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Vertical Motion Simulator Familiarization Guide

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Foreword

This document was written under the direction and guidance of the Simulation Engineering Group at Ames Research Center. The Simulation Engineering Group is composed of personnel from the Simulation Experiments Branch, the Simulation Systems Branch, and their support contractors. The group's purpose is to improve the quality, fidelity, and efficiency of the simulation facilities operated by the Flight Systems and Simulation Research Division.

The title "Familiarization Guide" denotes this document's purpose: to describe the Vertical Motion Simulator thoroughly and completely, at a level of detail and technical complexity appropriate for the intended audience—the users of the Vertical Motion Simulator, the scientists and engineers who employ it for research and development.

The subtitle reflects the building-block nature of the Vertical Motion Simulator and emphasizes that the document deals mainly with hardware elements.

The information presented herein was extracted primarily from technical reports, operating manuals, maintenance manuals, and product description documents. These documents are listed in the final section, and they are available for reference if more detailed information is desired.

Since its inception, the Vertical Motion Simulator has been upgraded continually to keep up with the technologies it was designed to support. This practice is sure to continue, so this guide will be updated periodically to reflect future modifications. With this in mind, feedback from readers of this document is heartily welcomed.

Table of Contents

Table of Contents (continued)

Summary

The Vertical Motion Simulator Familiarization Guide
provides a synoptic description of the Vertical Motion
Simulator (VMS) and descriptions of the various
simulation components and systems. The intended
audience is the community of scientists and engineers
who employ the VMS for research and development. The
concept of a research simulator *system* is introduced and
the building block nature of the VMS is emphasized.
Individual sections describe all the hardware elements in
terms of general properties and capabilities. Also included
are an example of a typical VMS simulation which
graphically illustrates the composition of the system and
shows the signal flow among the elements and a glossary
of specialized terms, abbreviations, and acronyms.

Introduction

The Vertical Motion Simulator (VMS) is a one-of-a-kind
research and development facility. It is, first and foremost,
a *research simulator* that offers unparalleled capabilities
for conducting studies and experiments in some of the
most challenging aerospace disciplines. But because of its
design and operational philosophy, the VMS is really a
simulation system made up of many components, each of
which is a highly complex system in its own right. In
addition, these simulation components are largely inter-
changeable so that simulations can be tailored to serve the
needs of individual research programs.

This guide starts with a description of the VMS as a
whole and then describes the various simulation compo-
nents and systems. The hardware is described in terms of
general properties and capabilities. This report is not
intended to provide detailed technical specifications or a
comprehensive list of available equipment. Component
and system descriptions are followed by an example of a
typical VMS simulation that graphically illustrates the
composition of the system and shows the signal flow
among the elements. The appendix contains a glossary of
specialized terms, abbreviations, and acronyms.

Overall System Description

The VMS is distinguished by its most striking feature, the
world's largest flight simulator motion base. The motion
base is so prominent, in fact, that many people think it
alone constitutes the VMS. It is critical, however, to
appreciate that the motion base is only one part of the
VMS simulation system.

The simulation system concept is fundamental to all major
simulator facilities operated by the Flight Systems and
Simulation Research Division, and stems from a design
and operating philosophy aimed at supporting the widest
possible range of aeronautical research. The concept is
based on a building-block approach that involves
maintaining as distinct resources a conglomeration of
simulation elements or components that can be integrated
to form a complete system in a variety of different ways.
The entire collection of simulation components, support
equipment, and associated facilities located mostly in the
Flight and Guidance Simulation Laboratory (Build-
ing N243) is familiarly known as *SimLab*. The simulation
system approach allows the simulator configuration to be
tuned to the needs of specific research by (1) employing
only those components necessary for a particular test,
(2) tuning these components specially for the test, and
(3) using the most appropriate of several interchangeable
components to suit specific test requirements. Other
advantages are that specialized equipment can be
integrated more easily and facility improvements can be
implemented by upgrading individual components rather
than the entire simulator.

The elements of a typical VMS simulation can be grouped
into functional categories as follows: (1) Host Computer,
(2) Interfaces, (3) Test Operations and Control, (4) Crew
(Pilot) Station, and (5) Cueing Systems. These elements
and the ways they interact are depicted in figure 1. The
lower, closed-loop portion of the diagram illustrates the
basic concept of real-time man-in-the-loop simulation.
The pilot executes *control actions*, which are transmitted
to a computer that calculates (1) resultant aircraft states
and (2) corresponding drive signals for cue-producing
devices, which, in turn, generate *cues* that stimulate the
pilot's various sensory organs in a manner similar to that
which would occur in actual flight. Hence, the pilot
receives a sensation of actually flying. The upper portion
of the diagram illustrates the interplay between the operat-
ing personnel (researchers and simulation engineers and
technicians) and the real-time simulation flow. Examples
of such interplay are starting and stopping a run, introduc-
ing a simulated failure, and monitoring test data.

The Host Computer is the nucleus of the simulation
system because it solves the equations that represent the
mathematical model of the aircraft and performs all the
computations required to command and control the other
parts of the system. Most importantly, it does all this in
real time,[1] that is, fast enough to allow the pilot to inter-
act with the simulator as though it were the actual aircraft.
At this writing, SimLab operates three host computers that
can be used with the VMS—the VAX 9000 Model 210,
the VAX 4000 Model 300, and the AD 100. These are

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[1] Precise definitions of the terms *real time* and *real-time
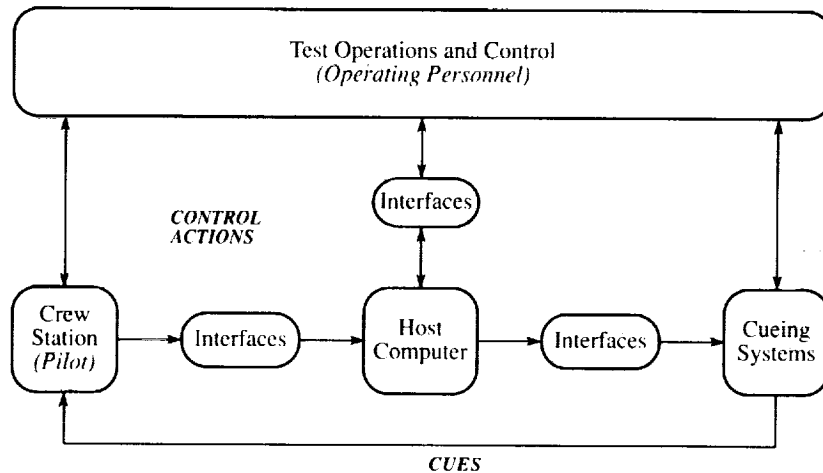simulation* are provided in the glossary.

Figure 1. Simulator system schematic.

described in more detail in the section entitled "Host Computers."

In general, an interface is an item that provides a shared boundary defined by common physical interconnection characteristics, signal characteristics, and meanings of interchanged signals. The term is used here in a more specific sense to denote equipment that serves as a part of the communications path between the host computer and the other elements of the simulation system. Because of the wide variety of equipment and computers at SimLab and attendant variations in performance requirements, the demands on interfaces are particularly severe. The interfaces are of three general types: (1) Local Area Networks, (2) Interface Devices, and (3) Interface Computers. Local Area Networks (LANs) are communications subsystems that connect and provide communication paths for a number of computers, terminals, and other equipment spread over a large area. SimLab has two commercial LANs, Ethernet and Micom, to provide for VMS communications needs. Interface Devices are special-purpose items that are designed to provide communications between specific types of electronic equipment. SimLab uses unique interfaces that were developed at Ames called Remote Input/Output Units (RIOUs) and Computer Input/Output Units (CIOUs). Interface Computers are simply general-purpose digital computers that are employed to perform specialized communications functions requiring significant computing capability. VMS simulations use two such computers, called VMS SIO and PIO. Interfaces of all three types are described in more detail in the section entitled "Interfaces."

Test Operations and Control activities are centered in a specialized control room known as the VMS Lab. This is the work area and focal point for the personnel who conduct and direct simulations, and it contains all the necessary operating consoles, control consoles, and other essential test support and monitoring equipment. Foremost are the primary control centers for real-time simulation operations—two work stations known as the SEP Station and PEP Station. Other equipment located in the VMS Lab are used to display the various types of data and imagery associated with the simulation. These include data displays and recorders, terminals to access the various computers, and video monitors. The VMS Lab also provides a convenient location for electronics chassis that are part of some of the cueing systems, for interface computers, and for several racks containing interface devices. All these items are discussed in more detail under "System Components."

Just as the VMS Lab serves as the work area for test operations personnel, the Crew Station is the work area for the simulator pilot(s). The Crew Station is provided by a stand-alone structure called a cab or, more specifically in the case of the VMS, an Interchangeable Cab (ICAB). The main function of the cab is to represent the cockpit of the simulated aircraft. It must therefore contain seating for the crew and space for all the controls, instruments, and auxiliary equipment required to perform the simulated flying task. The cab must also support and house additional simulation-related equipment, and, most importantly, it must provide a safe environment for human occupation. In keeping with the simulation systems concept, there are four ICABs that can be used on the VMS. The primary reason for maintaining a number of cabs is to improve test project throughput. Since the VMS is used for simulating virtually all types of aerospace vehicles, the chances are high that the cockpit configuration will vary greatly from one simulation to the next. For example, a space shuttle simulation may be followed by a helicopter simulation and then by the simulation of a

2

conceptual fighter plane. ICABs allow cockpit outfitting and other preparations to be accomplished "off-line" in a separate development area so that these time-consuming activities do not require the VMS to remain idle, as would be the case if they were performed with the cab mounted on the motion base. The delay experienced in changing cockpit configurations is reduced to the time required to remove the old cab and install and check out a new one.

In addition to being easily changeable as a unit, ICABs are designed for rapid and efficient cab reconfiguration. The structural framework is essentially identical for all four ICABs, and the equipment and subsystems used to outfit the interior are modular and interchangeable except for one major item. This exception is the Image Presentation System (IPS), an arrangement of monitors and associated optical elements (called "windows") used to display the external visual scene. The IPS in each ICAB is unique and fixed, because it is not feasible to design rapid changeability into such a large, complex, and safety-critical structure. The IPSs in the four ICABs do, however, accommodate a wide variety of aerospace vehicles. There are two four-window configurations used primarily for helicopter and V/STOL simulations called NCAB and RCAB; a three-window, continuous wraparound configuration for single-seat fighter-type applications called FCAB; and a three-window, two-seat, side-by-side configuration that can be used to simulate transport aircraft or the space shuttle called SCAB. More detailed descriptions and technical specifications for the four ICABs are presented in the later section entitled "Interchangeable Cabs."

The term "cueing systems" is used to denote the collection of items whose primary function is to generate and present sensory stimuli to the pilot. They are typically designed to stimulate specific human sensory systems; hence they tend to take on the names of the corresponding human-sense counterpart. A large variety of cueing systems are available for use on the VMS; these vary from extremely large, complex, and expensive devices such as the motion and visual systems to tiny devices mounted in the cab.

The Motion System is a large servomechanism that imparts motions to the cab in all six degrees of freedom. Its function is to generate cues that stimulate the human motion-sensing organs, thereby providing a more realistic sensation of flying. The VMS motion system was specially designed to provide high performance and extremely large translational displacements based on requirements to simulate the sensations of rotorcraft nap-of-the-earth flight. Details are provided in the section entitled "Motion System."

The Visual Display System is a complex arrangement of computer, video, and optical equipment that generates and presents imagery representing the view of the "outside world" from the pilot's seat. Its primary function is to generate cues to stimulate the pilot's visual sense to provide the sensation of actually being within, and moving through, the simulated environment. It is composed of two major subsystems: (1) the image generator, which produces the scene, and (2) the IPS (described above), which presents the scene in a form visible to the human eye. There are two Computer Image Generators (CIGs) available for use with the VMS, a Singer-Link DIG1 and an Evans and Sutherland CT5A; these are described in detail in the section entitled "Image Generators." Details of the four IPS configurations are provided in the section entitled "Image Presentation Systems."

Auxiliary Electronic Displays are another class of cueing system and are used to simulate devices such as Head-Up Displays and electronic instrumentation. They are similar to the Visual Display Systems in that they are composed of a display device in the cab and a display generator located elsewhere. Both the display generators and the display devices are covered in the section entitled "Auxiliary Electronic Displays."

"Cockpit Cueing Devices" is a catchall category for a number of cueing systems located primarily within the cab. These include the control loader, vibration generator, sound system, auxiliary controls, and flight instruments. The control loader is a sophisticated electrohydraulic servosystem used to simulate the force-feel characteristics of the primary aircraft flight controls (stick, wheel and column, rudder pedals, and collective) over a wide range of conditions. The vibration generator, another electrohydraulic servosystem, provides a high-frequency, small-amplitude vertical motion to the pilot and is used to simulate vibratory environments beyond the bandwidth of the motion system. The sound system is used to represent sounds that occur in the cockpit of the simulated aircraft and consists of speakers located in the cab and a sound generator electronics cabinet located in the VMS Lab. Auxiliary controls are other devices that are used to effect control actions; these are usually relatively simple devices such as throttles, joysticks, pushbuttons, and switches of various types. Flight instruments are the classical electrical or electro-mechanical gauges and indicators. Details and specifications for the Cockpit Cueing Devices are provided in the section entitled "Cockpit Cueing Devices."

There is one additional element that doesn't fit into any of the categories discussed above—the Video Switch. This element serves as a distribution system and router for virtually all the video signals generated and used in

SimLab. All the Image Generators, some of the Auxiliary Display Generators, and various other equipment that produce video signals are connected to the Video Switch, which in turn allows the signals to be transmitted to appropriate display devices located throughout SimLab.

System Components

All the system components described in the following sections are located in the Flight and Guidance Simulation Laboratory, Building N243, at Ames Research Center. The locations of some of these items and related areas are indicated in figure 2 to illustrate how they are spread around the building and to provide a sense of scale and perspective for the physical layout.

Host Computers

There are three different host computers available to SimLab users. Two of these machines, the VAX 9000 Model 210 and VAX 4000 Model 300, are members of the VAX family of general-purpose computers manufactured by Digital Equipment Corporation (DEC). All VAXes are designed around a 32-bit architecture and
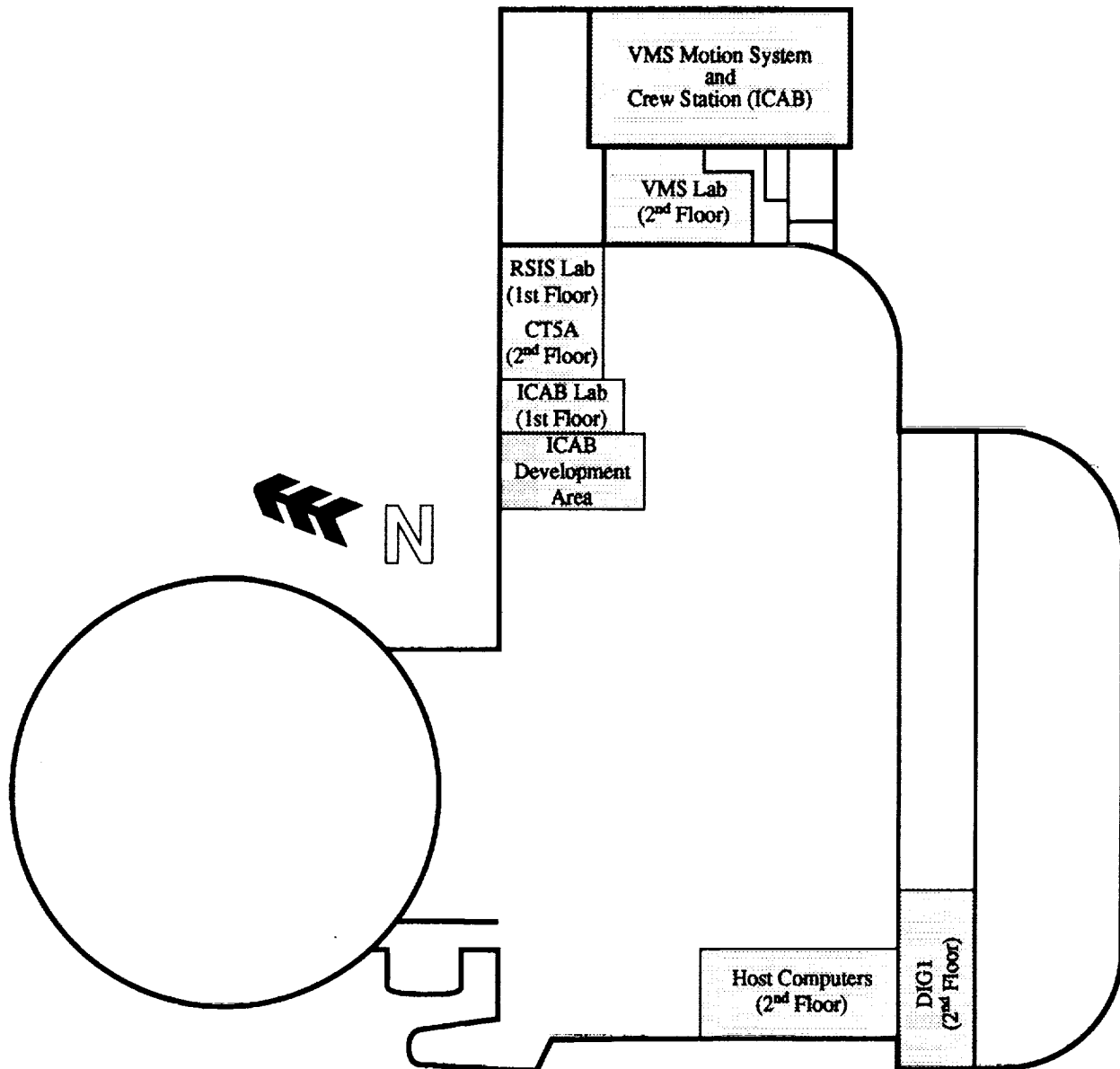

Figure 2. Building N243 plan view.

4

share a collection of common attributes, called the "VAX Architecture," that allows software to run without change on any VAX system.

The third host computer is a special-purpose machine manufactured by Applied Dynamics International called the AD 100.

VAX 9000 Model 210– The VAX 9000 Model 210 is a mainframe-class digital computer that is, at the time of this writing, the highest performance single-processor machine produced by DEC. Its design emphasizes high reliability and availability in addition to high performance. The VAX 9000 provides a performance level of 40 VUPs, where a VUP (VAX Unit of Processing) is a parameter used by DEC and defined as the performance equivalent of one VAX-11/780 system. (As a point of reference, the VAX-11/780 is often referred to as a 1-million-instruction-per-second, or 1-MIPS, machine).

The high performance is the result of several design features including high-density packaging, balancing the performance of the Central Processor Unit (CPU), Input/Output (I/O), and memory subsystems and parallelism implemented in various subsystems. Parallelism is manifested in the I/O subsystem by multiple buses, and in the central processor by *pipelining*, a process by which macroinstructions are decomposed into individual operations that are then executed by optimized, independent functional units. The idea behind pipelining is to keep the processors working as much of the time as possible and to minimize idle time while data is in transit to or from the processors.

The high level of reliability/availability is provided through error detection, correction, and isolation processes implemented primarily by hardware elements in the CPU. The system is designed to detect intermittent failures, report any to the operating system, and perform recovery procedures, thereby minimizing system crashes.

The VAX 9000 is made up of the following major subsystems: (1) CPU, (2) System Control Unit (SCU), (3) Main Memory, (4) I/O, (5) Service Processor and Scan, and (6) Power. A schematic illustrating the system hardware organization is presented in figure 3. The CPU subsystem contains the hardware that fetches, decodes, and executes instructions, and memory interface and control hardware. A 128-kilobyte (kB) data cache and an 8-kB instruction cache help increase performance. The CPU is interconnected to the Main Memory and I/O subsystems through the SCU. The SCU subsystem employs intelligent crossbar-switch technology to manage the data flow among the other subsystems. Multiple simultaneous data transfers are accomplished over four concurrent paths.

The Main Memory subsystem consists of 256 megabytes (MB) of storage that is operated in a two-way interleaved mode to shorten memory access times. Double-bit error detection and single-bit error correction are provided by an error-correction code stored with the memory data. The I/O subsystem functions as the communications link between the VAX 9000 and external interfaces which, in turn, communicate to the other simulation systems. (Interfaces used with the VAX 9000 include LANs and a CIOU, which are covered in the section entitled "Interfaces"). It is based on a dedicated I/O bus called the XMI bus that can deliver a sustained throughput of 80 MB per second. Adapters provide connections to the aforementioned LANs and also to peripheral equipment such as disk drives, tape drives, and printers. The CIOU is connected through another bus called the BI bus. The Service Processor and Scan subsystem serves as the operator's console for the VAX 9000 and also as a central point for handling and reporting system errors. Disk and tape drives are provided to store and update console software, as are interfaces for remote and local user access. Operator functions supported include loading CPU microcode and initializing the system. This subsystem can actually test and diagnose a failing CPU or SCU, determine whether or not the error is correctable and, if so, invoke error-handling routines and return the system to normal operation without human intervention.

The Power subsystem contains conditioners and regulators that convert alternating current available from the electrical utility into direct current needed to operate the system hardware and a system to monitor and control these. It also includes two battery backup units that can maintain main memory for up to 10 minutes in the event of a power failure.

