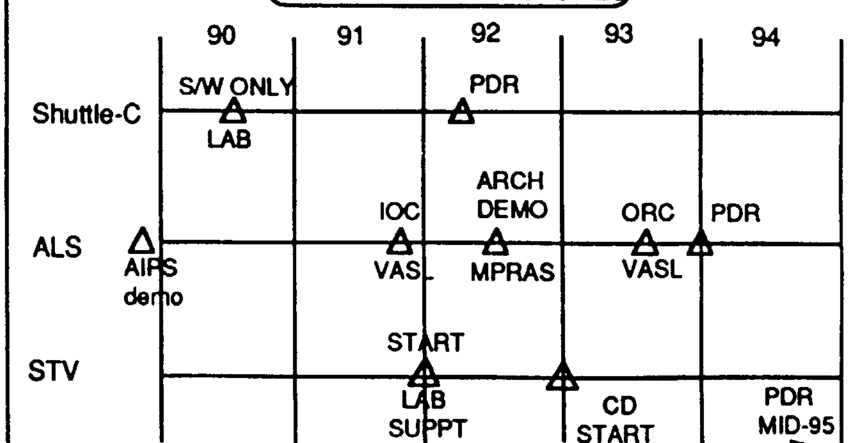
CANDIDATE PROGRAMS

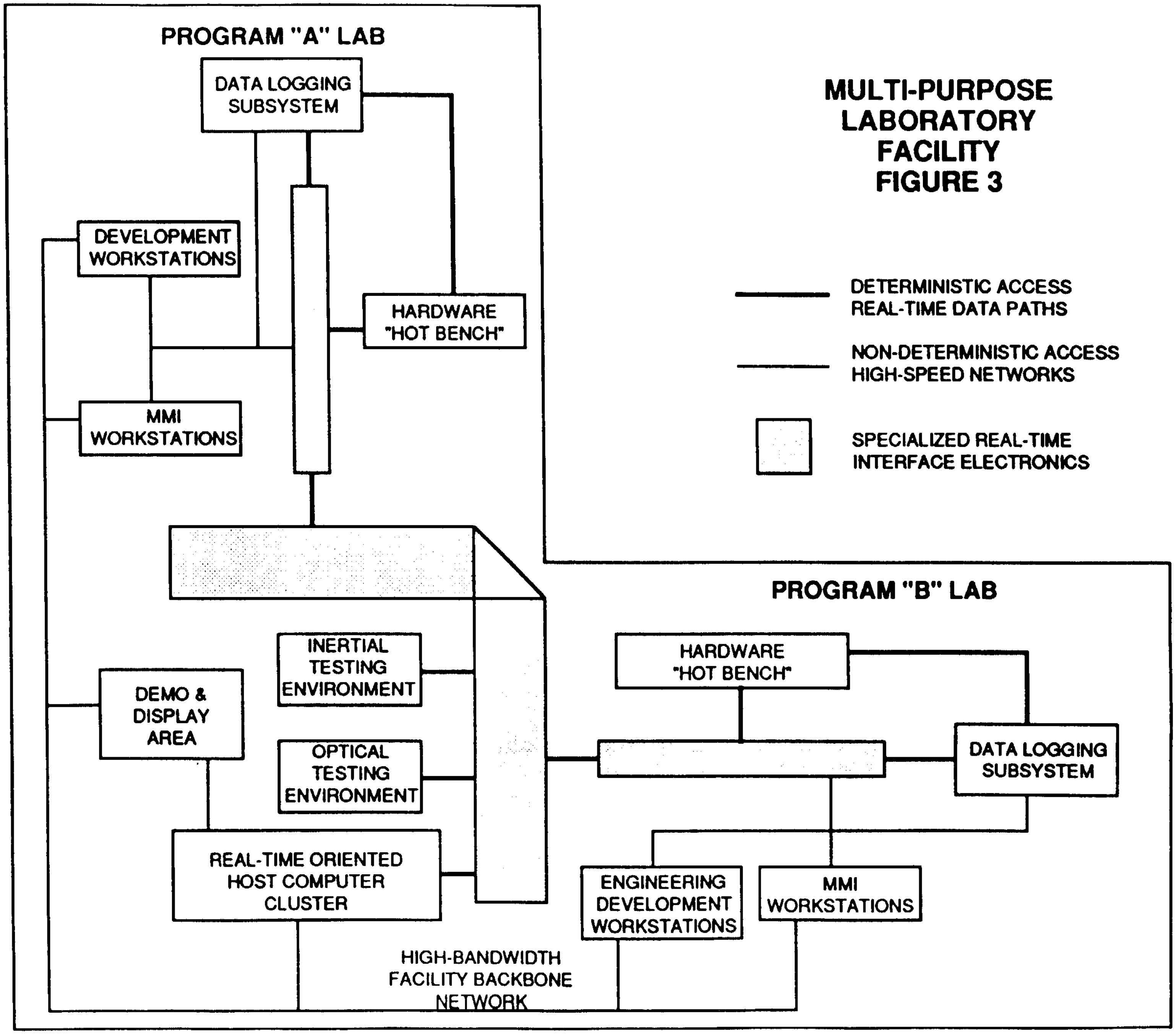
- ALS
- ELV Upgrade Programs
- Shuttle
- Shuttle-C
- NASP
- Advanced upper stages (STV)
- Spacecraft programs (AXAF, others)
- Lunar/Mars Vehicles

MAJOR ACCOMPLISHMENTS

- Test, Evaluation, Integration, and Test Facility at CSDL - Oct 89
  - Supports LaRC-sponsored AIPS Distributed System
- HLCV/MAST Laboratory
  - Preliminary designs completed Feb 89
  - Concept demonstrations performed May-Sep 89

SIGNIFICANT MILESTONES





MULTI-PURPOSE LABORATORY FACILITY
FIGURE 3

PANEL REPORTS

- OPERATIONAL EFFICIENCY
- FLIGHT ELEMENTS
- PAYLOAD ACCOMMODATIONS
- SYSTEMS ENGINEERING AND INTEGRATION (SE&I)

PANEL REPORTS