VAX 4000 Model 300– The VAX 4000 Model 300 was introduced in 1990 as the high-end computer in DEC's entry-level systems family. It offers a performance level of 8 VUPs, has 32 MB of main memory and employs a widely used DEC bus architecture called Q-bus . The entire system is contained in two pedestal-style enclosures with a built-in power supply. The basic system components include the enclosures, a CPU module, a memory module, disk drives, and a terminal interface. The enclosure provides a Q-bus backplane with 12 slots (5 of which are dedicated to the system) and a shelf that accommodates mass storage devices. The CPU module includes the central processor, a floating-point accelerator, a memory controller unit, cache memory, and also interfaces for Ethernet and two disk controllers. These interfaces are important for two reasons. They free up backplane slots and they allow Ethernet and disk traffic to bypass the Q-bus, thereby increasing system throughput. Communications between the VAX 4000 and other simulation
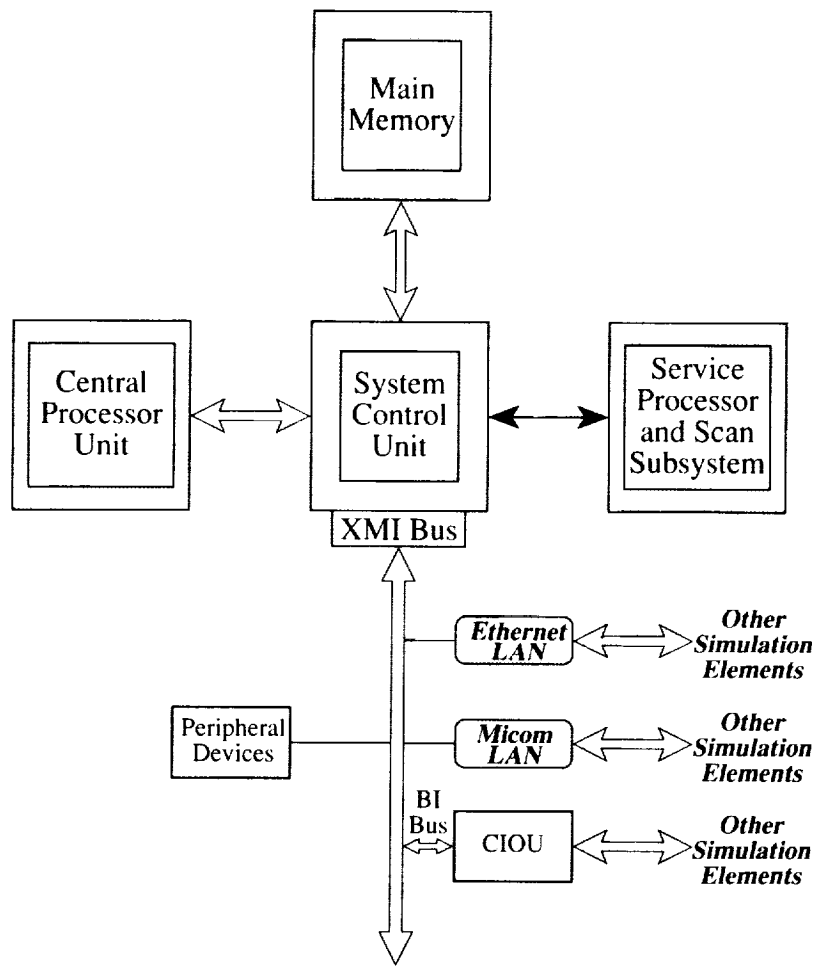
Figure 3. VAX 9000 hardware organization schematic.

components are provided by the Ethernet and Micom LANs and a dedicated CIOU.

AD 100– The AD 100 is a high-speed computer designed specifically for the time-critical simulation of continuous dynamic systems. It is a bus-oriented multiprocessor system that features totally synchronous operation, a computation rate of 20 million floating-point operations per second, a 16-MB data memory with 64 KB of program memory, and an integral I/O system.

The basic layout of the AD 100 and its supporting systems is illustrated in figure 4. The AD 100 equipment is housed in two cabinets. The cabinet labeled "AD 100" contains computational hardware, primarily the bus structure and processors; and the other, labelled "I/O Cabinet," contains a custom I/O system called the AD Real-Time Input/ Output (ADRIO) System. Note that the AD 100 is not a stand-alone computer; the front-end processor is typically one of the family of DEC VAX computers, and in this case is a MicroVAX II. Other VAXes connected to the

front-end computer through the SimLab Ethernet LAN can be used for off-line program development.

The AD 100 provides separate program and data memories, and every processor has its own program memory, program counter, and instruction decoder. Each processor has an instruction fetch rate of one instruction per 100 nanoseconds.

Figure 4 also shows details of how the various buses and processors in the two cabinets are linked together. The main bus in the computer cabinet (called the PLUSBUS) has slots for a total of nine circuit assemblies. Six of these are filled and three are available for expansion (EXP) assemblies. The Supervisor (SUP) provides the interface path to the front-end computer. The Communication and Control Processor (COM) controls all of the AD 100 resources at run time and provides the interface to the ADRIO. The Arithmetic Logic Unit Processor (ALU) and Multiplier Processor (MUL) perform arithmetic logic and multiplication operations, respectively, as their names
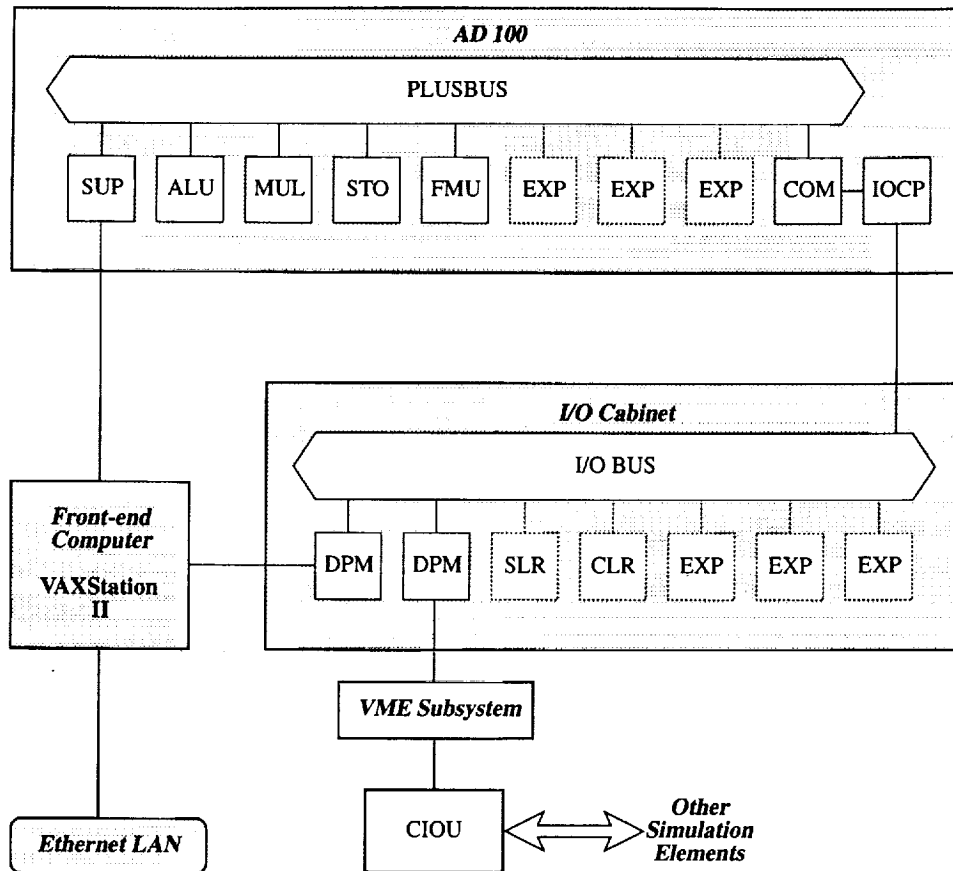
Figure 4. AD 100 system schematic.

imply. The Storage Processor (STO) provides limited high-speed data storage for 64K words; this memory is used for program variables and coefficients. The Function Memory Unit Processor (FMU) is an optional processor that provides an extra two million 64-bit words (16 MB) of data memory. Symbolic variables in 32-bit floating-point format are converted to the required 64-bit floating-point format using a special data-logging function.

A unique feature of the AD 100 is separate clocks for setting cycle time and determining total elapsed time (run time) for an operation. The former is, of course, programmable, and the latter has a resolution of 100 nanoseconds and a maximum count duration of 30 hours.

The ADRIO is the system through which the AD 100 communicates to the rest of the simulation elements. Although it is technically an interface, for the purposes of this document it is considered part of the AD 100 because it is used exclusively in connection with the AD 100 and, in terms of the way AD 100/ADRIO links to the other elements, it functions as a separate and distinct system.

The most important hardware components in the SimLab ADRIO are the Input/Output Control Processor (IOCP)

and the Dual-Port Memory Units (DPMs). As indicated in figure 4, the ADRIO also contains expansion slots and a minimum complement of Sense Line Registers[2] (SLRs) and Control Line Registers (CLRs). These are not used, however, for real-time communications, since their functions are provided by other devices as described in the later section on Interfaces.

The IOCP is mounted on the COM processor (that is, it is located in the AD 100 cabinet) and is connected to the I/O Cabinet by cables. The COM memory is dual ported and serves two functions, as program memory for the COM and as a buffer for the transfer of data to and from the IOCP. All communications between the AD 100 and the IOCP take place through COM memory. Like the other processors, the IOCP has its own program memory, and it operates in parallel with the rest of the AD 100. This provides for independent, parallel control of the ADRIO System and therefore allows the computational tasks to be completely separated from the I/O tasks. Where required,

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[2]Sense Line Registers and Control Line Registers are often referred to as Discrete Inputs (DIs) and Discrete Outputs (DOs), respectively.

flags are used to synchronize I/O and computational operations. The IOCP also provides other I/O-related features such as format conversions, counters, jump operations, a logic processor, and flags.

In general, the DPMs provide parallel communication paths between the I/O bus and programmable digital devices. Like the COM memory, these memories are dual ported; they have two independent ports, one of which is connected to the I/O bus and the other to the external device. The connections on either end are effected through DR11[3] cards, which are omitted in figure 4 for the sake of clarity. In the SimLab architecture, one of the DPMs is connected back to the front-end computer and is used only to collect real-time data from an operating simulation. The other DPM is connected to a CIOU interface device through a custom VME-based subsystem, and it is through this link that the AD 100 communicates with the other elements of the VMS simulation system. The VME subsystem is unique to the AD 100 and simply provides a DR11-based connection between the DPM and a CIOU.

Distributed Processors

Distributed throughout SimLab are a number of additional relatively powerful digital computers that are used to support simulations in various ways. Some are used for general purposes, while others are dedicated to specific functions; these latter computers are covered both here and in separate sections as appropriate. All these computers are DEC products.

DEC MicroVAX series computers– SimLab has a total of six DEC MicroVAX computers available for general support of VMS simulations. The MicroVAXes also employ a 32-bit architecture and are completely compatible with the VAX host computers. Some MicroVAXes use the Q-bus, while others have an earlier bus system called UNIBUS. In order to avoid confusion, each SimLab MicroVAX is identified by a distinct, familiar name that usually relates to its use or origin. Table 1 lists these MicroVAXes and summarizes their general properties. Note that there are four types listed under "Computer" and four types under "System Configuration." Over the years, DEC has marketed a number of basic MicroVAX computers that vary widely in cost and performance, and the "Computer" column

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[3]The DR11 is a general-purpose, direct-memory access device originally developed by DEC for interfacing their UNIBUS-based computers. The concept is so widely used and accepted that it has become a de facto standard. DEC, other computer manufacturers, and third-party vendors market a wide variety of DR11-compatible products.

identifies which basic member of the MicroVAX family is contained in each system. The different system configuration types arise from the fact that DEC markets the MicroVAX line as both basic computer systems and as integrated work stations.

The MicroVAX II was marketed as DEC's standard-line supermicrocomputer for several years and was the lowest cost member of the VAX family to use the Q-bus. The MicroVAX II CPU consists of a single processor board which includes, among other things, the 32-bit central processor chip, the floating-point coprocessor chip, one MB of on-board memory, a bus interface, an interval timer, and a boot and diagnostic facility. A backplane interconnect provides connections to tightly coupled memory-expansion modules. The nominal performance level of the MicroVAX II is 0.9 VUPs. The maximum I/O throughput is 3.3 MB per second (this is actually a characteristic of the Q-bus, not the computer).

The MicroVAX 2000 is a lower cost single-board implementation of the MicroVAX II with two major hardware differences—it does not contain a Q-bus (the busless architecture severely limits its I/O capabilities), and its maximum memory capacity is only 6 MB. It does, however, use the same central processor and floating-point coprocessor chipset as the MicroVAX II, so its processing speed is also 0.9 VUPs.

The MicroVAX 3600 and MicroVAX III represent the high-performance end of the MicroVAX family. These systems process data three times faster than the MicroVAX II (2.7 VUPs), mainly because they use complementary metal oxide semiconductor (CMOS) microchip technology for the central processor and the floating-point coprocessor. Other speed-enhancing features are an increased operating speed for the central processor (90 nanoseconds) and an improved caching architecture. Another difference from the MicroVAX II is the lack of a main memory board. MicroVAX II local memory architecture is retained, but is implemented in the form of private memory modules.

The term VAXStation is used to indicate a complete work station based on one of the MicroVAX computer systems. In addition to the basic computer, a VAXStation typically includes a video display monitor, additional system memory, and an Ethernet interface. The VAXStation II also incorporates a VLSI graphics coprocessor that off-loads text and graphics computations from the central processor to enhance system performance.

The VAXlab product line is primarily oriented to real-time applications. Like the VAXStation, the VAXlab packages one of the MicroVAX computer systems with other special-purpose equipment to form a complete work

Table 1. MicroVAX summary

Familiar name	System configuration	Computer	Memory capacity	Usage
ADVAX	VAXlab	MicroVAX II	16 MB	AD 100 front-end processor
ADWS	VAXStation 2000	MicroVAX 2000	4 MB	AD 100 off-line development
SIMVAX	VAXlab	MicroVAX III	16 MB	Real-time/interface computer
STARVAX	VAXStation II	MicroVAX II	16 MB	Real-time/interface computer
ADDEV	MicroVAX 3600	MicroVAX 3600	32 MB	AD 100 off-line development Real-time data processing
SIMDEV	MicroVAX 3600	MicroVAX 3600	32 MB	Off-line development, status center, parts inventory, on-line tutorials, and real-time data processing

station. Unique VAXlab features are a real-time clock/counter, special termination/connector panels, and a special software library.

DEC PDP-11 series computers– Every VMS simulation utilizes two DEC PDP-11 series computers simply because they are elements of the interfacing system that connects the host computer to equipment in the VMS Lab. These two particular computers are known as PIO and VMS SIO and are, respectively, a MicroPDP-11/73 and a MicroPDP-11/83.

Like VAXes, DEC PDP-11 systems are a compatible set of processors that employ a common architecture and a common instruction set. They can also be easily connected to MicroVAX systems and Ethernet. There are two distinct lines of PDP-11 systems, with the major difference being the bus structure (Q-bus or UNIBUS); both the MicroPDP-11/73 and the MicroPDP-11/83 are designed as Q-bus systems. PIO and VMS SIO have been modified, however, to include a UNIBUS in addition to the standard Q-bus to enhance flexibility and maintain compatibility with equipment designed around UNIBUS standards. Additional information on PIO and VMS SIO is provided in the later section entitled "Interface Computers."

Interfaces

Local area networks–

Ethernet: Ethernet is a relatively high speed, limited-area LAN. It provides a data rate of 10 MB/sec and can operate over a maximum separation of 2.8 km. The network consists of transceivers, terminal servers, multiplexers, and other special-purpose devices connected by shielded coaxial cable. An Ethernet controller, mounted in the computer chassis, is required to connect each computer to the network. The SimLab Ethernet LAN covers essentially all of the Flight and Guidance Simulation

Laboratory with major connection points spread strategically throughout the building. In addition to the VAX host computers, MicroVax systems, and PIO discussed earlier, the SimLab Ethernet LAN also connects to the following: (1) Silicon Graphics IRIS display generators, (2) two terminal servers, which in turn connect to the Micom LAN, (3) another MicroPDP-11/73, used for off-line program development, (4) a VAXStation 3100 system used for advanced system software development, and (5) a Macintosh II computer located in the VMS Lab.

Micom: The Micom LAN provides data communications within Building N243, between buildings at Ames Research Center, and even to locations outside the center. For simulation purposes, it is used for communicating between computer terminals distributed around the building and the various computers involved in a simulation. It allows, for example, a single terminal in the VMS Lab to control any of the host computers or off-line programming from terminals and personal computers located in office areas. The network consists of a Micom Micro600 Port Selector that controls and coordinates terminal access and a system of dual twisted-pair cables strung throughout the building. The Micro600 serves as an interface and switching device between the computers and the terminals and functions like a telephone rotary, providing first-come, first-served contention between the incoming channels and the computer communications ports. The system supports user-selectable data rates of 75 to 9600 bits per second (baud).

Interface devices– The CIOU and RIOU data transmission systems were designed and built at Ames Research Center specifically for use at SimLab. Although they share similar design and hardware features, they provide different interfacing functions; CIOUs are bi-directional and are used for computer-to-computer communication, while RIOUs are unidirectional and serve as conversion nodes between digital and analog equipment. The systems

9

use a bit-serial transmission technique operating at a raw transmission speed of 10 megabits per second. This transmission technique is unique to SimLab. Data are transmitted in blocks of up to 256 16-bit words, and each transmission requires a response from the receiving site before another message can be sent. The systems also have extensive error-detection and reporting features. Components are connected by twinaxial cables, and the overall network topology is point-to-point. Each connection requires a CIOU or RIOU at both ends; that is, each interface requires a pair of the units, either two CIOUs or a CIOU and an RIOU.

CIOUs are located near the computer to which they attach, and each one can connect to as many as eight other CIOUs and RIOUs. CIOUs were originally custom designed to match the input/output system of each type of computer, but this is no longer the case. Instead, CIOUs now have a DR11 interface, and the matching function is furnished, if necessary, by an additional DR11-compatible interface device. CIOUs use transmit and receive buffers to minimize transmission delays. A data transmission operation progresses as follows: (1) the data block is transferred from the transmitting computer to the CIOU's transmit buffer, (2) data are fetched from the transmit buffer, serialized, and sent to the receiving CIOU, (3) at the receiving CIOU, a serial-to-parallel conversion is performed and the data are loaded into the receive buffer, and finally, (4) the data block is transferred from the receive buffer into the receiving computer.

RIOUs provide communications between digital computers and analog devices, which is the reason they are called conversion nodes. The original impetus to develop these unique units was the desire to minimize the length of analog lines in an effort to reduce common analog transmission problems such as noise and drift. The design approach was to locate the conversion equipment near the analog hardware, and therefore remote from the computer, so that signals are in digital form over most of the transmission distance. The RIOU chassis has 16 slots for printed circuit boards containing various types of converters. Various board types can be fitted into various slots, so that quantities of different converters can be adjusted to suit individual simulation requirements.

Available converter types and their operational parameters are presented in table 2. A Motorola M6800 microprocessor on each RIOU board controls and monitors that particular board's function. Employing a microprocessor on each board provides flexibility to meet new requirements because the control algorithm can be modified easily, and it also allows extensive self-test diagnostics.

Table 2. RIOU converter characteristics

Converter type	Resolution	Number per board
Digital-to-Analog Converter (DAC)	16 bit	16
Analog-to-Digital Converter (ADC)	16 bit	16
Discrete Output (DO)	~	16
Discrete Input (DI)	~	16
Digital-to-Synchro Converter (DSC)	15 bit	4

Interface computers–

PIO: PIO is employed as a printer interface, hence the acronym, which stands for Printer Input/Output. It is a MicroPDP-11/73 and its features include a 15-megahertz central processor chipset and cache memory to enhance processing speed. Its memory capacity is 0.5 MB.

PIO serves as a common link and distribution center for the three host computers and Versatec printer/plotters located in three different simulator labs.[4] It is required because the printer/plotters are not directly compatible with the host computers and it is more efficient to use a computer for this function rather than providing separate interfaces. PIO connections are shown in figure 5. The VAX Host Computers are connected directly to PIO through the Ethernet LAN. The AD 100 is connected to PIO's Q-bus through its MicroVAX front-end computer and the SimLab Ethernet LAN. The printer/plotters are driven by special controllers that connect to the UNIBUS.

VMS SIO: VMS SIO is employed as a centralized interface between the host computer and four RIOUs that, in turn, connect to equipment in the VMS Lab and cueing systems. The acronym stands for Simulation Input/Output, and the computer is located in the VMS Lab. It is a MicroPDP-11/83, one of the highest performance Q-bus PDP-11s. Its processing speed is approximately 130% that of the MicroPDP-11/73 as a result of an 18-megahertz central processor chipset, a floating-point accelerator, and a private-memory interconnect feature. VMS SIO has a memory capacity of 2 MB.

VMS SIO connections are illustrated in figure 6. A CIOU/CIOU link connects VMS SIO to any of the three host computers. Another CIOU connects VMS SIO to four RIOUs, which are designated RIOU 0, RIOU 1,

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[4]In addition to the VMS Lab there are two simulator labs used for fixed-base simulations—the ICAB Lab and the RSIS Lab.
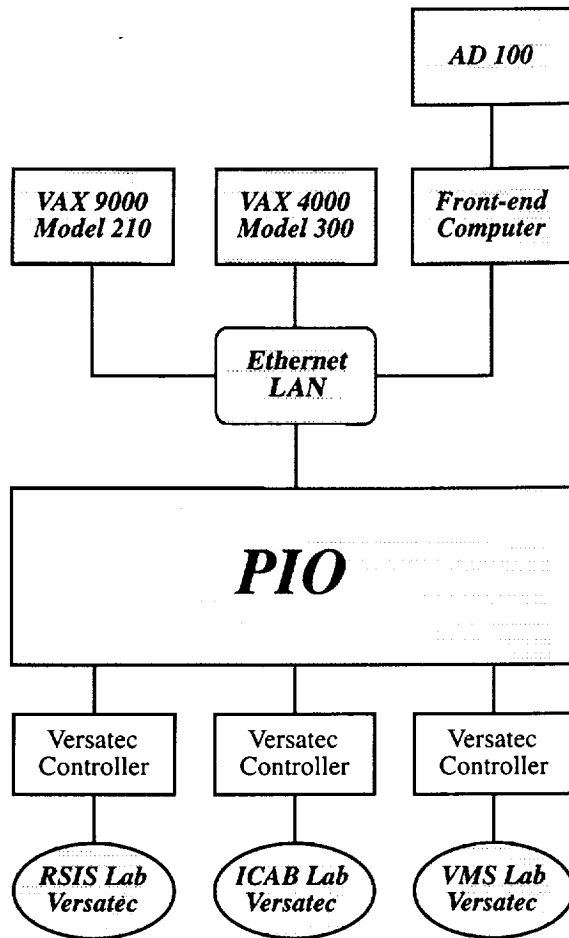
Figure 5. PIO connections.

RIOU 2, and RIOU 4. RIOU 0 is located in the VMS Lab and provides interfaces to the SEP, the PEP, and the strip-chart recorders. RIOU 1 is located in the simulator cab and provides interfaces to cueing systems and auxiliary controls inside the cab. RIOU 2 is also located in the VMS Lab and provides interfaces to two major cueing systems, the Control Loader and Sound System, that have control chassis located in the VMS Lab. RIOU 4 is located nearby in the motion control room and provides interfaces to the VMS Motion System.

Test Operation and Control

VMS Lab– As stated earlier, the VMS Lab is the main work area for personnel who direct and conduct the simulation and also provides a location for essential test support equipment. A plan view of this room is shown in figure 7, and Test Operation and Control equipment is discussed in the sections immediately following.

The VMS Lab is arranged around the SEP and PEP Stations, which together form the nerve center for simulation operations. The Motion System can be viewed through the window in front of them, and directly behind are the primary real-time data displays—eight strip-chart recorders and a Versatec electrostatic printer/plotter that is used as a line printer for the host computer. To the side are a DEC VT320 terminal and a Printronix line printer that service VMS SIO and another VT320 terminal. There is one additional VT320 terminal in the VMS Lab that is connected to the Micom LAN and also an Apple Macintosh computer that is available for general-purpose test support.

The observation area opens onto the main hallway and is separated from the VMS Lab by a wall to prevent disruptions from tour groups. The McFadden control-loader electronic controller chassis, an EAI 2000 analog computer, and another chassis containing a video patch panel are located next to the observation area wall. Just in front of these items are the VMS SIO and a row of four electronics racks that contain the following five items: two CIOUs, RIOU 0, RIOU 2, and the control electronics chassis for the sound system. Scattered around the perimeter of the room are several desks and tables to provide work space for test support personnel. Television monitors mounted overhead are connected to the Video Switch and are most commonly used as repeaters for pilot displays such as the out-the-window scene and auxiliary display imagery.

SEP/PEP stations– The SEP and PEP Stations are two similar work stations that provide the simulation engineer and researcher with a central control and communications facility for test operations. The names derive from the Simulation Engineer's Panel (SEP) and Project Engineer's Panel (PEP). These custom-designed panels provide a primary means to control the simulation and interact with the mathematical model operating in real time. The SEP and PEP contain 32 software-configurable switches and indicators that are connected to DIs and DOs located in RIOU 0. Four of these switches and indicators are dedicated to selecting the operating mode of the host computer, three others are dedicated for motion-system and host-computer control functions, and one is used as a "host-computer cycling" indicator light. The remaining 24 switches and indicators are available for general simulation control functions such as failure mode initiators, print controllers, or display mode selectors.

The SEP Station also contains two DEC VT320 computer terminals, a time-of-day display, an intercom station, and a video selection panel that controls what is displayed on the overhead monitors. The terminals are connected to the Micom LAN, and either can be used for foreground
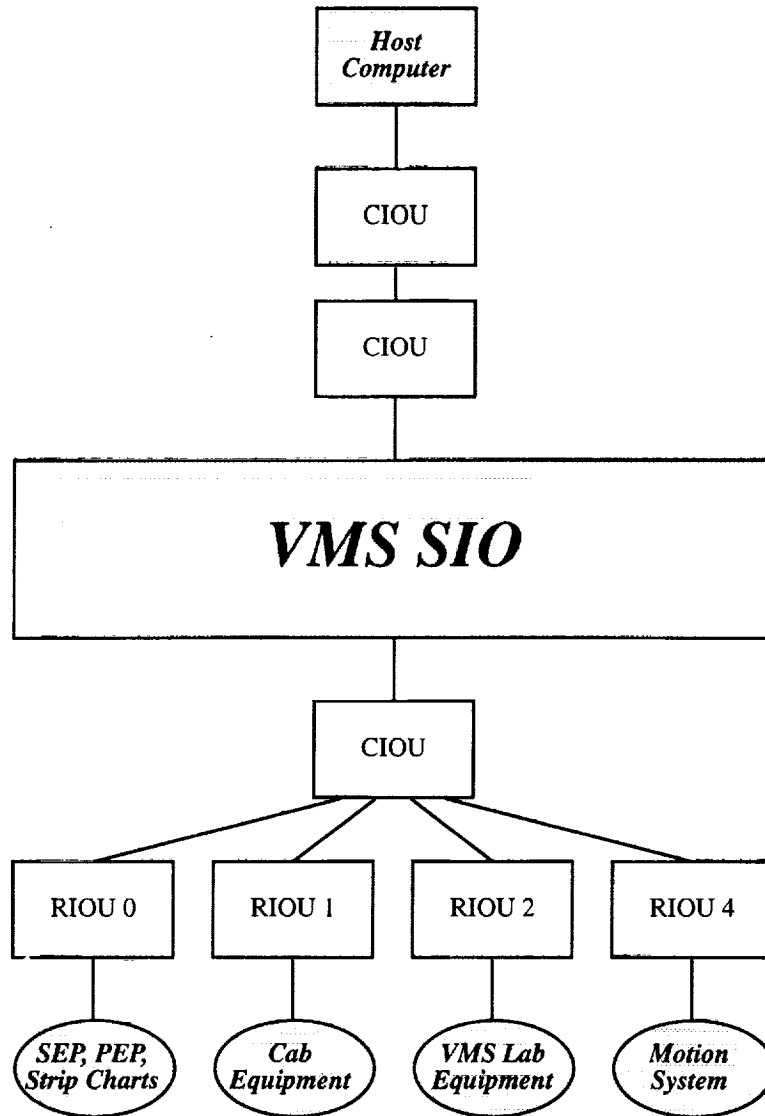
11

Figure 6. VMS SIO connections.

(real-time) or background (non-real-time) communication with the host computer.

Additional equipment located at the PEP Station include an audio tape recorder for recording voice communications and two video recorders—a Sony U-matic 3/4-in. professional-grade model and a standard VHS-format unit. The PEP station also provides room for video monitors that can be used to display various types of imagery such as image-generator scenes and auxiliary displays, depending on test requirements.

Strip-chart recorders– The control room contains eight Gould 200 strip-chart recorders that are connected to RIOU 0 for recording real-time simulation data. These devices operate by drawing chart paper at a controlled rate under a series of pressurized ink pens that deflect perpen-

dicular to the paper motion in response to input voltages. The input voltages are provided by DACs that are programmed and scaled by software in the host computer to represent the real-time data of interest. The result is a continuous time history (data versus time recording) of the desired parameter. Three of the recorders are dedicated to recording motion-system parameters, and the other five are available for general-purpose use. Each recorder has eight separate data channels; however, special software allows multiplexing two parameters per channel, so a maximum of 128 parameters can be recorded of which 80 are user-selectable. All the recorders have standard three-position, bidirectional event markers in the right and left margins of the chart, and most of them have seven additional event markers between the data channels.
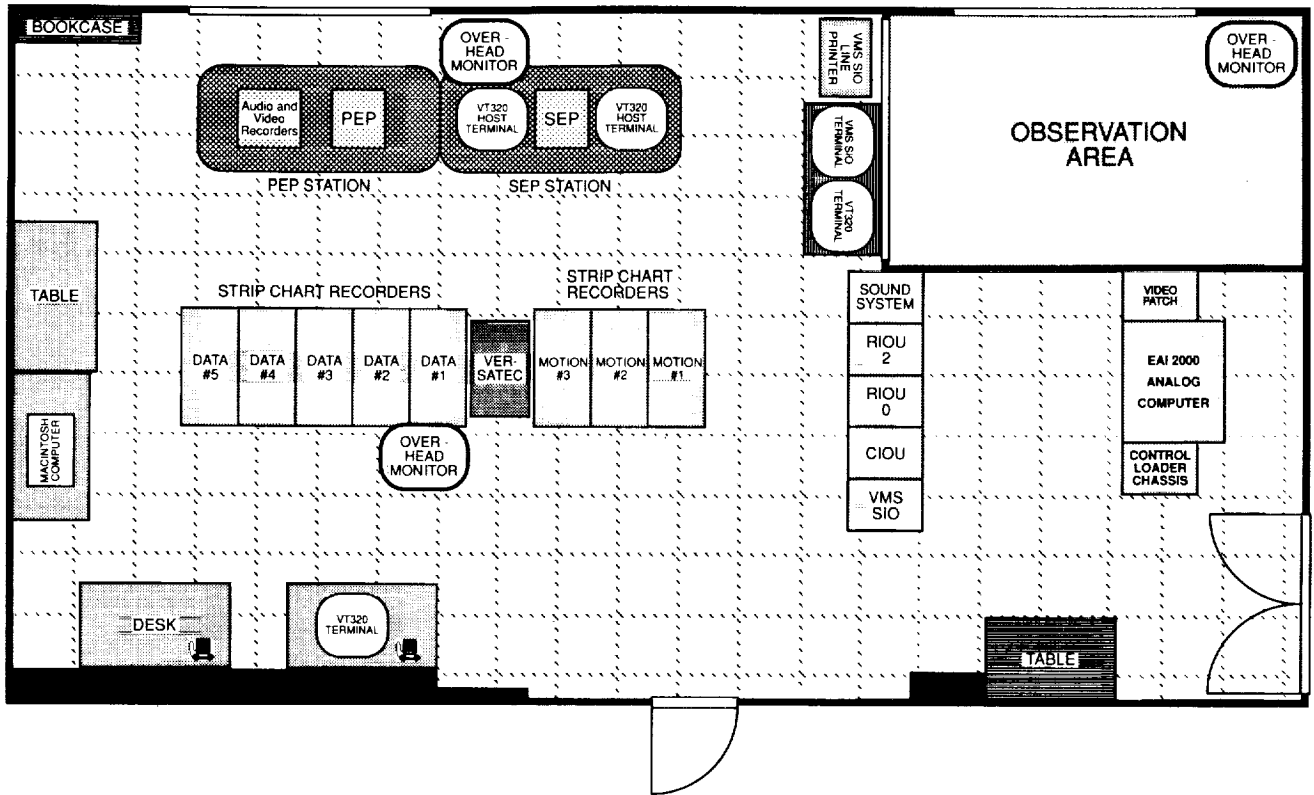
12

Figure 7. Plan view of the VMS lab.

Twelve chart speeds varying from 0.05 to 200 mm/sec are available, and these can be selected manually using push-buttons on the horizontal panel in front of the recording surface. In addition, a full remote-control capability is available that allows control of chart speed and start/stop from the host computer. Each data channel is 40 mm wide, and typical chart paper divides this into 50 divisions. A vertical panel behind the recording surface provides manual controls for setting sensitivity, pen position (bias), attenuation, and input polarity for each channel. Convenient pushbuttons provide for selection of seven sensitivity settings ranging from 0.05 to 5 volts per division (2.5 to 250 volts full scale) and an OFF selection. Zero-volt pen position can be biased anywhere over the entire deflection range. The controls are normally set up for positive polarity, zero attenuation, zero bias, and ±10 volts full-scale deflection, since the polarity, bias, and sensitivity for the individual parameters are effected through DAC scale settings as mentioned above. The strip-chart recorders also have an automatic chart-logging feature that prints recorder number, date, time of day, and a user-defined run number directly on the chart paper at the end of a data run.

Intercom– The intercom is a critical simulation component because it provides communication among the pilot(s), test conductors, and the other personnel involved in the simulation. It is, in fact, the only direct communication link to simulator pilots when the motion system is in operation. SimLab uses a commercial intercom system produced by Roh, Inc., that is networked throughout Building N243 and several adjacent buildings. The system has 10 separate channels, which are allocated to the different labs and other areas where simulation-system components are located.

The intercom system consists of a master station and a number of network stations connected by cables. The master station contains central switching hardware and power supplies, including a battery backup so the system can continue to operate in the event of a total building power failure. The network stations provide a means for connecting into and using the system and are distributed around SimLab at key locations. The system is compatible with various types of microphones and speakers, although special adapter cables may be required for certain items. Each network station provides three microphone jacks, three headphone jacks, and three headset (combination microphone/headphone) jacks. It also contains a built-in speaker, volume controls for all speakers, and channel-selector pushbuttons. Although pilots commonly use

13

lightweight headsets, the stations are compatible with the intercom features of common aircraft helmets.

Interchangeable Cabs

General features and construction– The four Interchangeable Cabs maintained and operated by SimLab provide the capability to simulate the cockpit/crew station for almost any imaginable aerospace vehicle. The ICABs are built up around essentially identical structures that furnish a basis and framework for installing and mounting the numerous items that make up a crew station. The basic design and construction of the ICABs is illustrated in figure 8. In order to achieve the desired interchangeability, the ICABs are built to rigid mechanical, hydraulic, and electrical interface specifications. The structure of each cab is composed of four substructures—the base structure, the fixed-canopy section, the removable canopy, and the Image Presentation System support structure.

The base structure is a large, flat weldment fabricated from aluminum channels, tubing, and plate. It forms the floor of the cab and serves as the attachment to the Motion System. All the other substructures are bolted to

it. Detachable front and rear sections facilitate transporting the cab between the off-line development area and the VMS. The under-floor structure is designed to provide three adjacent oil-tight bays to accommodate the electro-hydraulic control loaders used to simulate the primary aircraft flight controls. The three different locations allow for either a single, centrally located pilot station or a two-place, side-by-side arrangement. Wiring harnesses, hydraulic lines, junction boxes, instrument panels and consoles, electrical power outlets, as well as other items are mounted directly to the base structure.

The fixed-canopy section is a weldment built from square-section aluminum tubing, channel, and formed sheet with a sheet-aluminum outer skin. It forms the rear wall of the cab and provides a sturdy structure for mounting a number of items including cab lighting fixtures, sound-system speakers, and the main electrical power distribution box. It contains built-in, standard-size electronic racks for necessary equipment such as the cab RIOU. The fixed-canopy section also contains the personnel access door, several equipment access doors, and an air-conditioning unit that is mounted on its roof.
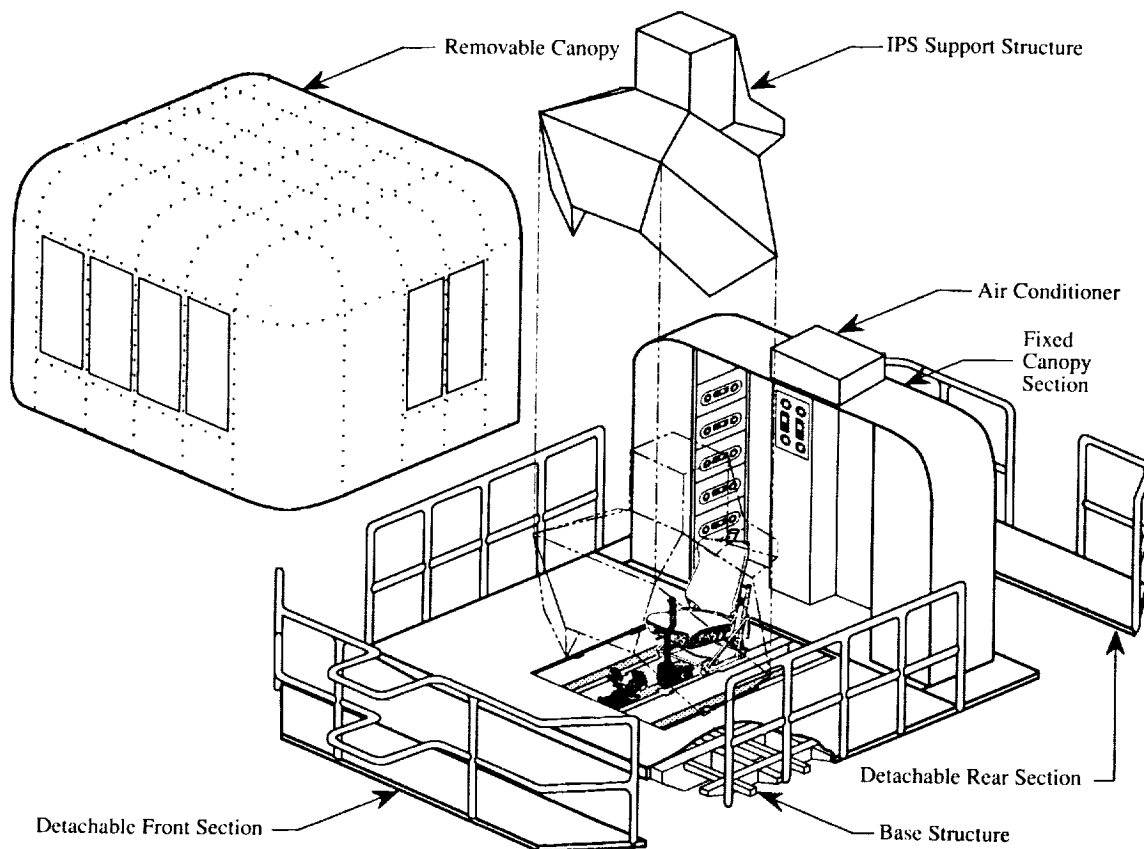

Figure 8. Exploded view of a typical ICAB.

14

The removable-canopy section is a lightweight shell made of welded aluminum, square-section tubing covered by aluminum sheet. It forms the front wall, side walls, and the roof of the cab, and its primary functions are to enclose the equipment contained inside the cab and to provide a sound and light barrier to prevent distractions to the pilot. The interior surfaces are covered with sound-deadening foam. As its name implies, this section can be easily removed by taking out 16 cap screws and lifting it with an overhead crane. This is useful because it allows unrestricted access to the other substructures and items mounted inside. The canopy also contains a number of strategically located, removable panels to provide access to internal equipment and two large panels that pop out to provide emergency egress openings.

As indicated in the Overall System Description, the Image Presentation System support structure is the only ICAB substructure that varies markedly from cab to cab. Each, however, is fabricated from similar materials using similar construction techniques. Each IPS support structure forms a space frame that accurately locates the individual display windows and provides secure attachments for the components of the IPS . These components consist of the video monitors and virtual imaging optics, and since these items are relatively large and heavy, the IPS support structure must be strong, stiff, and resistant to fatigue. The primary structure is made of aluminum channel and angle beams with aluminum-sheet shear panels. Mechanical fasteners, either bolts or rivets, are used exclusively in all but the NCAB IPS, which has some welded joints. Details concerning the geometry of the four different IPSs are presented in the later section entitled "Visual Display System."

In addition to the basic design and structural layout, the four ICABs share other features and items of equipment. In some cases the equipment is shared in a literal sense (for example, safety equipment) because it is only necessary when the cab is mounted on the VMS Motion System. A detachable railing encircles the base structure and provides a safety barrier for personnel walking on the deck outside the cab canopy. This railing has an opening that leads onto the boarding ramp for personnel access. A doorstop that activates automatically when the boarding ramp is pulled away causes the normal access opening in the railing to be blocked by the cab door, so the door acts as a safety barrier whenever the boarding ramp is not in place. Attached to the deck is a retractable ladder that provides emergency egress from the cab to the lateral carriage of the Motion System should the normal boarding ramp be unusable for any reason. Other safety-related items in each ICAB include fire detectors, emergency lights, fire extinguishers, and emergency oxygen packs.

Each ICAB has two interface panels mounted externally on the back wall of the fixed-canopy section. The first panel contains 32 electrical connectors and serves as the interface for all electrical and video signals entering and leaving the cab. The second panel is a hydraulic interface for the control loaders. Both these interfaces are strictly controlled to assure compatibility among the four ICABs. Each ICAB also has a set of signal distribution boxes attached to the lower portion of the IPS support structure. These boxes provide a convenient and flexible means for connecting the numerous small electrical devices in the cab, such as flight instruments, control buttons, and switches. All the ICABs feature a modular instrument panel that allows the instrumentation/display layout to be specially designed for each simulation. In addition, modular consoles can be installed to the side of the seat(s) and outfitted as required to simulate center or side consoles to suit specific research requirements.

NCAB– The NCAB is the original ICAB and is a single-place cab designed primarily to support helicopter simulations. The pilot station is located in the center of the cab, and the IPS consists of four windows that are separated to spread the area of coverage. One window is located directly in front of the pilot, with two others on either side of it. The field of view provided by these three windows is approximately rectangular and spans from +70° to –60° in azimuth and +9° to –15° in elevation. The fourth window is located below the upper right window, in an area where a helicopter's right-side chin window might be. Two types of pilot seat are available—either a commercial airliner First Officer's seat manufactured by Weber Aircraft, Inc., or a Sikorsky UH-60 Blackhawk helicopter seat.

RCAB– The RCAB is another single-place cab designed to support helicopter simulations. The IPS arrangement is very similar to that of the NCAB, with three windows in a line in front of the centrally located pilot station and a fourth "chin window." The RCAB windows, however, employ an improved design that makes much better use of the available monitor display area, thereby providing a larger total field of view with smaller gaps between the windows. The three upper windows in the RCAB span a field of view from +78° to –77° in azimuth and +12° to –17° in elevation. The choice of pilot seat is the same as for NCAB.

FCAB– The FCAB is designed to simulate single-seat fighters and similar aircraft types. The single pilot station is centrally located, and the IPS uses three windows to form a continuous wraparound display. The display is in the shape of a shallow, inverted U and is symmetric about the vertical axis. Because of this, the area available for the primary instrument panel is somewhat limited compared to that of the other ICABs. Again, two types of pilot seat

are available—the Blackhawk helicopter seat and a British Aerospace Harrier seat modified for use in the FCAB.

SCAB– The SCAB was originally developed to support Space Shuttle simulations, but is appropriate for any simulation requiring a two-place, side-by-side cockpit. Two crew stations are provided. These use the left and right control loader bays, and the center bay is left empty to provide floor space for a center console. The IPS consists of two windows focused at the pilot (left-seat) design eyepoint and one at the copilot (right-seat) design eyepoint, so that the pilot station has a forward and left-side window while the copilot station has only a forward window. The field of view provided by the IPS spans from $+19°$ to $-56°$ in azimuth and $+6°$ to $-21°$ in elevation for the pilot station and from $+17°$ to $-17°$ in azimuth and $+6°$ to $-15°$ in elevation for the copilot station. The SCAB uses two Weber First Officer's seats for crew seats.

Motion System

General description– The VMS Motion System is a very large, six-degree-of-freedom electromechanical/ electrohydraulic servosystem. It is located in, and partially supported by, a specially constructed tower at the east end of Building N243. The tower's dimensions are 73 ft wide by 36 ft deep by 120 ft high, and the motion system uses virtually the entire interior volume of this tower. The physical layout of the motion system and major support equipment and facilities is shown in figure 9. The motion system is really two integrated motion generators, an electrically driven system that provides two translational degrees of freedom and a hydraulically driven system that provides the remaining translational and three rotational degrees of freedom. Figure 10 is a cutaway view of the VMS tower that illustrates the motion system and some of its major components.

The basis of the entire motion system is a fabricated beam structure called the *vertical platform* that completely spans the width of the tower. The vertical platform is mounted on two columns that extend downward into 75-ft-deep shafts under the tower floor. It is restrained at both ends and at the center of its span by wheel assemblies that ride along vertical guide rails attached to the tower walls. Each vertical column is also part of a unique system called an equilibrator, which acts as a pneumatic
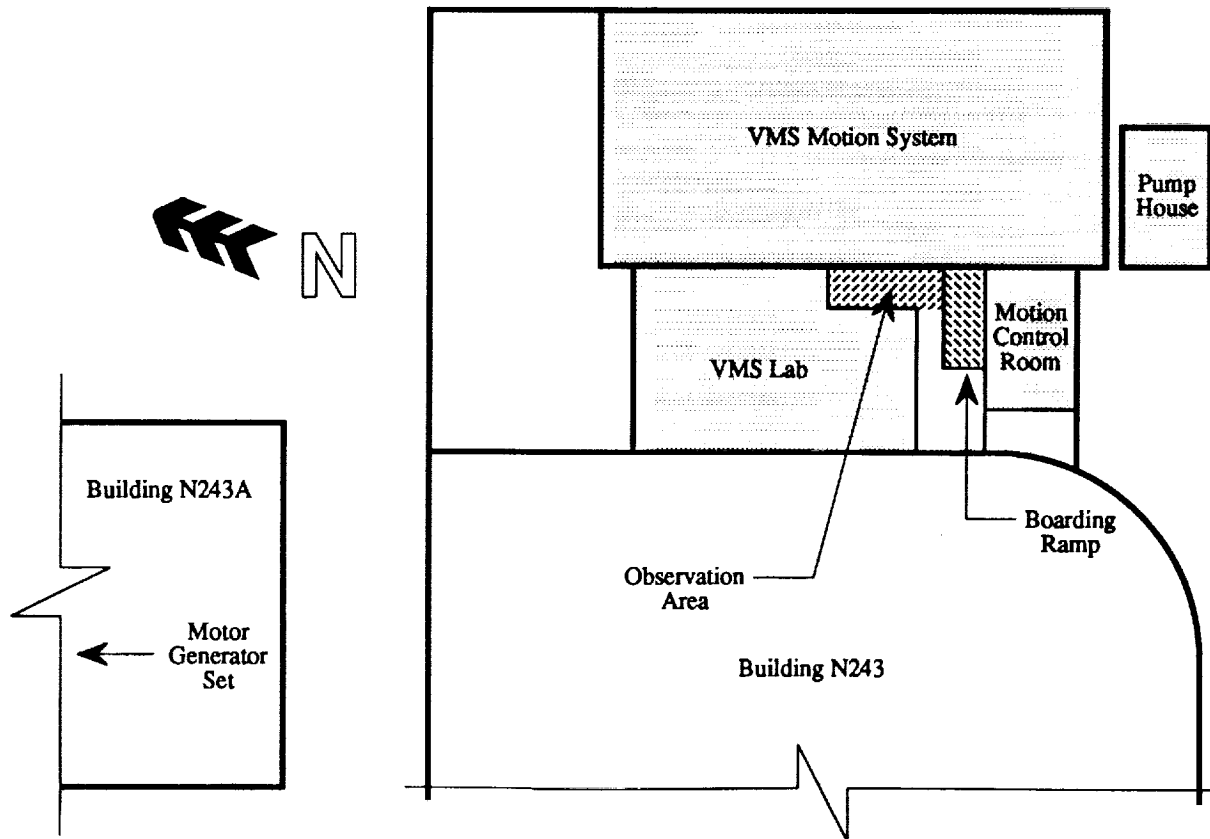

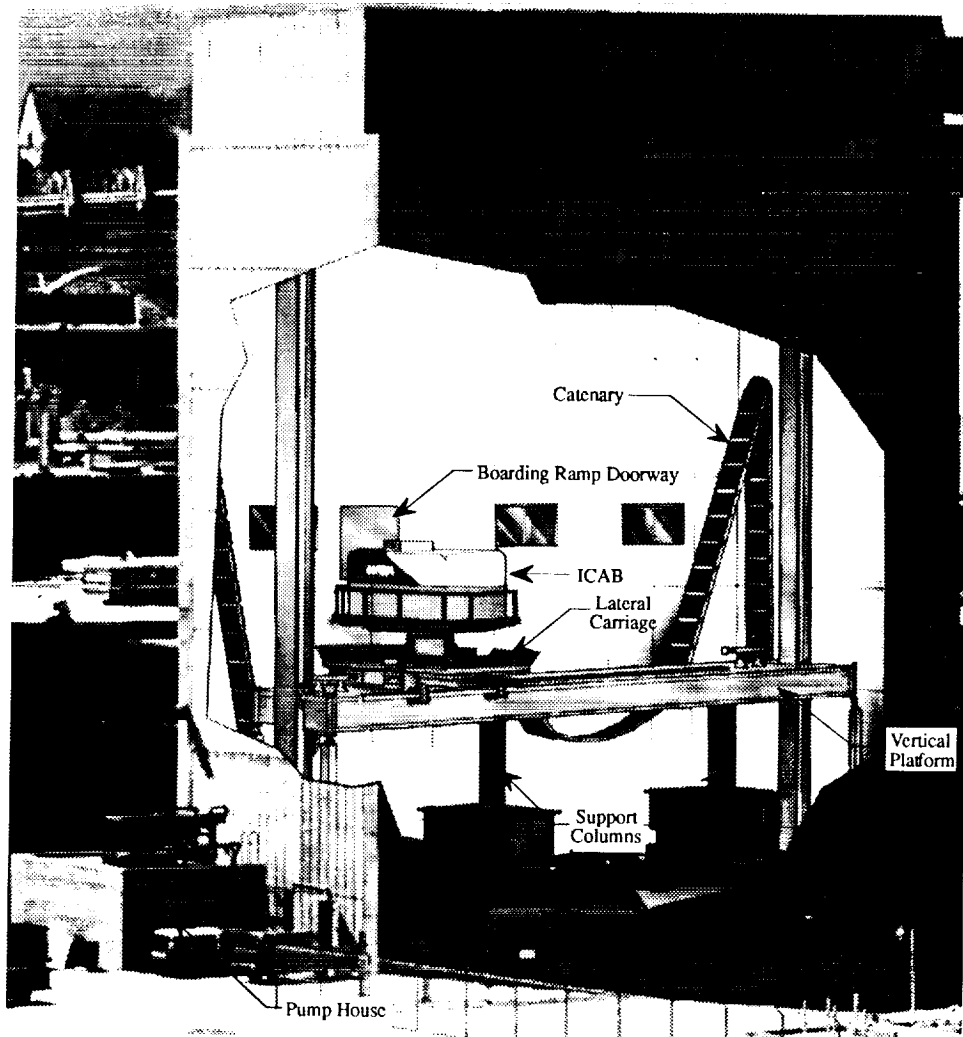*Figure 9. VMS motion system physical layout.*

16

Figure 10. VMS tower cutaway showing motion system at Dock.

counterweight. The column, which is hollow, slides over another tube mounted inside it so that the two, along with a gas-tight seal between them, form a cylinder/piston arrangement. The equilibrators are pressurized with nitrogen gas supplied by a special storage system so that the pressure forces[5] just balance the weight of the motion system and its payload, a total of approximately 140,000 pounds. The entire assembly is driven in the vertical direction by eight mechanically coupled 150-horsepower direct-current servomotors through reduction gearboxes and a rack-and-pinion drive system with the racks mounted on the vertical columns. Motions along the long dimension of the VMS tower are provided by a smaller platform called the *lateral carriage* that is mounted on the vertical platform. The lateral carriage is supported and restrained by wheel assemblies, which ride

along two guide rails that are attached to the top front and rear edges of the vertical platform and that run its entire length. Motive power for the lateral carriage is provided by four 40-horsepower direct-current servomotors mounted on it. These drive through reduction gearboxes and rack-and-pinion drive systems with the rack mounted on the top surface of the vertical platform. Electrical power for the VMS drive systems is provided by a dedicated transformer in conjunction with a motor-generator set located in Building N243A. The motor-generator set consists of two large direct-current generators driven by a single 12,000-horsepower synchronous motor.

The hydraulically powered motion generator is mounted atop the lateral carriage. The remaining translational motion is provided by the *longitudinal carriage*, which is mounted on 32 recirculating ball-bearing block assemblies that in turn ride on two linear tracks bolted to the lateral carriage. Yawing motion is provided by a 48-in.-diameter

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[5]Equilibration pressure for the current configuration of the motion system is 425 psi.

circular crossed-roller bearing mounted in the center of the longitudinal carriage. This bearing supports a conical center post that has a two-axis gimbal at its upper end to provide pitch and roll motions. The outer gimbal serves as the mounting surface for the ICAB. Linear hydraulic actuators that differ only in stroke length drive all four degrees of freedom. These actuators feature a patented telescoping configuration that results in equal, effective hydraulic operating areas in both directions of travel. The nominal working pressure of the hydraulic system is 2000 psi, and the maximum total flow rate is 300 gal/min. Hydraulic power is furnished by a specially designed hydraulic power supply located in a pump house just south of the VMS tower.

Hydraulic fluid pressure and return lines and electrical power and signal cables are carried on flexible, ladder-like structures called "catenaries" that stretch between the lateral carriage and the tower walls. Personnel access to the cab is provided by an extensible boarding ramp at the second-story level of Building N243. The boarding ramp rolls outward 10 ft from the west tower wall to meet with the cab floor when the motion system is at its dock position.

Control and safety systems– Overall control of the motion system is vested in a specially trained and certified person called the Motion Operator. The Motion Operator is stationed in the Motion Control Room, which is located across the hall from the VMS Lab and contains the necessary operating consoles as well as servocontrol equipment for the motion system. The consoles contain controls for operations such as activation of the electrical and hydraulic power sources, system start-up, normal and emergency shut-down, and manually controlled movement of the system. The Motion Control Room also contains annunciator panels, gauges, and other equipment to monitor the status of the motion generator and its safety systems.

The electrically powered servos (vertical and lateral) require three input signals proportional to displacement, velocity, and acceleration. The displacement commands require a specified scaling, but the velocity and acceleration scalings are adjustable and are varied to tune the dynamic characteristics of the servos, in effect functioning as variable feed-forward compensation. Custom-designed electronics process and condition the input signals to generate control signals for the drive motors. Displacement, velocity, and pseudo-acceleration (actually motor current) feedback loops are closed using signals from appropriate sensors. For the vertical servo, control signals are fed to two thyristor controllers, each of which regulates the current to the control field of one of the generators in the motor-generator set mentioned above. The

generators are cross-connected to the vertical-drive motors so that each one drives two motors on the north column and two on the south column. For the lateral servo, control signals are fed to four thyristor controllers, each of which rectifies and modulates current from the dedicated transformer to power one of the lateral-drive motors.

The hydraulically powered servos require only one input signal, a displacement command. Input signals are filtered through a selectable-frequency notch filter to remove the effects of "staircasing" caused by the digital-to-analog conversion process. Each axis of motion has a servocontrol system that employs displacement, velocity, and differential pressure feedbacks, an internally generated velocity feedforward, and compensation networks to generate a control signal. This signal is used to control a servovalve, which in turn controls the motion of the hydraulic actuator to which it is attached.

Also located in the Motion Control Room is another extremely important system, the Mode Control Unit (MCU). The MCU serves as the primary interface between the motion RIOU and all six servosystems and also provides control over the mode of operation of the motion system. During normal operations, the Motion Operator manually selects modes using switches mounted in the operating console. There are five modes, identified as (1) Dock Position, (2) Pre-Dock Position, (3) Center Position, (4) Initial Position, and (5) Operate. The Dock Position mode is the rest state for the motion system; the system is stationary, all inputs are disconnected, and the servos are locked in the position that allows personnel access to the cab. In Operate mode the motion system is under the control of the host computer and can be at any dynamic state within its performance limitations. The other three modes are steps between these two extremes. The MCU processes command and feedback signals and solves complex logical relationships to assure that the motion system is in the proper mode at all times and to properly transfer between modes. The MCU also assures that only input signals appropriate to the mode currently in effect are applied to the motion servos.

The motion system incorporates a comprehensive and complex set of safety features and devices to protect both the machinery and its occupants from injury. For example, every servosystem has built-in acceleration, velocity, and displacement limiters to assure that the motions stay within safe operating ranges under all conditions. In addition, each servo includes end-of-travel shock absorbers to safely arrest motions in the event of a runaway. There is also an integral safety interlock system. The MCU continuously monitors the status of a number of critical parameters and can disallow startup or automatically execute an

orderly shutdown if a parameter is out of tolerance. If, for example, the host computer fails while the system is in Operate mode, the MCU senses the change in the logical state of the system and automatically selects Center Position mode. As a result, the computer command signals are disconnected and the servos are slowly driven to their respective neutral positions, at which point appropriate actions can be taken by the Motion Operator and other personnel.

Performance– Up to this point the discussion of the VMS Motion System has considered the hardware exclusively. The performance characteristics of the system cannot be adequately addressed, however, without some attention to the *motion drives,* the host-computer software that computes motion-system drive signals. There are several facets of system performance that are affected or even determined by the motion-drive software, and these are discussed as they arise in the following paragraphs.

Maximum performance capabilities of the motion system in terms of displacement, velocity, and acceleration for each degree of freedom are presented in table 3. Included are two sets of limits: (1) *system limits,* which represent the absolute maximum levels attainable under controlled conditions and (2) *operational limits,* which represent levels that are attainable for normal piloted operations under control of the host computer. In cases where the system limits are greater than the operational limits, they are reduced by limiters in the motion drives. The operational limits listed in table 3 include the effects of all the limiters in the system, both hardware and software. The motion system also incorporates another type of limiter that is not reflected explicitly in table 3, the so-called parabolic limiter. A parabolic limiter acts to command maximum acceleration opposite to the direction of travel whenever the velocity and displacement are such that this maximum acceleration will stop the motion just short of a displacement limit. Each degree of freedom has parabolic

limiters implemented in both hardware (in the servocontrol electronics) and software (in the motion drives).

A unique feature of the VMS is that the translational degrees of freedom in the horizontal plane can be readily interchanged. The yaw actuator can be attached in two different locations, 90° apart, so that the fore-and-aft axis of the cab can be aligned either perpendicular to the vertical platform or along it. The larger displacement degree of freedom can therefore be used for either sidewards or fore-and-aft cab motions, whichever is more suitable for the particular simulation. The larger displacement degree of freedom is referred to as "lateral" throughout this document because this is the most commonly used configuration.

Describing functions for all six degrees of freedom are presented in figure 11. In addition to the variable velocity and acceleration commands for the electrically driven servos mentioned above, the motion-drive software includes for each degree of freedom, digital feed-forward compensators that can also be used to tune system dynamics. The plots in figure 11 represent the standard configuration of the motion system, with all these tunable parameters set to their nominal values. The describing functions also represent the motion system alone and do not include phase effects (time delays) associated with host-computer cycle time.

Another feature related to motion-system performance and implemented in the motion-drive software is the ability to modify the effective center of rotation for the roll and pitch axes. This is necessary because the cab floor is high enough above the gimbal center that pure roll and pitch accelerations produce significant anomalous translational accelerations at the pilot station. An algorithm in the motion drives calculates appropriate accelerations and applies commands to the longitudinal and lateral servos to effectively cancel the unwanted accelerations so that the pilot is not subjected to these anomalous motion cues.

Table 3. VMS motion system performance limits

| Degree of freedom	Displacement		Velocity		Acceleration	
	System limits	Operational limits	System limits	Operational limits	System limits	Operational limits
Longitudinal	± 4 ft	± 3 ft	± 5 ft/sec	± 4 ft/sec	± 16 ft/sec/sec	± 10 ft/sec/sec
Lateral	± 20 ft	± 15 ft	± 8 ft/sec	± 8 ft/sec	± 13 ft/sec/sec	± 13 ft/sec/sec
Vertical	± 30 ft	± 22 ft	± 16 ft/sec	± 15 ft/sec	± 22 ft/sec/sec	± 22 ft/sec/sec
Roll	± 0.31 rad	± 0.24 rad	± 0.9 rad/sec	± 0.7 rad/sec	± 4 rad/sec/sec	± 2 rad/sec/sec
Pitch	± 0.31 rad	± 0.24 rad	± 0.9 rad/sec	± 0.7 rad/sec	± 4 rad/sec/sec	± 2 rad/sec/sec
Yaw	± 0.42 rad	± 0.34 rad	± 0.9 rad/sec	± 0.8 rad/sec	± 4 rad/sec/sec	± 2 rad/sec/sec
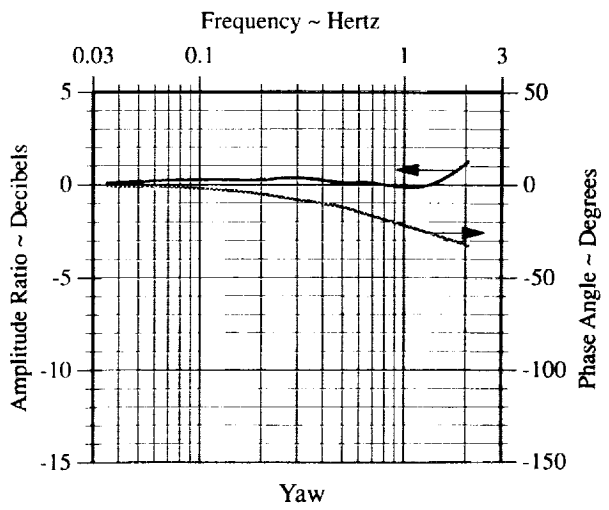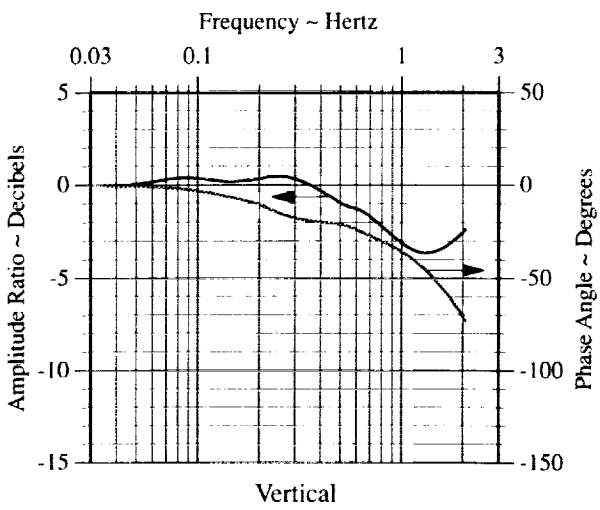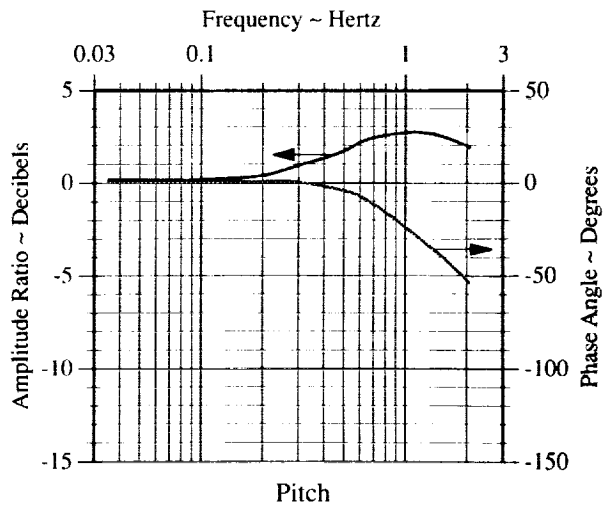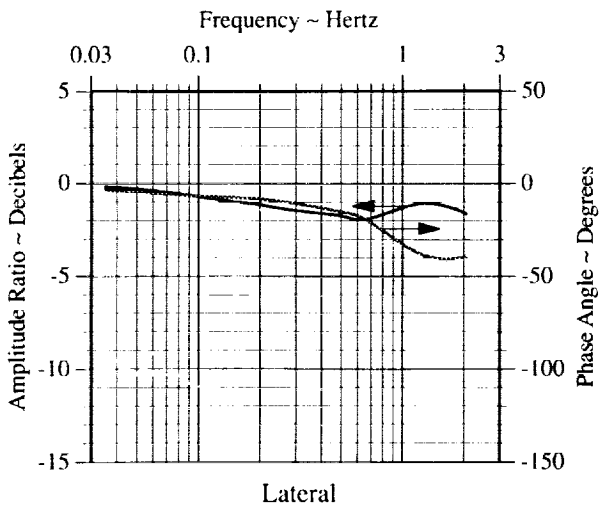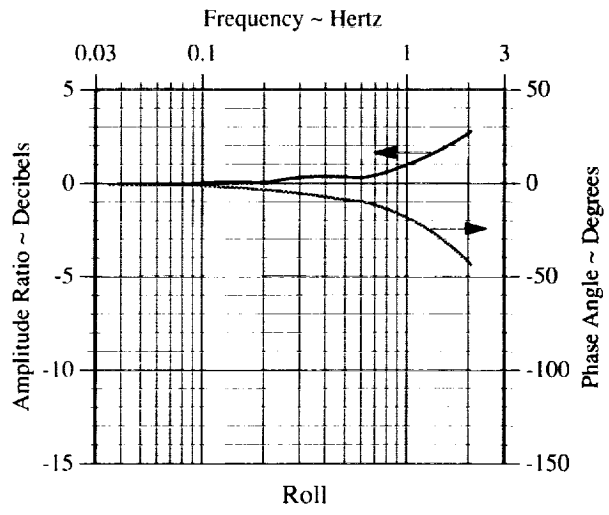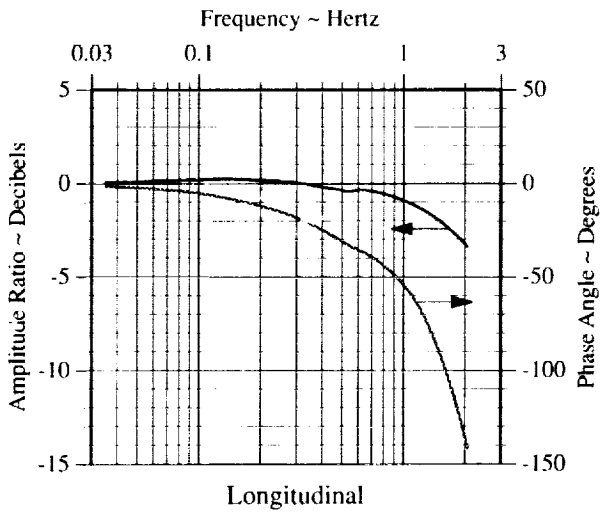
Figure 11. VMS motion system describing functions.

20

Visual Display System

Image generators– There are two Computer Image Generators (CIGs) available for VMS simulations—the Singer Link DIG1 and the Evans and Sutherland CT5A. The DIG1 has been in service since 1978 and is considered a first-generation CIG; the CT5A was delivered in 1985 and it is a second-generation system. The CT5A is newer and has significantly enhanced capabilities in many areas; however, the DIG1 has been developed and improved almost continually over its life span and has certain features which are not available on the CT5A.

DIG1: The DIG1 was produced by the Link Flight Simulation Division of the Singer Company originally for use in the Air Force's FB-111 Weapon System Trainer. It is a full-featured system that represents the state of the art in the late 1970s.

The SimLab DIG1 has four channels and two eyepoints.[6] The DIG1 is a raster-scan system, similar to normal television, except that its field is composed of many more scanlines, allowing a much higher resolution image. In addition, the scanlines run vertically rather than horizontally. The system operates at a field rate of 60 Hertz, and raster lines are interlaced in a 2:1 ratio. Each channel has a total capacity of 1024 raster lines of which 1003 are active video lines. Each line is composed of 875 pixels, so the pixel capacity is 877,625 pixels per channel or 3,510,500 total pixels. The DIG1 uses "edges" (described later) as the primitive to generate objects and therefore for specifying scene content; it can generate a total of 8192 edges or 4000 objects, whichever is less for a given scene. A more stringent limitation on maximum image complexity, however, is the inherent system limit of 256 edge crossings per scanline.

The DIG1 uses smooth shading to enhance image reality and has full color capability. The system can produce imagery representative of all lighting conditions—day, dusk, or night; and it can simulate a variety of atmospheric and meteorological effects such as clouds, fog, haze, and scud. Additional features that fall into the category of special effects are summarized in table 4. The DIG1 can also provide images of up to four independent

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[6]Each *channel* represents a distinct viewing area or "window" for which imagery can be generated and displayed. In fact, an image generator channel corresponds exactly to an IPS window. An *eyepoint* is the point in space from which the scene is viewed, and typically corresponds to the physical "eyepoint" of the pilot. Other eyepoints may be necessary, e.g., that of a second crew member or an adversary in a combat situation, or simply useful such as a "God's eye view" that depicts the scene from outside the simulated vehicle and shows its motion from the perspective of an external observer.

Table 4. DIG1 special effects

Effect or model	Description and comments
Scene illumination	Daylight, dusk, and night conditions can be simulated.
Clouds	Scattered, broken, and ragged clouds; overcast and towering cumulus cloud bank.
Ground lights	Runway lighting, runway strobe lights, VASI lights, obstruction lights, PAPI lights, and Ball Bar lights (Space Shuttle landing aid).
Ship lights	Shipboard PAPI lights and HAPI, CAI, and port side lights for LPH.
Weapons	Explosion, flash, and tracer streak.
Beacon	Blinks, multiple colors.
KC-135 refueling boom	Extends and retracts.
Sky object	
Farmland	Replicated patterns.
Lightning flash	
Raindrops on windshield	

moving models (for example, ground vehicles or other aircraft), and these are totally dynamic. Available moving models are listed in table 5.

The DIG1 can detect and report collisions between a simplified geometric representation of the simulated aircraft (referred to as the ownship) and solid objects modeled in the visual scene. One shortcoming of the system is its inability to calculate the distance between the ownship and any arbitrary point or object in the scene, which means that parameters such as radar altitude and line-of-sight distance to a target are not directly available.

A number of visual databases are available to DIG1 users, and these are summarized in table 6. Even though the existing databases cover a wide variety of generic terrain, cultural features, and real-world sites, a given database rarely suits a researcher's imagery requirements exactly. Almost every project has some special requirement, unique feature, or combination of special effects that necessitates modification of one of the standard databases. For this reason, SimLab maintains a staff of skilled graphics programmers who modify and develop databases to fulfill researchers' needs on a case-by-case basis.

Table 5. DIG1 moving models

Model	Description and comments
AV-8B	U. S. Marine Corps Harrier assault aircraft.
C-17	U. S. Air Force transport aircraft.
F-111	U. S. Air Force Aardvark strike aircraft.
E7-STOVL	General Dynamics short takeoff/vertical landing design concept research aircraft.
KC-10	U. S. Air Force aerial refueling tanker based on the McDonald Douglas DC-10.
KC-135	U. S. Air Force aerial refueling tanker based on the Boeing 707.
MiG-21	Soviet Fishbed fighter aircraft.
MiG-23	Soviet Flogger fighter aircraft.
MiG-27	Soviet Forger fighter aircraft.
Shuttle	NASA space shuttle orbiter.
STOVL	McDonald Douglas short takeoff/vertical landing design concept research aircraft.
Hind	Soviet Mi-24 troop transport/attack helicopter.
Hokum	Soviet attack helicopter.
RAH-66	U. S. Army Commanche scout/attack helicopter.
UH-60	U. S. Army Blackhawk utility helicopter.
V-22	U. S. Marine Corps Osprey tiltrotor aircraft.
Carrier	USS Coral Sea Midway class aircraft carrier.
DD963	Spruance class destroyer (with helicopter landing pad).
Inchon	USS Inchon Iwo Jima class amphibious assault ship.
SAM	Soviet surface-to-air missile system mounted on a tracked vehicle.
ZSU	Soviet radar-directed anti-aircraft gun mounted on a tank hull.
Chute	Space shuttle drag chute.
Flare	An orange and red colored, cone-shaped object used to represent a decoy for infrared missiles.
Sting	A white and gray colored, cone-shaped object used to represent a missile plume.

DIG1 hardware consists of four major subsystems as depicted in the hardware architecture diagram in figure 12. The Controller is actually a general-purpose computer that is located in an adjacent room, whereas the Frame Calculator, Scanline Computer, and Video Generators are all custom-built, special-purpose units mounted in their own cabinets.

The Controller is a Perkin Elmer Model 3244 computer that operates on a 32-bit word and has 4 MB of directly addressable central memory. This computer controls the flow of data throughout the entire DIG1 system. It receives inputs from the host computer, retrieves database information from disk storage, performs its own calculations, and transfers relevant data and commands to the Frame Calculator. It also performs diagnostic control and monitoring functions and furnishes color-table update data to the Video Generator. The calculations include extrapolating position and attitude data for the ownship and other moving objects and calculating object priorities, which are later used to determine occulting. The disk storage unit is the device used to store the visual database (as well as other data) in digital form. Other peripheral devices that support the Controller are a magnetic tape unit, an input terminal, several printers, and a flight control console that allows "flying" through the database independent of a host computer. Also located in the vicinity are several monitors that are used to observe the actual video output of the system.

The Frame Calculator operates on the imagery in a global sense. It accesses objects from the database in the form of vertices and, after applying appropriate coordinate transformations, tests to ascertain if faces are visible from the selected eyepoint. It then translates the information to coordinate systems corresponding to each output channel (display monitor) and calculates intensity descriptors. Lines and objects are then "clipped" to eliminate everything not within the displayed field of view. Finally, the vertices are transformed into a display-compatible, two-dimensional form called edges along with an associated set of display parameters.

The Scanline Computer receives the imagery data in the form of edges and breaks it down into a digital description of individual scanlines. Edges are first sorted according to scanline, and redundant parameters are discarded. Edges are then sorted and prioritized for each scanline. At this stage, the hardware can store data for a maximum of 256 edges, and this is the basis for the aforementioned display content limitation. Next, each intersection of an edge with a scanline is evaluated for occultation, and occulted edge crossings are discarded. This circuitry has a maximum capacity of 256 occulting priorities. The final operation in the Scanline Computer is to map the imagery data into individual pixels.

Imagery is now in the form of digital data that characterize (1) each intersection of an edge and a scanline and (2) display parameters that describe the scanline segment up to the next edge crossing in terms of intensity, fading, color, and shading. The four Video Generators expand these digital descriptions into the red, blue, and green

Table 6. DIG1 visual databases

Database name	Description and features
A109NOE	A very complex database designed to provide a nap-of-the-earth (NOE) flight gaming area. One half is a large valley with two artificially gridded regions to provide enhanced ground surface cues and numerous trees, some arranged in clumps and others in regular rows. The other half consists of winding ravines filled with trees surrounded by a perimeter of steep mountains.
OAHU/HIKM	A conventional airport database modeled after Honolulu International Airport. Cultural features include Pearl Harbor, Diamondhead, mountains, and some city details.
Crows landing	An airport database modeled after Crows Landing Naval Air Station. There are two crossing runways surrounded by a dark green patchwork groundplane with mountains in the distance. Also included are taxiways with an artificial checkerboard pattern for enhanced ground surface cues and "hover boards" used for conducting vertical and lateral flight test maneuvers.
FTRIM and STO series	This is a series of databases that are all based on of the Crows Landing database. All versions have the Crows Landing runways, taxiways and hover boards. The variations that distinguish the different versions include the addition of cultural features (trucks, cones, pylons, and oil drums), color changes and demarcation stripes. The STO series includes STOL markings on the runway and AV-8B takeoff assist ramps.
RATAC	A database designed to support helicopter air combat simulations. The terrain is basically mountains, hills, and valleys. Cultural features include a vertiport, a farm site, multiple SAM launchers, a river, and a highway.
C17DB	A very simplistic database composed of rolling hills and a basic runway.
MV22TFTA	Another simplistic data base composed of hills, mountains, flat terrain, and a basic runway.
OIL.RTB	An ocean database that includes an oil derrick. Various sea states can be simulated.
Space shuttle series	A series of databases developed to support Space Shuttle simulations, all representing Shuttle landing sites. Included are Edwards Air Force Base, Kennedy Space Center, Zaragosa, Banjul, Ben Gurier, Dakar, and Moron.
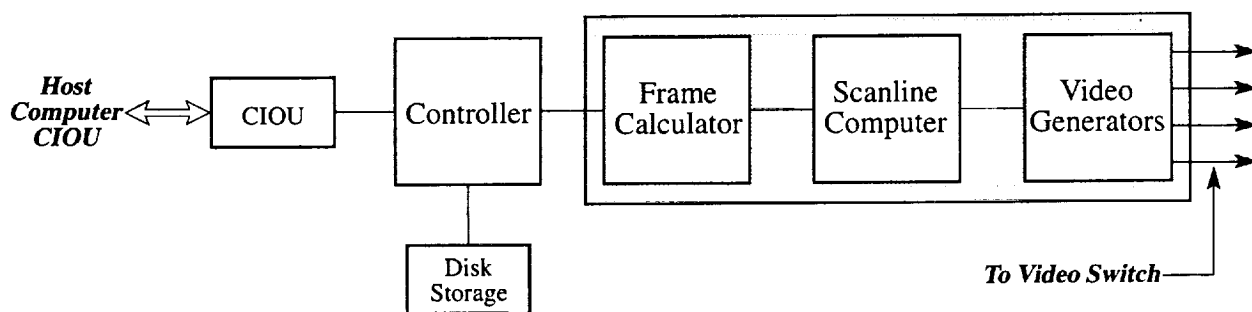
Figure 12. DIG1 system architecture.

components of the color, intensity, and fading for each pixel, convert them to analog form, and sum them to generate drive signals for each of the display monitors. The Video Generators also perform vertical and horizontal edge smoothing to alleviate "staircasing" and generate vertical and horizontal synchronization signals required by the monitors. Signals from the Video Generators are transmitted to the Video Switch for routing to the Image Presentation System in the cab and other monitors.

CT5A: The CT5A is approximately a decade newer than the DIG1, and its design and construction reflect improvements in electronics and computers that occurred over that period. The CT5A was manufactured by Evans and Sutherland (E&S) and was procured for SimLab as a part of a joint NASA/Army effort to enhance VMS capabilities for helicopter simulation called the Rotorcraft Systems Integration Simulator Project.

The SimLab CT5A is a three-channel, single-eyepoint image generator. It is a raster-scan system with a 2:1 interlace ratio, and it possesses a programmable scan capability that allows it to operate at a variety of scanlines and field rates, and with either horizontal or vertical raster

lines. Currently available scan capabilities are listed in table 7. The CT5A has a capacity of 786,432 pixels per channel or a total of 2,359,296 pixels for the entire system. The scene content capacity is a maximum of 1,500 polygons[7] per channel or 3,750 polygons for all three channels.

Table 7. CT5A programmable scan capabilities

Total scan lines	Field rate
875	50 Hertz
525	60 Hertz
839	60 Hertz
945	60 Hertz
1024	60 Hertz

The CT5A has many design features to enhance overall image quality. It incorporates advanced anti-aliasing techniques and multilevel overload management. Various types of shading are available including smooth shading, flat shading, fixed shading, and color blending. Three basic ambient lighting levels and a wide variety of atmospheric effects can be simulated. A total of 16,777,216 different colors are possible. A number of special effects are also available and are summarized in table 8. Up to four independent moving models can be presented simultaneously; these can be selected from a set of existing aircraft and ground vehicles, or a special model can be generated. In addition to solid objects, the CT5A can model point lights to simulate items such as airfield lighting, strobe lights, landing aids, rotating beacons, highways, and moving ground traffic.

The CT5A provides collision detection between selected points on the ownship and "collision volumes" that are modeled separately to represent items in the database. Height above terrain is also available, as is line-of-sight distance to other visible surfaces.

Like the DIG1, the CT5A has a number of visual databases available for general use, and these are presented in table 9. Also, these can be enhanced or modified, or new databases can be generated to suit individual research requirements.

Figure 13 illustrates the hardware configuration of the CT5A and the system architecture. The Image Generator is composed of a general-purpose computer and special-

[7]The CT5A employs polygons as the imaging primitive rather than edges. A typical database has an edge-to-polygon ratio of approximately 3:1.

purpose hardware called the Image Processor which together occupy a total of seven standard equipment racks. The Image Processor is further broken down into sections called the Viewpoint Processor and the Channel Processor.

The general-purpose computer is a standard DEC PDP-11/44, which is a midrange minicomputer that uses a 32-bit word and DEC's UNIBUS bus structure. This particular machine has 1 MB of central memory capacity. The general-purpose computer manages and monitors the rest of the system and also serves as an interface between the Image Processor and the host computer through a CIOU/CIOU link. In addition, it hosts a number of peripheral devices (including the Disk Storage unit on which the visual database is stored) and supports off-line activities such as database development and system maintenance.

The Image Processor is configured as a pipeline of processing units with computing tasks distributed along a chain of dedicated computing elements. Distributed throughout this chain are a number of field buffer memories as shown in figure 13. One display field time (the inverse of field rate) is allocated to process and transport data from one field buffer to the next, so that each device operates at its own pace and scene complexity is limited to that of a single image field.

The Viewpoint Processor contains two elements, the Object Manager and the Polygon Manager. These elements perform computations that apply to the system as a whole and are channel independent. The functions performed include identifying the subset of the database required for the given eyepoint, fetching the appropriate data, culling it to extract the minimal set of required scene elements, and ordering the scene elements from front to back relative to the eyepoint. The result is data that represent scene elements that are potentially in view, front-faced, and at the proper level of detail depending on the distance from the eyepoint.

The Channel Processor consists of a Geometric Processor and three Display Processors for each channel. The Geometric Processors transform the model space description of scene elements from the Polygon Manager into the two-dimensional perspective images that will be "drawn" on the face of each display. The operations performed include axis transformations, clipping to eliminate portions of scene elements outside the field of view, and perspective division. The result is data that represent an image-plane description of the entire scene, which is stored in the Geometric Processors' field buffers.

The Display Processors perform hidden-surface removal and convert the data into the appropriate scan format for

Table 8. CT5A special effects

Effect	Description and comments
Scene illumination	Three basic levels available to simulate day, dusk, or night conditions
Transparency	Can be used for windows or fixed geometry shadows
Horizon glow	Available for dusk and night conditions only
Hazy horizon	Similar to horizon glow
Ground haze and fog	Visibility controllable from 0 to 20 nautical miles
Patchy fog	Pseudo-random variations in visibility
Clouds	Overcast, scud, and tops of clouds from above available
Smoke	Visibility and color both controllable
Missile trail	Smoke plume either fixed or animated
Target destruction	Animated burst
Rotor effects on lighting	Simulated flicker through rotor blades

Table 9. CT5A visual databases

Data base name	Description and features
Hunter-Liggett	A very detailed database designed primarily to provide a rotocraft nap-of-the-earth (NOE) flight gaming area and to conduct typical rotorcraft flight test maneuvers. The NOE portion is modeled after the Gabilan Creek area of Fort Hunter-Liggett. There are a number of stylized "courses" for studying lateral, longitudinal, and vertical handling qualities and several confined landing areas. Other features include a small village, a lake, and a two-lane country road.
Seymour-Johnson	A conventional airport database modeled after Seymour-Johnson Air Force Base. Included are the airport runway, taxiways, buildings, and vehicles. The region around the airport contains housing tracts, vehicles, and roadways representative of suburban America.
Ocean	An ocean database that includes a realistic wave pattern, and a U. S. Navy destroyer.

the display system in use. They also color the scene elements and apply the effects of illumination, fog, and shading. The Display Processors employ a principle called span processing and operate on rectangular areas of the display field rather than scanlines. This technique avoids aliasing problems associated with scanline processing, leads to greater overall system performance, and produces high subjective resolution. The outputs of the Display Processors are video signals that are transmitted to the Video Switch for routing to the Image Presentation System in the cab and other monitors.

Image presentation systems– The Image Presentation Systems in the four ICABs are unique arrangements of similar components. Each IPS consists of either three or four virtual image windows mounted in a specially designed support structure as described under *Interchangeable Cabs*. The support structure serves both to mount the components rigidly to the cab and to position the viewing area of each window in the desired location relative to the pilot(s). All the windows are based on a common optical design called a collimation/beam splitter system, but they differ in construction details from cab to cab. This type of display system has good brightness characteristics and is free from geometric distortion and other off-axis aberrations except spherical aberration, which is negligible because of the large size of the mirrors used. Geometrical constraints limit the realizable field of view for such a system to approximately 25° by 40° per window for commonly available monitors.

Each window has three main elements, illustrated schematically in figure 14. These are the beam splitter, the spherical mirror, and the monitor. Light emanating from the faceplate of the monitor is reflected from the inner surface of the beam splitter to the mirror, which collimates it and projects it toward the viewing position. The pilot sees a collimated image (emerging rays are parallel), which makes the scene appear very distant. This is desirable for a flight simulator, because the vast majority of objects viewed from an aircraft cockpit are quite far from the pilot.

Image Processor
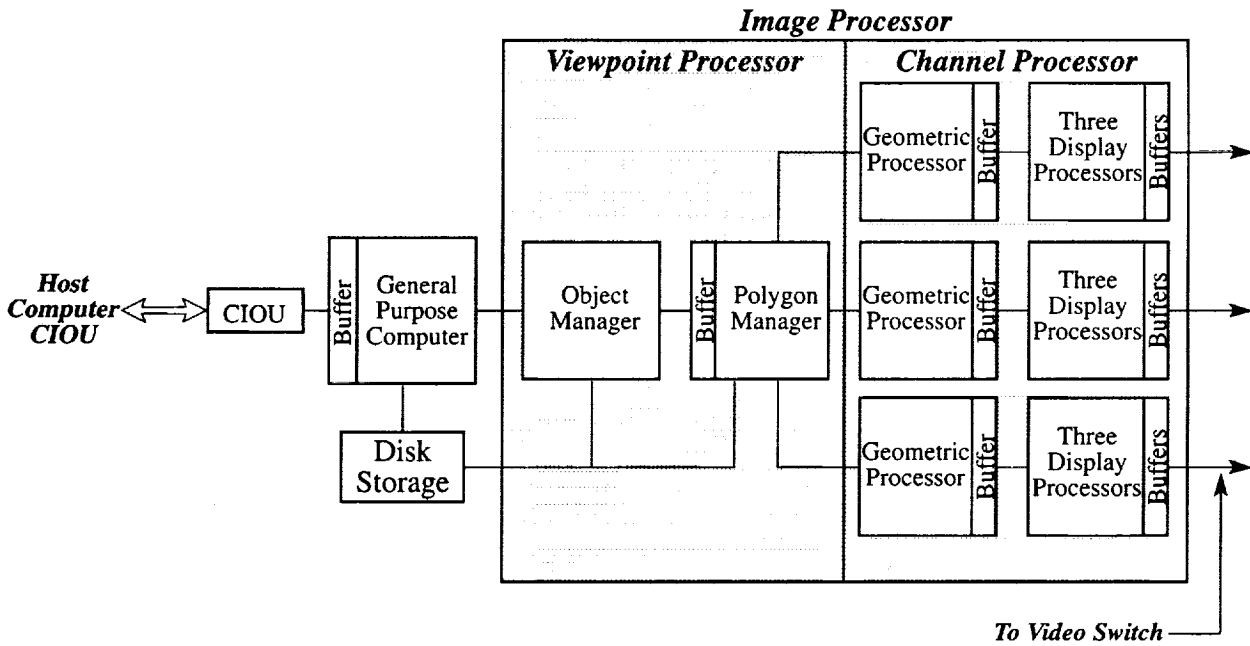
Figure 13. CT5A system architecture.
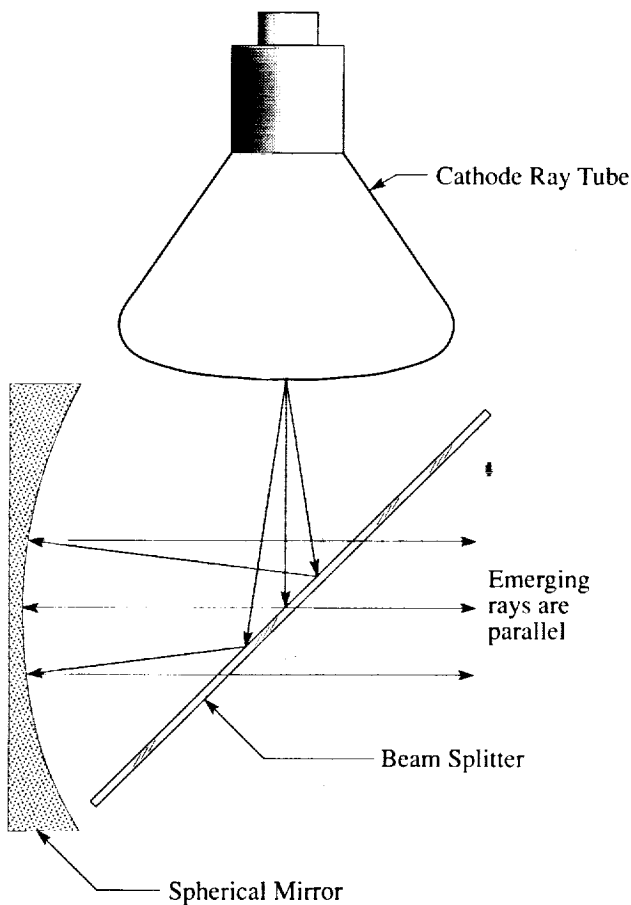
Figure 14. IPS window schematic.

The beam splitters are specially fabricated optical glass panels that are 35% reflective and 65% transmissive. The spherical mirrors have a 50-in. radius of curvature and are fabricated from two different materials. RCAB and FCAB have glass mirrors, and NCAB and SCAB have aluminum mirrors. SimLab currently maintains 16 monitors of three different model lines produced by the XKD Corporation. These monitors are shadow-mask color cathode ray tube (CRT) displays with magnetic deflection and electrostatic focus. The display tube and associated electronics are integrated in a sturdy chassis mounted in the IPS support structure, while the power supply is mounted remotely on the cab floor. All the monitors have a 25-in.-diagonal picture size, a video bandwidth of 25 Megahertz, and a raster scan of 1023 lines total with 1003 active video lines. The systems provide a brightness level of approximately 7 footlamberts at the design pilot eyepoint.

The window arrangements and approximate fields of view for the four ICABs were discussed in the earlier section covering the specific cabs. More precise field-of-view plots using the Hammer equal-area projection and based on actual measurements are presented in figures 15(a) through (d). The reference point for the Hammer Charts (0° elevation, 0° azimuth) is the pilot eye reference point for the NCAB, RCAB, and FCAB charts. The SCAB chart is somewhat of a special case, since there are two pilot stations and two pilot eye reference points. Figure 15(d) depicts the field of view for the two windows focused at the pilot station (left-seat) eye reference point. The field of view for the single window focused at the

26
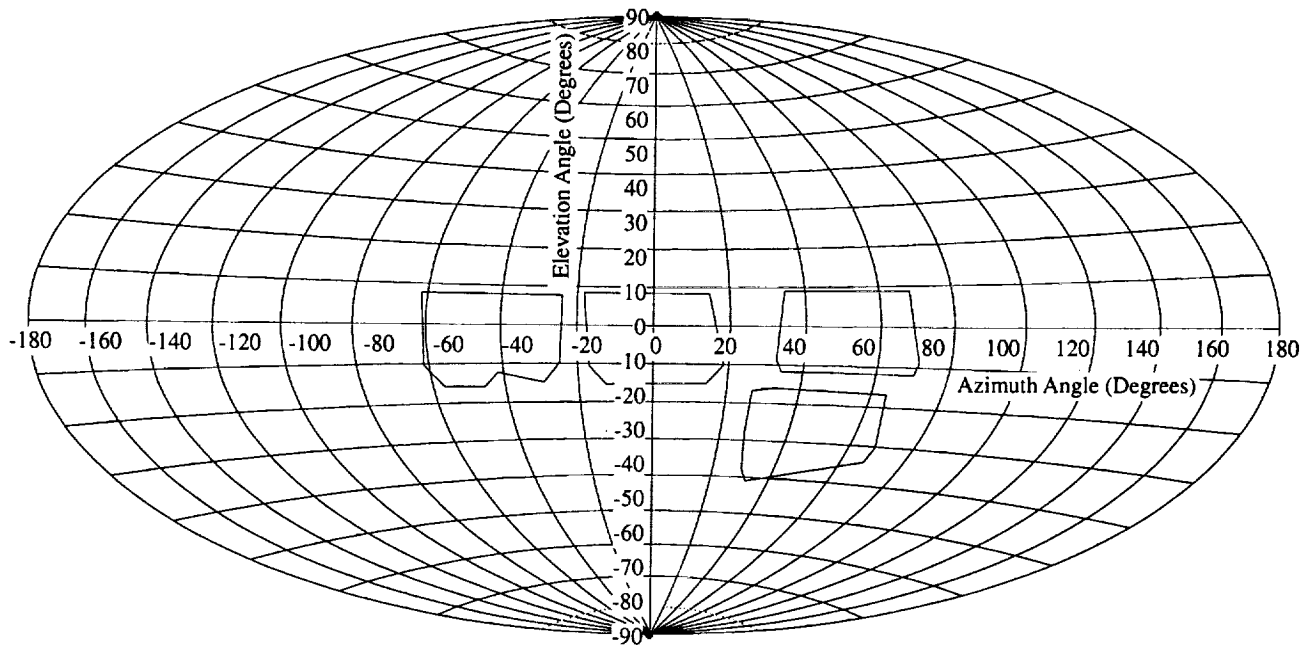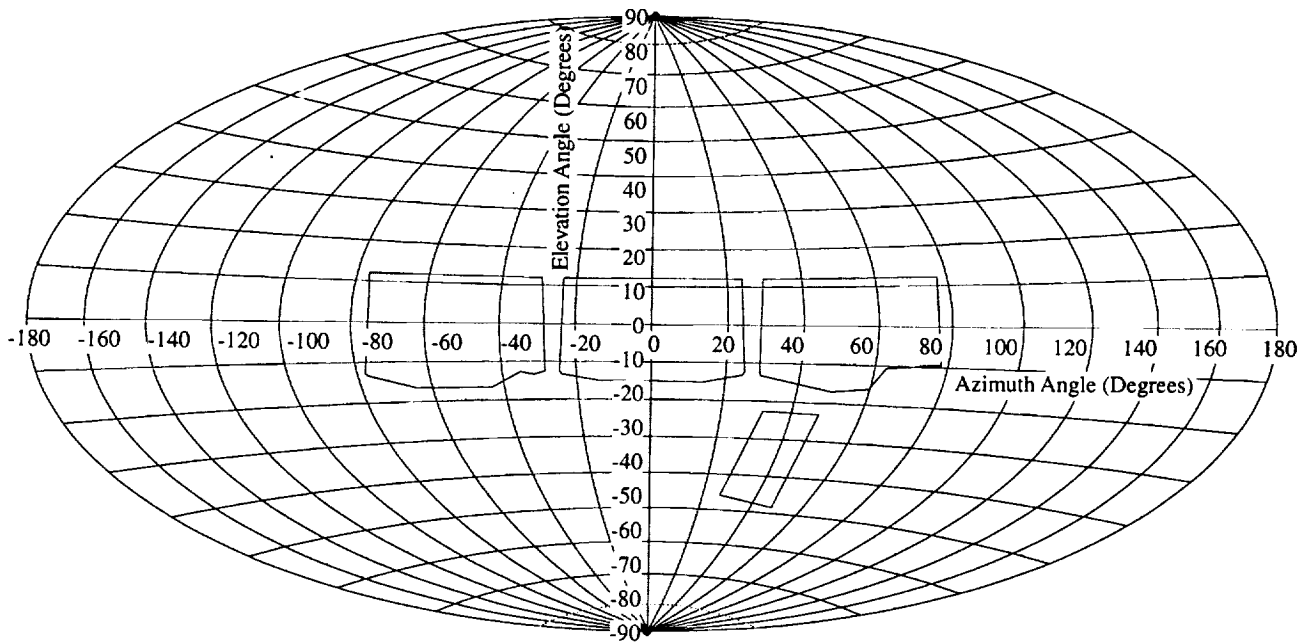
(a) NCAB IPS.

(b) RCAB IPS.

Figure 15. ICAB IPS field-of-view plots.

27
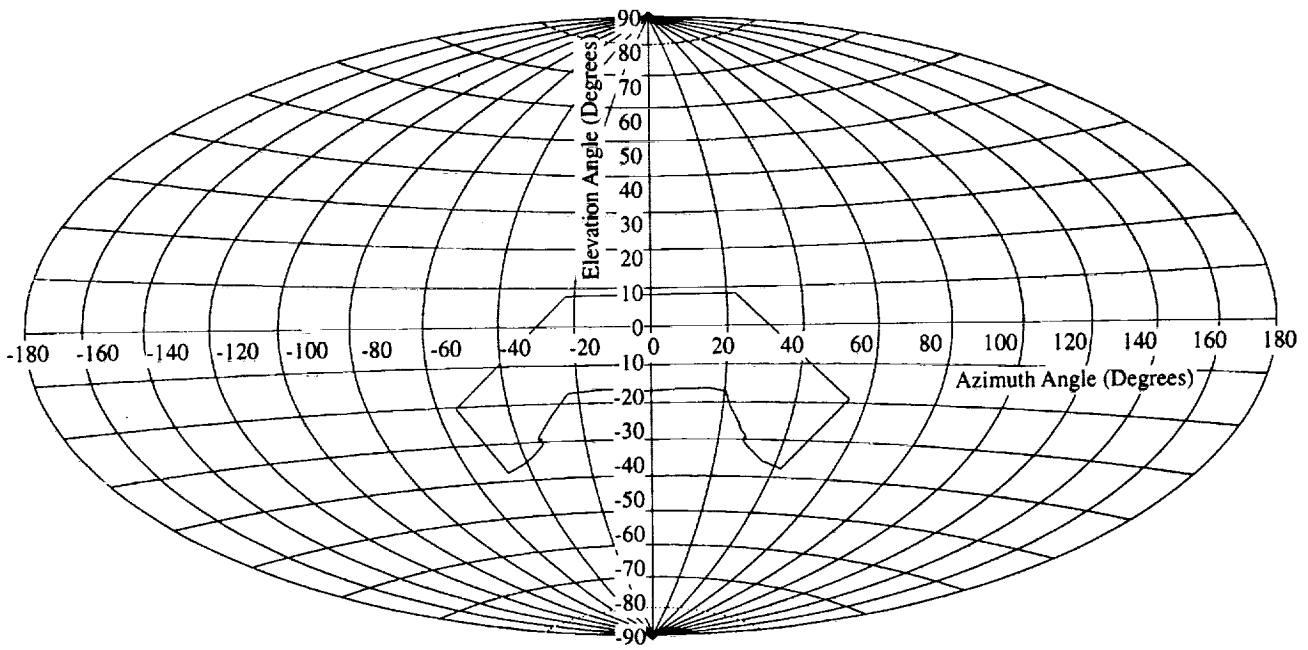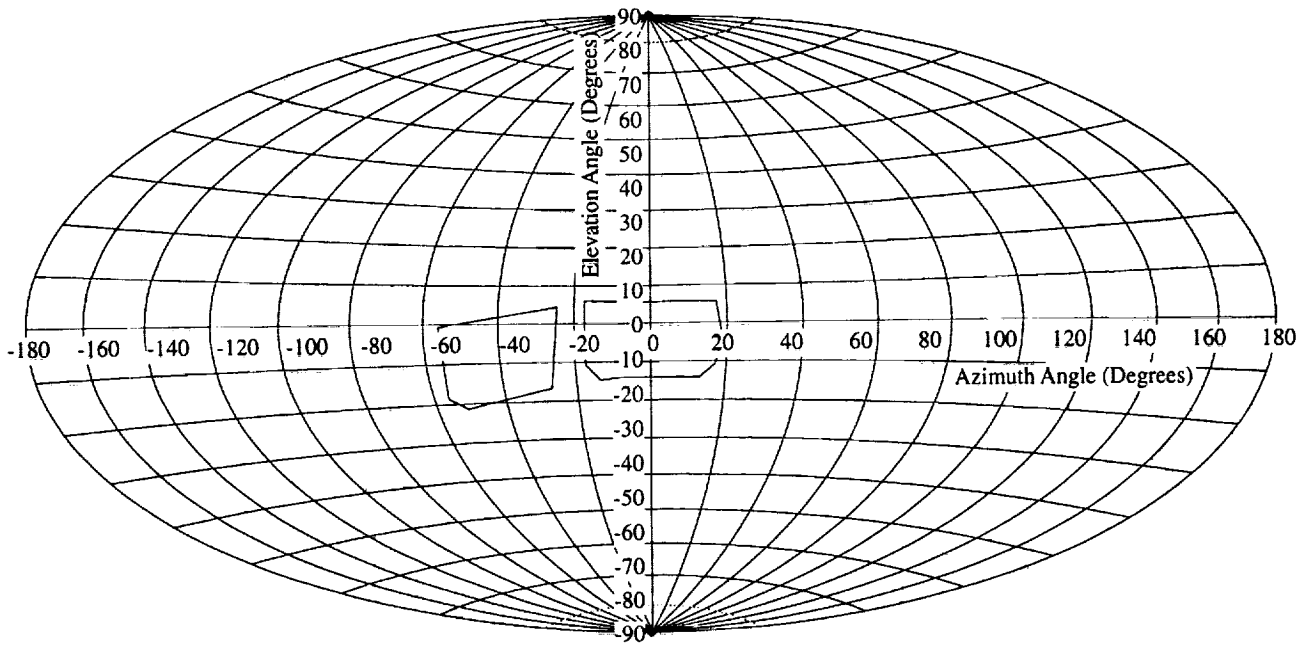
(c) FCAB IPS.

(d) SCAB IPS.

Figure 15. Concluded.

28

copilot station (right-seat) eye reference point is identical to the field of view of the forward window as seen from the pilot station.

Auxiliary Electronic Displays

Over the past several decades, as aerospace vehicles have become more and more complex, there has been a marked increase in the use of electronic displays to assist the pilot in accomplishing an ever more difficult and challenging set of control and system management tasks. Systems such as Head Up Displays (HUDs), multifunction, panel-mounted Head Down Displays (HDDs) and Helmet Mounted Displays have become common in actual aircraft and simulations. To simulate such devices effectively and efficiently, SimLab provides a variety of tools to a) generate the imagery and b) display it to the pilot. The former are called Auxiliary Display Generators and the latter, Auxiliary Display Devices.

Auxiliary display generators– SimLab maintains and operates a total of six Auxiliary Display Generators. Two of these are stroke-type systems manufactured by E&S and called PS1s, and the other four are raster-type systems from Silicon Graphics, Incorporated, called IRIS Systems.

PS1: The PS1 is a self-contained line-drawing system designed for generating real-time dynamically moving images of two- or three-dimensional objects. SimLab's two PS1s were acquired in 1975 and are, for all intents and purposes, identical. The PS1 operates on an entirely different principle than the image generators discussed previously. It controls the electron beam of the CRT display device to sweep out straight lines or *strokes*, which, in aggregate, make up the desired picture. Line segments can be solid or dashed, either steady or blinking, and their intensity is variable. The line endpoints are constrained to a matrix of 4096 vertical by 4096 horizontal addressable points on the display screen, a characteristic

that determines the limiting resolution of the system. Point lights are generated using a single endpoint, and curved lines are approximated by a sequence of short, straight lines. The PS1 is essentially a monochrome system, although a limited range of colors can be obtained using a special monitor.

The basic components of the PS1 are the Picture Controller, Picture Processor, Refresh Buffer, Character Generator, and Picture Generator as illustrated in figure 16. The Picture Controller is either a DEC PDP-11/45 or PDP-11/55. It serves as the interface between the special-purpose hardware processing units that make up the rest of the system and the host computer through a CIOU/CIOU link. It also supports the peripheral devices required to program and operate the system. The Picture Controller stores and transfers the database, which defines imagery in the form of endpoint coordinates, and characters in the form of special character strings. Additional functions include computing parameters that describe object movement, controlling the downstream processors, and controlling overall system timing. The Picture Controller uses special-purpose graphics software provided as part of the system.

The Picture Processor receives data from the Picture Controller and first performs operations to properly translate, rotate, and scale the raw database imagery. (Character strings pass through the Picture Processor unmodified.) Data is then clipped to eliminate imagery outside the viewing window. At this point, any three-dimensional coordinates are converted to a two-dimensional perspective (or, alternatively, orthographic) representation, and the intensity value is computed. The Picture Processor's final stage maps the data into a user-specified region of the display area called the viewport. The viewport is based on the coordinate system of the display device, but is not necessarily the same size. Its use allows the database to be generated in a separate, possibly
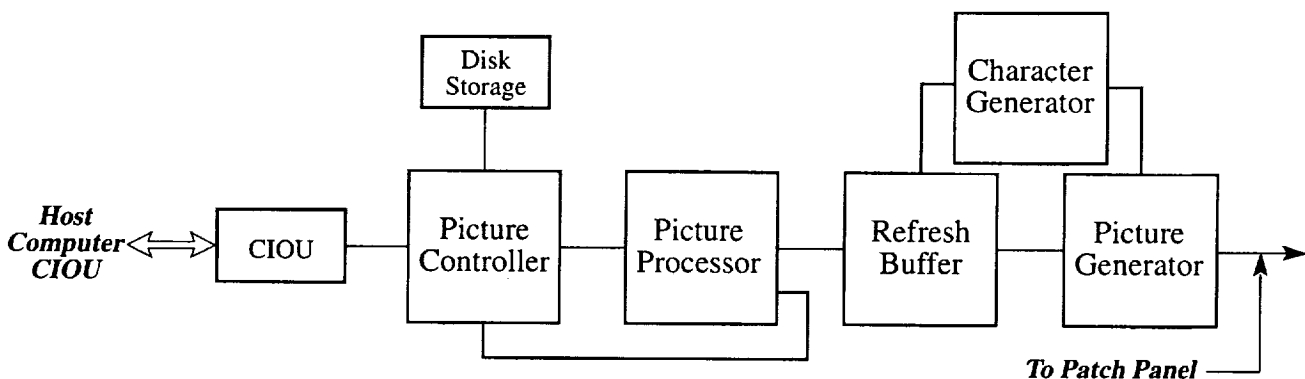

Figure 16. PS1 system architecture.

more convenient, coordinate system and also provides for displaying several views or even different pictures on a single display device. An additional off-line feature of the Picture Processor is the capability to transfer data back into Picture Controller memory for such purposes as generating hard copy output or performing additional processing.

The Refresh Buffer stores data from the Picture Processor in digital form and allows it to be used to refresh the display any number of times before the next frame of data is finished computing. This allows imagery update rate and display refresh rate to be optimized independently, since the two need not be identical. The refresh rate may be any of 16 submultiples of 120 Hz, but the most typical values are 60 Hz and 30 Hz. Two modes of operation are provided—single-buffered and double-buffered. In single-buffered mode, the entire Refresh Buffer contains one frame of data, which is simply overwritten when a new frame is received. In double-buffered mode, the Refresh Buffer is split into two equal regions. Data in one region is left intact and used for refreshing the display until an entire new frame is received in the other buffer region, then the roles are reversed. Double-buffering is advantageous because it precludes displaying data while an update is in progress, which can produce undesirable effects. It does, however, require a frame small enough to fit in one-half of the Refresh Buffer.

The Character Generator receives character strings from the Refresh Buffer and uses them to extract character stroke data from an internal read-only memory. The entire 96-character, extended ASCII character set is available. Other parameters are used to select character size and character width from eight preset increments and to specify horizontal or vertical orientation.

The Picture Generator converts line endpoint and intensity data from the Refresh Buffer and character stroke data from the Character Generator (both in digital form) into the analog voltages that drive a stroke-type or *calligraphic* display device. The output of the Picture Generator is transmitted to a special patch panel for distribution to display devices as required.

IRIS systems: Silicon Graphics produces a large number of products under the IRIS name—devices ranging from relatively simple servers with no graphics capabilities to extremely powerful systems that can function as single-channel CIGs similar to the DIG1 and CT5A. SimLab has four IRIS Systems available for general use. All four are 4D 310 VGX models and are used almost exclusively to generate auxiliary display imagery. Like the SimLab MicroVAXes, the IRIS Systems are known by familiar names so that they can be easily distinguished. The familiar names are IRIS 4, IRIS 5, IRIS 6, and IRIS 7; some of their more important features and capabilities are summarized in table 10.

All IRIS systems employ a similar overall architecture, although individual components may differ significantly from model to model. The basic approach is to use dedicated subsystems (CPU and Graphics) and buses for specific tasks so that the entire system cannot be bogged down by a single process. The CPU Subsystem is a tightly coupled, symmetric, shared-memory multiprocessing design. It serves as the interface to the host computer and system memory and as the controller for the other IRIS subsystems. It can also be used for general-purpose computations. The CPU Subsystem in the 4D models is composed of a Reduced Instruction Set Computer (RISC) microprocessor chip and companion floating-point coprocessor designed by Mips Computer Systems.

The Graphics Subsystem is composed of a pipeline of four lower level subsystems that contain an even greater variety of proprietary processors. These are, respectively, the Geometry Subsystem, the Scan Conversion Subsystem, the Raster Subsystem, and the Display Subsystem. The Geometry Subsystem operates on data from the CPU Subsystem to convert a model-space representation of the imagery into a two-dimensional screen-space representation. The Scan Conversion Subsystem then breaks down points, lines, polygons, and meshes into data representing individual pixels. The data is then sent to the Raster Subsystem, which eliminates hidden surfaces, performs various blending and texturing functions on a pixel-by-pixel basis, and stores the resulting data in a frame buffer. Finally, the Display Subsystem converts the

Table 10. SimLab IRIS systems performance characteristics

Memory (MB)	Clock speed (MHz)	Processing speed			Colors	Pixel capacity
		MIPS	MFLOPS	Vectors per second		
48	33	30	4.9	1M	16.7M	1280 by 1024

digital data in the frame buffer to analog signals, which are sent to the Video Switch for distribution to the appropriate display devices.

Three separate Input/Output buses are incorporated: Ethernet, VME, and Small Computer System Interface (SCSI). The Ethernet bus is used as the real-time interface to the host computer, the SCSI bus is used to connect to disk and tape drives, and the VME bus is available for any applications that require this protocol.

SimLab IRIS Systems use a UNIX-based operating system. Both C and FORTRAN compilers are available on all the systems.

Auxiliary display devices–

Panel displays: SimLab has a total of five calligraphic and four raster-type Auxiliary Display Devices available for use as general-purpose cockpit displays.

All five calligraphic displays are products of Xytron, Ltd. There are two different model designations that are essentially identical except for size—four of the units have 9-in.-diagonal rectangular screens and one has a 3-in. circular screen. Both models are a two-chassis design. The Driver Chassis contains power supplies, power amplifiers, and geometric correction and phosphor-protect circuitry, and it is mounted in one of the equipment racks at the rear of the cab. Gain and position controls for both horizontal and vertical axes are located on the chassis's front panel. The CRT Chassis contains the CRT, the deflection yoke, a video amplifier, and additional power supplies. Since this chassis contains the actual viewing screen (the CRT faceplate), its location is dictated by research requirements; it is typically mounted in the instrument panel. Intensity and focus controls are contained in another small panel, which is connected to the CRT Chassis by a cable so that it can be mounted within the pilot's reach. The Driver Chassis receives horizontal and vertical deflection input signals and performs distortion corrections and

adjustments for display size and position. The CRT Chassis receives the output of the Driver Chassis and generates drive signals for the horizontal and vertical deflection coils of the CRT. Characteristics and technical specifications of the Xytron displays are summarized in table 11.

Of the four raster-type Auxiliary Display Devices, two are manufactured by Gigatek, Ltd., and two by Electrohome, Inc. Both types are general-purpose displays that have been modified to function as panel-mounted monitors. These systems share a number of common features including full color capability, multiple-frequency scan compatibility, and multiple-format input compatibility. The only major difference between the two types is size— the Gigatek displays have a 9-in.-diagonal screen and the Electrohome displays have a 13-in.-diagonal screen.

Head-up displays: Head-up displays (HUDs) are electro-optical devices that display imagery directly in the pilot's forward field of view. Their use allows the pilot to view the outside-world scene simultaneously with important flight information and other data. SimLab has two types of HUDs, one manufactured by Flight Dynamics, Inc., (FDI) and the other by Kaiser Electronics.

FDI HUD. The FDI HUD is a high-brightness, wide-field-of-view, overhead-mounted holographic Head Up Display. The arrangement of the optical elements and some of the other major features are illustrated in figure 17. Although produced especially for simulator applications, it is based on a design used in commercial transport aircraft. SimLab maintains three of these units, and they can be used in any of the ICABs.

The field of view of the FDI HUD is 24° vertical by 30° horizontal. The horizontal field of view is symmetrical about a vertical axis through the eye reference point, and the vertical field of view is adjustable over a depression angle range of 0 to 7° below the horizon. The viewing

Table 11. Calligraphic auxiliary display device characteristics

Model number	Quantity	Screen size		Drift	Geometric distortion	Writing speed	Response (full screen)	
		Total	Usable area				Step function	Sine wave
A9R-17A	4	9-inch diagonal rectangle	5 inches by 7 inches	< 0.5% in 8 hrs.	± 2%	0.5 inches per μsec	8 μsec	1.5 MHz
A3R-233	1	3-inch diameter circle	2.6-inch diameter circle	< 0.5% in 8 hrs.	± 2%	0.2 inches per μsec	8 μsec	0.75 MHz

Video Amplifier and Power Supplies

CRT

Relay Lens

Stow Position

Eye Reference Point

Viewing Volume

Combiner/Collimator

Breakaway Position
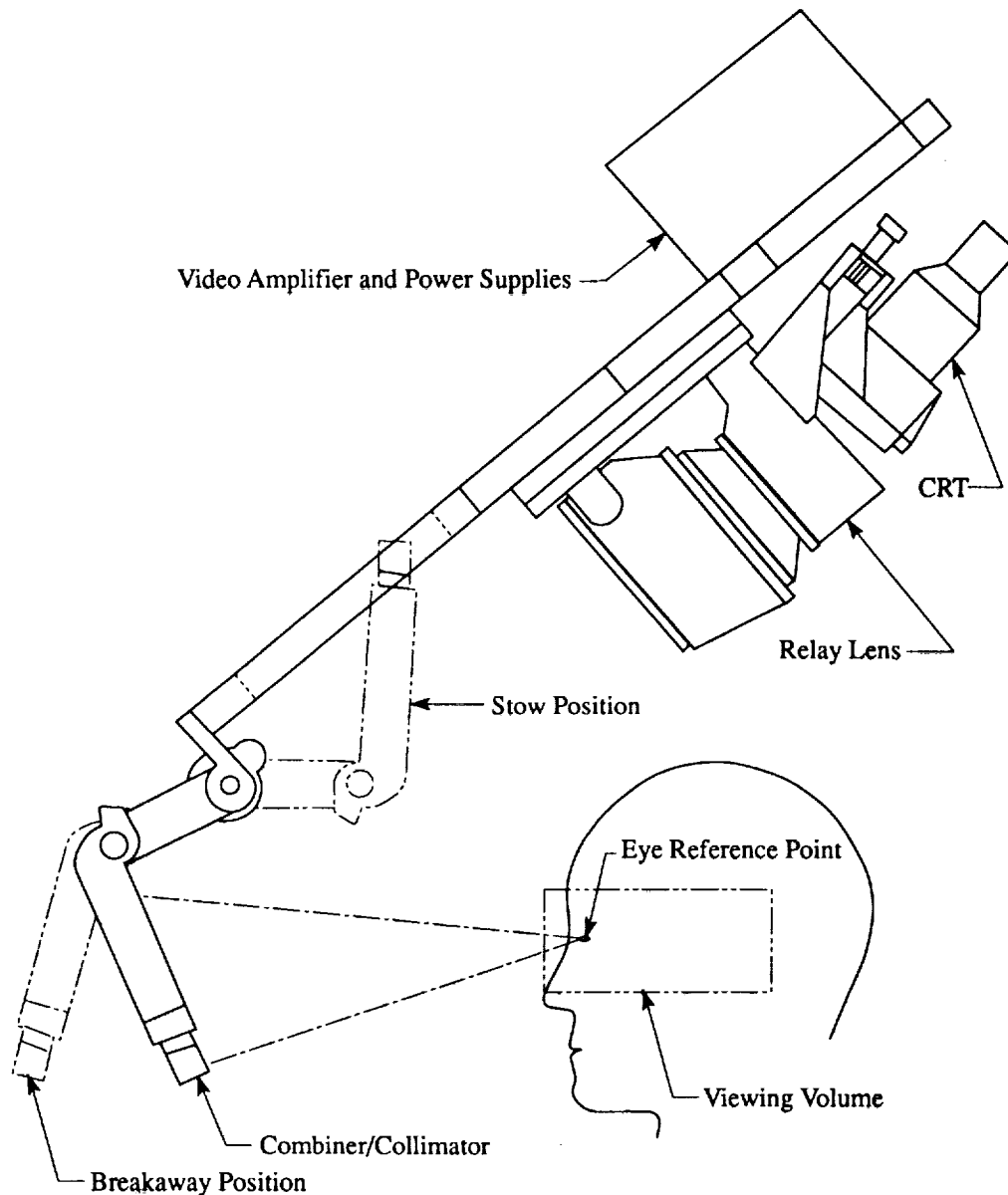
Figure 17. FDI HUD schematic.

volume is approximately a rectangular parallelepiped measuring 2.7 in. high by 4.7 in. wide by 5 in. long. The minimum display brightness is 500 ft-L, and the display linewidth varies between 0.8 and 1.2 mrad over the field of view. The focus point for the displayed image is adjustable so the HUD can be set to match the collimated image of the IPS.

The FDI HUD is composed of three subsystems—the Deflection Amplifier Unit, the Control Panel, and the Overhead Display Unit. The Deflection Amplifier Unit is a rack-mounted chassis that contains the horizontal and vertical deflection amplifiers that convert the input signals from the display generator into the high-current drive

signals required by the CRT deflection yoke. The Control Panel is another rack-mounted unit that contains horizontal and vertical gain and offset controls. The Overhead Display Unit contains a video amplifier, high-voltage power supplies, the CRT assembly, the relay lens, and the optical combiner. The CRT uses a special narrow-band phosphor and is a 4-in.-diagonal Xytron display similar to the ones described earlier under Panel Displays. The relay lens is a complex, nine-element assembly that forms an intermediate real image of the display, which is projected to the optical combiner. The combiner reflects and collimates the image; it consists of a thin holographic layer imbedded between precision glass components. The

32

external glass surfaces have a high-efficiency anti-reflective coating, and the holographic layer is designed to diffract the wavelength produced by the CRT phosphor with very high efficiency to enhance overall brightness. The combiner can be stowed when not in use, and it also has a "breakaway" feature to prevent injury in the event of a head strike.

Two of the three FDI HUDs are compatible only with calligraphic display generators, but the third has been modified to allow it to display calligraphic, raster, or a combination of calligraphic and raster signals. The modification consisted of adding a custom-designed device produced by Xytron, Inc., that multiplexes the display between two sources and generates the sweep signals necessary for the raster imagery. The multiplexor will operate at any line rate from 525 to 1023, either interlaced or non-interlaced, and at a field rate of either 30 or 60 Hertz.

Kaiser HUD. The Kaiser HUD is a highly modified commercial Head Up Display that is similar to the Pilot Display Unit developed for the Space Shuttle. SimLab has a single Kaiser HUD, and it is compatible only with the SCAB. Its layout and features are schematically illustrated in figure 18.

The Kaiser HUD has a field of view that is approximately 15° in both the vertical and horizontal directions. The horizontal field of view is symmetrical about a vertical axis through the eye reference point, and the center of the vertical field of view can be depressed from 0 to 5° below the horizon. The viewing volume is a truncated rectangular pyramid with the apex pointing forward; the rear surface is a 3-in. square and the front surface is a 1.5-in.-wide by 2.5-in.-high rectangle. The image can be focused at optical infinity to match the collimated image of the IPS.

The Kaiser HUD is a two-chassis design. The CRT, relay optics, and the optical combiners are integrated into a structural module that is mounted on the instrument panel in front of the pilot. A Control Panel containing brightness controls and a mode switch is located directly beneath the combiners. Deflection amplifiers are located in another unit that is rack-mounted. The CRT is a 3-in. circular Xytron display similar to the ones described earlier under Panel Displays. The relay optics set consists of six lenses and a folding mirror, and two combiners are used to extend the vertical field of view. The Kaiser HUD is compatible only with calligraphic display generators.

IHADSS: The Integrated Helmet and Display Sighting System (IHADSS) is a production helmet-mounted display with an integrated head-tracking capability that was developed for use on the AH-64 Apache attack helicopter. The system was originally designed to aim a Forward-Looking Infrared (FLIR) system mounted in a gimballed chin turret and to display the FLIR imagery along with superimposed symbology from a separate symbol generator. This symbol generator is not included in the SimLab IHADSS because, in the simulation
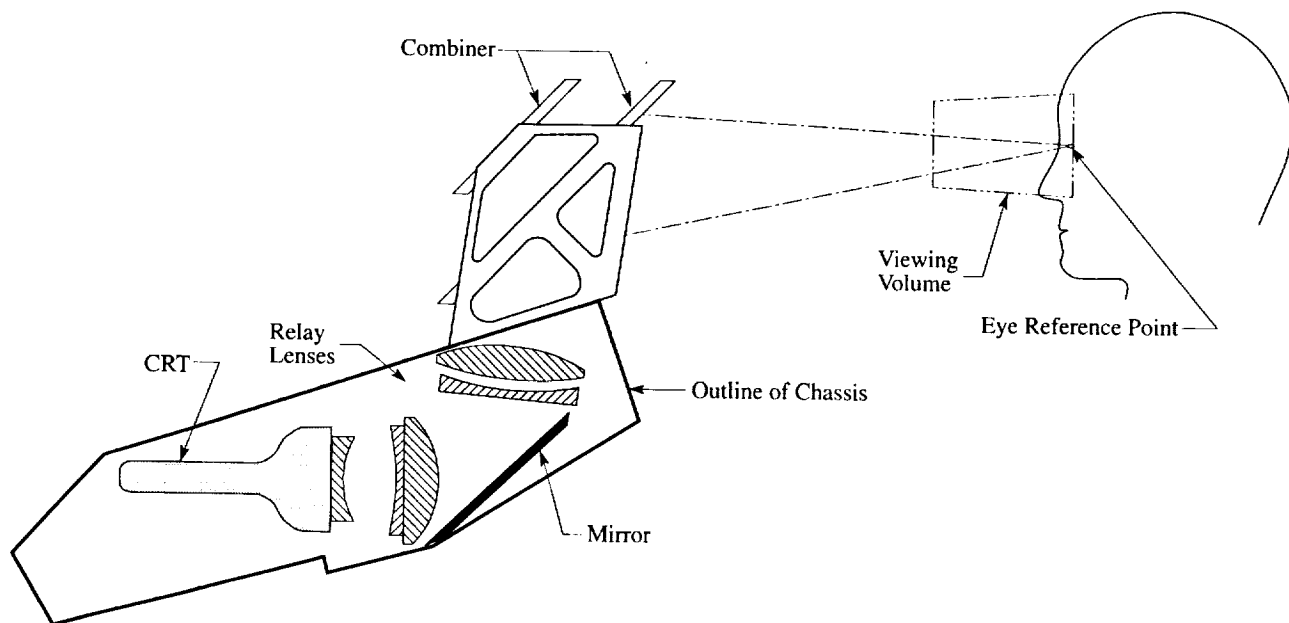

Figure 18. Kaiser HUD schematic.

application, the imagery is generated by electronic display generators of one type or another.

The IHADSS measures the pilot's line of sight in terms of elevation and azimuth angles relative to a reference coordinate system and presents a 40°-wide by 30°-high, monochromatic, collimated display to the pilot's right eye through a small CRT/projection optics package mounted on the side of a special flight helmet. The display seen by the pilot is equivalent to a 19-in.-diagonal television viewed from a distance of 20 in. The total head-supported weight is approximately 4 pounds. The IHADSS is a raster-type display and can accommodate either 525- or 875-line video input. IHADSS performance characteristics are summarized in table 12, and a sketch of the helmet portion of the system is presented in figure 19.

Table 12. IHADSS performance characteristics

Display field of view	40 degrees horizontal by 30 degrees vertical
Display format	0.75-inch diagonal rectangle
Exit pupil	0.4 inch
Maximum display brightness	125 foot-lamberts
Maximum helmet slew rate	120 degrees per second
Azimuth pointing angle range	120 degrees left to 120 degrees right of center
Elevation pointing angle range	40 degrees above to 70 degrees below horizon
Pointing accuracy	less than 10 milliradians RMS error

The IHADSS is composed of three main subsystems: (1) the Helmet Mounted Sight (HMS), (2) the Helmet Mounted Display (HMD), and (3) the Integrated Helmet Unit (IHU). The HMS is the subsystem that measures the line-of-sight angles. It consists of two fixed infrared radiators located above and behind the pilot's shoulders and a processing unit that is contained in a separate package mounted behind the pilot's seat. The processing unit receives signals from the infrared radiators and from four infrared detectors mounted in the helmet, and operates on these to compute the two line-of-sight angles. The HMS will function properly as long as the helmet stays within a rectangularly shaped volume 10 in. wide by 5 in. high by 13.5 in. deep. An ancillary device called the Boresight Reticle Unit provides a collimated target reticle that is used as a visual reference for boresighting the system.
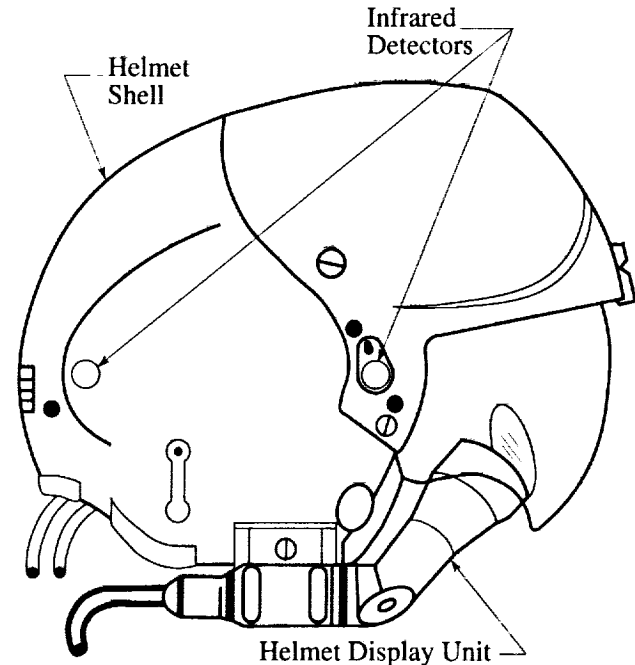
Figure 19. IHADSS helmet-mounted display.

The HMD subsystem processes and displays the imagery. It consists of three elements: (1) a floor-mounted package that contains video processing electronics, support electronics, and deflection circuits for the CRT, (2) an adjustment unit that contains a video amplifier, a power supply, and manual controls for adjusting display size, position, and focus, and (3) the actual Helmet Display Unit or HDU. The HDU is an extremely compact, detachable package, and its details are highlighted in figure 20. A 1-in.-diameter high-resolution CRT and a precision optical system composed of nine ground glass lenses and a glass prism are contained in a sturdy housing made of high-impact plastic. A semitransparent combiner is attached to the front of the HDU. The combiner's inner surface is treated to selectively reflect the wavelength produced by the CRT, and the outer surface is treated with an anti-reflective coating. Transmittance of incident external light is 50 percent and reflectance of light from the CRT is 85 percent. The HDU also contains adjustments for infinity focus, image rotation, and rotation of the HDU itself to accommodate differences among pilots. The entire assembly is secured to a mounting plate on the earflap of the helmet, and the cable connection includes a "breakaway" feature for added safety.

The IHU is a lightweight, protective helmet that is especially designed to integrate the helmet-mounted components of the other two subsystems. It is fully flightworthy and incorporates all normal aircraft helmet

Combiner

Infinity Focus Ring

Sliding Clip

Video Cable

HDU Rotation Ring

Image Rotation Rings

HDU Rotational Stop

Figure 20. IHADSS helmet display unit.

features and functions. The helmet shell is made of Kevlar- and graphite-reinforced plastic and contains an energy-absorbing insert and webbed suspension liner for crash protection. The infrared detectors discussed earlier are mounted within the shell. The IHU also includes a microphone, noise-attenuation material, and special acoustical earphones that are adjustable for fit. The inner suspension system incorporates a nylon cap, insertable pads, and adjustable straps to allow customizing the fit.

Proper fitting of the helmet is extremely critical because helmet slippage cannot be tolerated during operation; and adjusting the helmet to be snug and still comfortable can take from 20 minutes to 2 hours. SimLab maintains an inventory of four IHUs in two sizes, so several pilots can support a given simulation using the single available HDU without having to continually refit the helmets.
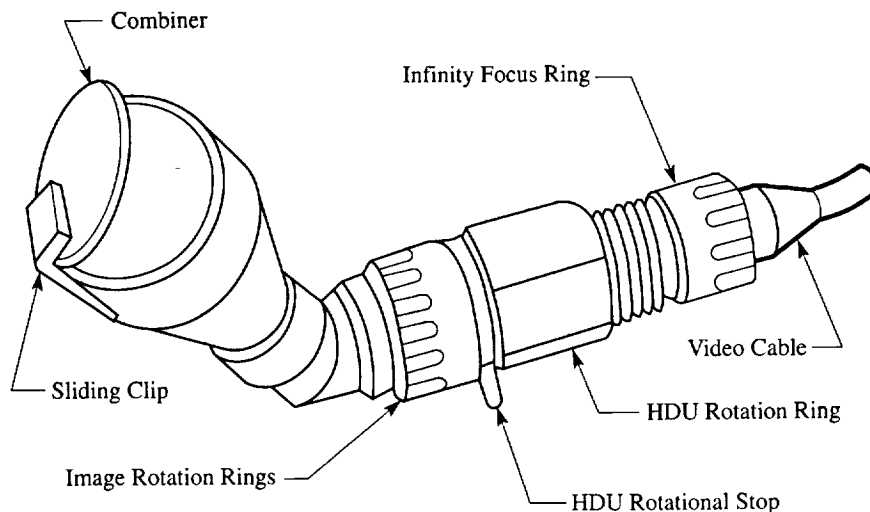
Cockpit Cueing Devices

Control loaders– Since its earliest days, a large portion of the research supported by SimLab has been in the area of controllability and handling qualities, and control feel is an extremely important cue in this type of simulation. The resulting emphasis on realistic control feel coupled with the need to accommodate all varieties of aircraft prompted SimLab to develop a unique capability to simulate control-feel characteristics. The VMS control loading system consists of a line of commercial control loaders manufactured by McFadden Systems, Inc., an EAI 2000 analog computer manufactured by Electronic Associates, Inc., and a custom hydraulic power system. The McFadden control loader is a sophisticated electrohydraulic force servo that can be programmed to produce realistic force-feel cues over a wide range of operating

conditions. The company produces different controller configurations that physically resemble many different types of aircraft primary flight controls. SimLab has examples of a number of the configurations; these are pictured in figure 21. Table 13 lists the quantity of each configuration available along with nominal specifications for a number of the most important performance characteristics. It should be noted that these are the manufacturer's specifications and that significantly improved performance is possible for many of these parameters because of the unique setup employed at SimLab to drive the basic hardware. The individual units can be used either separately or in various combinations to suit research requirements. The most common combinations are the fighter configuration (2-Axis Control Stick with Pedals), the transport configuration (Wheel and Column with Pedals), and the helicopter configuration (2-Axis Control Stick with Pedals and Collective). It is also possible to change the control grip and "stick" portions of the 2-Axis Control Stick and Collective units, if necessary, to more closely match those of the simulated aircraft.

Each control loader axis is a separate servosystem that is controlled independently. Conversely, all the axes are made up of functionally identical subsystems and, in most cases, identical components. These are the control device (the part the pilot actually manipulates), the hydraulic actuator assembly, the EAI 2000 analog computer, and the electronic controller. A hydraulic power supply system provides power for all the axes. The block diagram in figure 22 shows the major elements of a typical control loader axis and illustrates how it operates. When the pilot moves the control device, which is rigidly attached to the hydraulic actuator assembly, the resulting displacement and velocity are measured by transducers and these

35

Conventional 2-Axis Control Stick

"High Roll" 2-Axis Control Stick

Wheel and Column

Helicopter Collective

Pedals
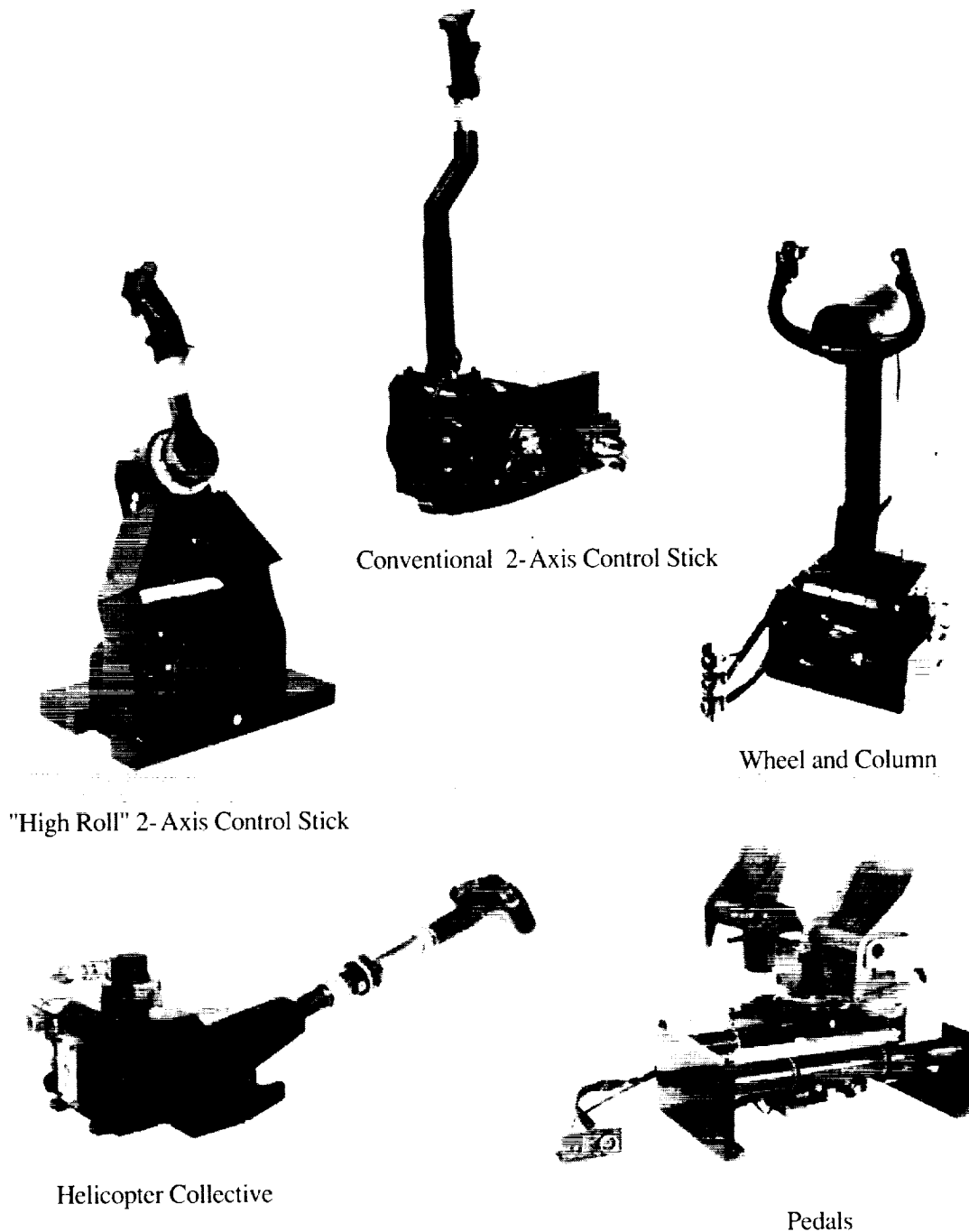
Figure 21. Available VMS control loader configurations.

signals are fed back to the EAI 2000 and the electronic controller. The hydraulic fluid pressure, which is proportional to the force acting on the control device, is also measured, and this signal is fed back to the electronic controller. The EAI 2000 and the electronic controller are located adjacent to each other in the VMS Lab. The EAI 2000 processes the displacement and velocity signals to

generate a force command signal corresponding to the desired force at the control device. This signal is sent to the electronic controller, which processes it along with the force (pressure) feedback to generate a servovalve command signal. The servovalve command signal controls the position of a servovalve in the hydraulic actuator assembly, which, in turn, controls the flow of

Table 13. Summary of control loaders and nominal specifications

	Conventional 2-axis control stick		High roll 2-axis control stick		Wheel and column		Pedals	Collective
	Pitch	Roll	Pitch	Roll	Pitch	Roll		
Quantity	7		1		2		7	2
Maximum force	150 lb	100 lb	100 lb	100 lb	150 lb	450 in-lb	200 lb	50 lb
Maximum travel	±7 in	±7 in	−5, +7 in	±7 in	−6, +10 in	±105°	±3.25 in	±7 in
Maximum velocity	50 in/sec	50 in/sec	50 in/sec	50 in/sec	50 in/sec	350 °/sec	50 in/sec	50 in/sec
Maximum force gradient	75 lb/in	75 lb/in	75 lb/in	75 lb/in	75 lb/in	30 in-lb/°	75 lb/in	10 lb/in
Maximum damping	0.5 lb/in/sec	0.5 lb/in/sec	0.5 lb/in/sec	0.5 lb/in/sec	0.5 lb/in/sec	0.5 in-lb/°/sec	3.0 lb/in/sec	0.5 lb/in/sec
Maximum breakout	20 lb	20 lb	20 lb	20 lb	25 lb	50 in-lb	25 lb	10 lb
Maximum friction	10 lb	10 lb	10 lb	10 lb	15 lb	30 in-lb	10 lb	10 lb
Maximum trim rate	2 in/sec	2 in/sec	2 in/sec	2 in/sec	2 in/sec	15 °/sec	2 in/sec	2 in/sec
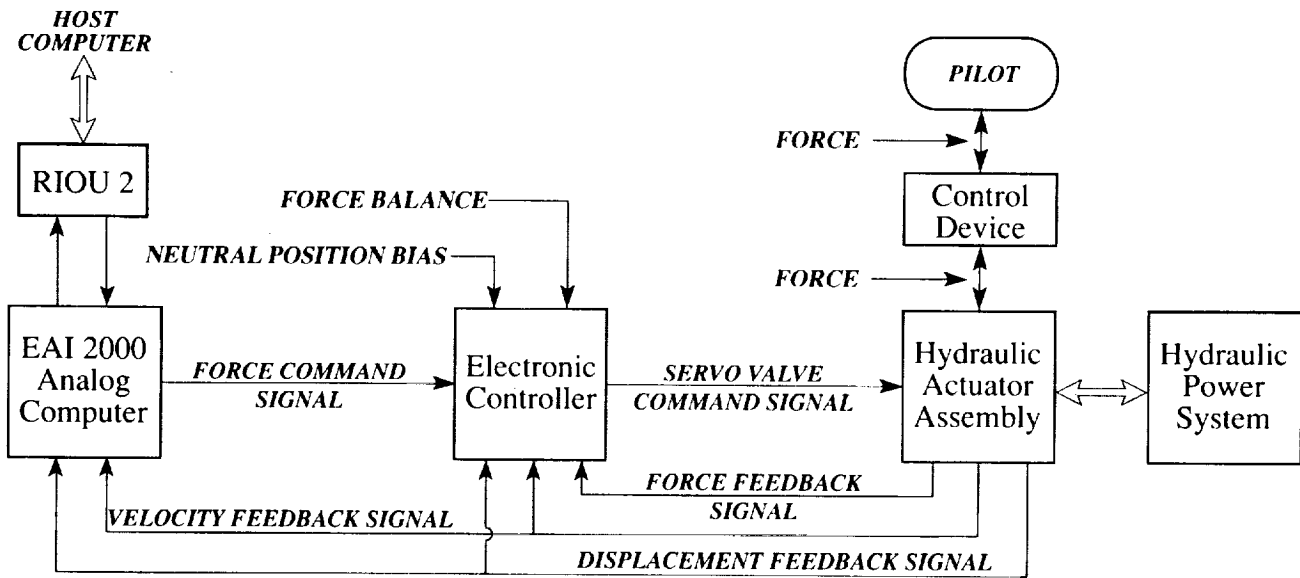
Figure 22. Block diagram for a typical control loader axis.

hydraulic fluid to the actuator. The actuator produces a force in relation to this flow that is transmitted back to the pilot through the control device.

Table 14 lists and describes the standard set of control loader characteristics programmed on the EAI 2000. As indicated earlier, these are all functions of control displacement or velocity, although some are linear and others are nonlinear. The friction and hard-stop functions are provided by custom circuits designed and built specifically for this purpose; the other functions are programmed using conventional analog components. In

Table 14. Summary of standard control loader characteristics

Characteristic	Description
Force gradient	Control force varies linearly with control displacement; also called spring rate or spring force. The force felt by the pilot is in the direction opposite to the direction of movement.
Damping	A force that varies linearly with control velocity. The force felt by the pilot is in the direction opposite to the velocity of movement.
Breakout	A constant force which acts whenever the control is displaced from the neutral point. The force felt by the pilot is in the direction opposite to the direction of movement.
Hard stops	An extremely high force gradient that acts only at set values of control displacement; used to simulate the mechanical travel limits.
Friction	A constant force which acts whenenver the control is moving. The force felt by the pilot is in the direction opposite to the velocity of movement.
Trim	The ability to adjust the neutral point of the control (the position at which control forces are null). The rate (velocity) of trim is constant and adjustable.

addition to the standard set, other force characteristics and features can be programmed to meet specific needs. Examples are bobweight effects, gravity (weight) compensation, magnetic brake, and "back-driving" the control device as would occur in a coupled, dual control system. Any extra features are, of course, limited by the capacity of the EAI 2000. It is also possible to effect variations from the host computer using signals transmitted through RIOU 2 and VMS SIO, which is the link used to transmit the pilot's control inputs to the host computer. The most common examples of this usage are nonlinear force gradients and trim inputs.

The electronic controller performs other functions in addition to the basic servoloop closure described above. These functions include signal conditioning, forward loop compensation to stabilize the system, and servovalve dither to minimize stiction effects. It also provides displacement and velocity loop closures with gains controlled by potentiometers on the front panel. These circuits provide force gradient and damping independent of the EAI 2000, which allows stand-alone operation for system checkout and can be useful for troubleshooting. Two other features are: (1) a force balance control that allows the force on the actuator to be nulled at the neutral position to compensate for any weight offset of the control device or voltage offsets in the circuitry or transducers and (2) a position bias that allows the neutral displacement point to be set as desired. The electronic controller also contains an abort or safety circuit to prevent violent motion of the control device in the event of an abnormal input or a malfunction. This circuit reacts to excessive acceleration of the control device by switching the overall loop gain to an extremely low value and shutting off hydraulic pressure to the actuator.

The hydraulic actuator assembly consists of a rotary hydraulic actuator, a servovalve, and the feedback transducers mentioned previously. The rotary actuator is specially designed to minimize friction; it employs hydrostatic fluid bearings and uses no seals. A vacuum scavenging system retrieves fluid that seeps out during operation.

The hydraulic power system was custom designed for the VMS control loader application. Each ICAB is provided with the basic plumbing and necessary on-board components, such as accumulators, to hook up appropriate control loader sets. Scavenge pumps are mounted on the motion system's lateral carriage, and the hydraulic power supply is remotely located in a special pump room on the ground floor of Building N243. The power supply consists of two large-capacity pumps with a built-in fluid reservoir, a fluid temperature control system, manifolding, plumbing, and other necessary components. The power supply is connected to the cab using steel pipe between the pumps and the VMS catenary and high-pressure, flexible hose strung on the catenary.

Vibration generator– The Vibration Generator is a unique mechanism that provides motion cues beyond the operating range of the VMS Motion System—the high-frequency, low-amplitude accelerations that are characteristic of aircraft vibrations. The system was designed and built at SimLab and is a modular unit that can be fitted to FCAB, NCAB, or RCAB. The performance envelope of the Vibration Generator was designed to cover an acceleration/frequency range typical of helicopter seat vibrations while avoiding magnitudes and frequencies that could be potentially injurious, even for long-term exposures. It can provide sinusoidal accelerations of up to ±0.05 in. displacement in a frequency bandwidth of 18 to 20 Hertz.

A functional schematic of the Vibration Generator module is shown in figure 23. All the parts are contained within an aluminum housing that bolts into the base structure of an ICAB. A reinforced platform that serves as the mounting surface for the pilot's seat is attached to the top of the housing using aluminum hinges with pressed-in bearings. The platform is driven by an electrohydraulic servo through a bellcrank and pushrod assembly, all of which are mounted inside the housing. Rotation about the hinges is small enough that the resulting motion is almost purely vertical.

The servo that powers the platform is a modified single-axis McFadden Control Loader, so the system is functionally identical to the Control Loaders described in the previous section. The only significant physical differences are in the mechanical arrangement of the rotary hydraulic actuator and the inclusion of external mechanical stops. The electronic controller is mounted in the same rack as those for the other control loader axes and is essentially interchangeable with them except for tuning details. The interfaces to the EAI 2000 and the Host Computer are the same, the same abort circuit is used, and the actuator is powered by the control loader's hydraulic power system.

Sound system– The VMS Sound System can reproduce a wide variety of sounds associated with different types of aircraft and helicopters. It is a commercial product of the Wavetek company, and SimLab has three such systems (the other two support the fixed-base simulation facilities). The Sound System consists of a quadraphonic sound generator in the VMS Lab and four speakers mounted in the cab. The sound generator produces simulated sounds using electronic oscillators, filters, and mixers, provides the capability to control the various aspects of the sounds through certain control parameters, and directs the sound to the appropriate speaker. Control may be exercised either manually using knobs and switches on the chassis-mounted control panel or automatically from the Host Computer using the link provided by RIOU 2 and VMS SIO. Table 15 summarizes the various sounds that the Sound System can simulate, and table 16 lists the parameters that are available to control the sounds. There are two types of control parameters—discrete and continuous. The discrete parameters simply activate (turn on or off) a sound, while the continuous parameters control variations in volume or frequency, for example, over a given range of these parameters.

Auxiliary controls– Auxiliary Controls are devices other than the primary flight controls (control stick, wheel and column, collective, and rudder pedals) used by the pilot to control the simulated vehicle and its systems. The most important class of Auxiliary Control is the Hand Controller, a device that produces control signals in response to being manipulated by the pilot. Hand Controllers are further subdivided into Sidearm Controllers and Joysticks to distinguish two different levels of capability; examples of both types are shown in figure 24. A typical Sidearm Controller is quite sophisticated, includes a contoured handgrip, and provides a number of control functions using buttons and switches. Sidearm Controllers are, in fact, used instead of conventional controls in many
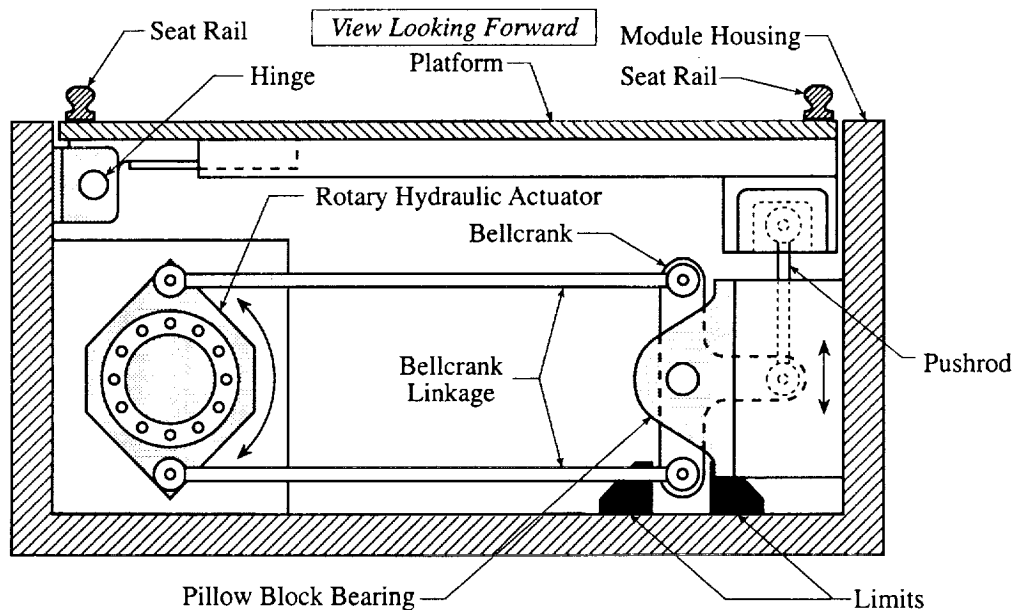

Figure 23. Vibration generator schematic.

Table 15. Sound system capabilities

Sound or sound source	Remarks
Engine and propeller noise	Up to four piston or jet engines
Landing gear touchdown	
Landing gear bounce	
Tire screech	
Runway rumble	
Cockpit air conditioner	
Helicopter rotor thrust	One or two rotors, up to five blades
Helicopter rotor pop	One or two rotors, up to five blades
Helicopter rotor gound echo	One or two rotors, up to five blades
Helicopter transmission	
Wind	
Slipstream	
Afterburner	
Thrust reverser	
Flap extension/retraction	Gearbox and electric motor noises
Spoiler extension/retraction	Gearbox and electric motor noises
Landing gear extension/retraction	Gearbox and electric motor noises
Flap buffet	
Spoiler buffct	
Landing gear buffet	

Table 16. Sound system control parameters

| Continuous variations	Discrete variations
Throttle	Afterburner operating
Propeller RPM	Weight on wheels
Helicopter rotor RPM	Left wheel on ground
Helicopter rotor thrust	Right wheel on ground
Helicopter rotor height	Flaps extending or retracting
Helicopter rotor pop control	Spoiler extending or retracting
Airspeed	Landing gear extending or retracting
Flap position	Landing gear down
Spoiler position	
Landing gear position	
Cockpit air conditioner volume	

operational flight vehicles. A Joystick, on the other hand, is very simple, providing only one or two control outputs. SimLab's inventory of Sidearm Controllers and Joysticks is summarized in table 17. The characteristics listed are (1) the type of controller (Sidearm Controller or Joystick), (2) the number of primary control outputs or degrees of freedom and whether these control outputs are signals proportional to applied force or displacement, (3) additional control functions provided, and (4) the style of grip.

The other major type of Auxiliary Control is the power controller, the device used to control the vehicle's propulsion system. The simulated power controllers available at SimLab vary from simple mechanical throttle quadrants to complex, multifunction units; these are summarized in table 18. Most of these were developed from or designed to replicate actual aircraft systems, and because of the emphasis at Ames on powered lift aircraft, SimLab has several power management consoles common to this type of vehicle. One unique device is a force servo throttle lever, which was built at SimLab from a McFadden Control Loader actuator. This power controller has a complete range of programmable force-feel characteristics similar to those provided by the standard control loaders.

Instruments– SimLab maintains an inventory of over 250 simulated flight instruments that are readily available for use and has several hundred more in inactive storage. SimLab also has a full-featured instrument shop for the maintenance, repair, modification, and calibration of all types of instruments. The available instruments fall into one of five general classes. *Flight Guidance Instruments* provide information pertaining to the vehicle's flight path and its position relative to the earth. *Propulsion Instruments* display the status and operating conditions of engines and characteristics of associated subsystems. *Control Indicators* are used to show information pertaining to controllers and control surfaces. *Air Data Instruments* provide information relating to the air mass through which the vehicle is flying. And finally, there are a number of *Generic Instruments* that can accommodate unique or special requirements by using specially designed dial faces that are produced locally in the instrument shop. Table 19 summarizes the active instruments in terms of general class and specific type and lists the number available of each type.

Video Switch

The Video Switch is a commercial product called the System 21 manufactured by DYNAIR Electronics, Inc. The System 21 is a microprocessor-controlled matrix routing switcher of modular design that can actually be
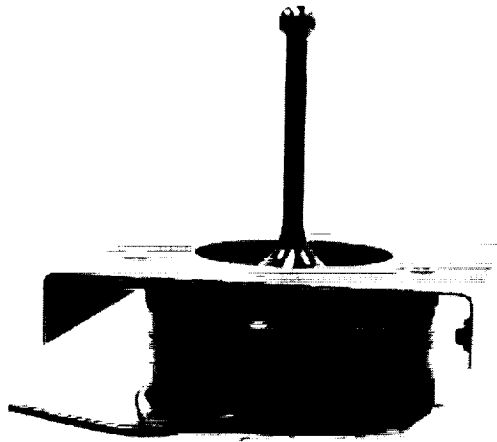
2-Axis Force Type Joystick

2-Axis Force Type Joystick
with Palm Rest
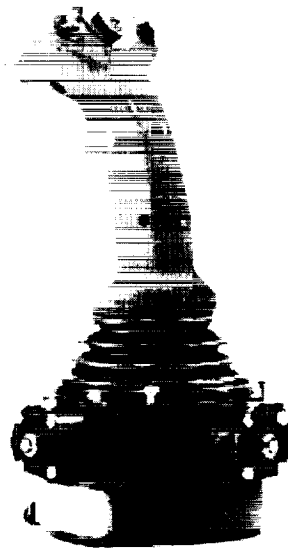
3-Axis Force Type
Sidearm Controller
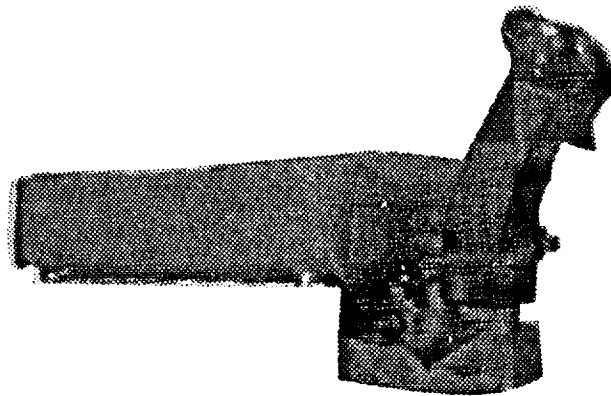
2-Axis Displacement Type Sidearm
Controller with Armrest

Figure 24. Examples of hand controllers.

used to switch other types of signals such as audio or high-speed time code if the proper components are installed. SimLab uses the System 21 strictly for switching video signals, however. The SimLab system is located in the same room as the DIG1 and has two sections: one for handling 1024-line interlaced video and the other for handling standard NTSC video. Both sections have a capacity of 30 inputs and 50 outputs.

The modules which comprise the System 21 are the switch frame, system controller, video switch module, video output module, power supply, and control panels of various types. The switch frame is the basic mounting structure for the switching modules and associated power supplies. It is designed to accommodate all possible configurations of System 21 components and, in turn, fits into a standard 19-in. electronics rack.

The video switch module and video output module work together to perform the actual signal routing under the control of the system controller. The switch module receives input signals from the various video sources through precision connectors, and its outputs are directed to an output module through a motherboard bus. Each

Table 17. Hand controller inventory

Controller type	Degrees of freedom	Buttons	Switches	Trigger	Grip
Sidearm controller	4 Force	2 Thumb pushbuttons, Little finger pushbutton	4-Position thumb switch	Double detent	Right hand contoured
Sidearm controller	3 Force	2 Thumb pushbuttons, Index finger pushbutton	2-Axis thumb controller, Paddle switch	Single detent	Right hand contoured
Space shuttle rotational hand controller	2 Displacement	2 Thumb pushbuttons	4-Position thumb switch	Double detent	Right hand contoured
Sidearm controller	3 Displacement	3 Thumb pushbuttons	None	Double detent	Right hand contoured
Sidearm controller	2 Displacement	1 Thumb pushbutton	2 Orthogonal thumbwheels	Double detent	Right hand contoured
Sidearm controller	2 Displacement	2 Thumb pushbuttons	4-Position thumb switch	Double detent	Right hand contoured
Sidearm controller	2 Displacement	2 Thumb pushbuttons, Little finger pushbutton	4-Position thumb switch	Double detent	Right hand contoured, Built-in arm rest
Joystick	2 Force	None	None	None	Right hand palm rest
Joystick	2 Force	None	None	None	None

Table 18. Power controllers

Controller name	Description and comments
Harrier power management console	A power management console from the YAV-8B Harrier modified for simulator use. The console includes a throttle lever, a nozzle angle control lever, various switches and buttons, and friction and stop controls. Two are available.
CVSONG power management console	A power management console functionally similar to that from the Harrier. It was designed and built at SimLab to support early Harrier display development simulations. The console includes a throttle lever, a nozzle-angle control lever, and a flap control lever. Two are available.
E7-STOVL power management console	A power management console that replicates that of the E7-STOVL research aircraft. The console includes a two-degree-of-freedom throttle lever with separate friction adjusters and an adjustable armrest.
Force servo throttle lever	A McFadden control loader modified to serve as a throttle lever. Typical programmable force-feel characteristics are available.
Six-lever throttle quadrant	A simple mechanical throttle quadrant with six separate power control levers.
Two-lever throttle quadrant	A simple mechanical throttle quadrant with two separate power control levers.
Single-lever throttle quadrant	A simple mechanical throttle quadrant with a single power control lever.

Table 19. SimLab active flight instrument inventory

Instrument	No.	Instrument	No.
Flight guidance instruments		**Control indicators**	
Accelerometer	1	Collective trim indicator	2
Altitude/vertical velocity indicator	1	Cyclic position indicator	7
Attitude director indicator	11	Dual Flap position indicator	2
Attitude director indicator, standby	1	Elevator position indicator	6
Clock, eight day	9	Flap position indicator	3
Compass (vertical tape)	1	Pedal position indicator	1
Compass repeater	2	Rudder angle indicator	1
Horizontal situation indicator	8	Speed brake position indicator	1
Normal acceleration indicator	1	Stabilator position indicator	1
Radio magnetic indicator	7		
Turn and bank indicator	10	**Air data instruments**	
		Airspeed indicator	10
Propulsion instruments		Alpha/mach indicator	1
Blade tip speed indicator	3	Angle-of-attack indicator	5
Engine pressure ratio indicator	5	Barometric altimeter	16
Engine/rotor RPM indicator	1	Instantaneous vertical speed indicator	2
Exhaust gas temperature indicator	10	Mach number indicator	2
Fan RPM indicator	4	Radar altimeter	1
Fuel flow indicator	1	Radio altimeter	11
Percent RPM indicator	12	True airspeed indicator, digital	1
Percent RPM indicator, dual Pointer	2		
Propeller RPM indicator	1	**Generic instruments**	
Tachometer, triple needle	14	Dual monitor center position	6
Torque indicator	1	Dual pointer center position	10
Turbine temperature indicator	4	Dual pointer vertical meter	5
Water quantity indicator	1	3-inch servo instrument	32
		Rectangular tape instrument	16

video switch module has 10 inputs and 10 outputs, and each video output module has 10 independent output buses with two outputs per bus. Up to 10 output modules can be connected to a single switch module.

The system controller serves as the central switchboard for the system. It receives switching commands from the control panels and directs them to the appropriate video switch and video output modules to rout the desired input signal to the desired output port. The main control panel for the System 21 is located at the system site, and there are several remote controllers, used primarily for maintenance and checkout purposes, located throughout the building.

Example Simulation System

Figure 25 presents an example of a complete VMS simulation system in the form of a schematic block diagram. It should be noted that this diagram is intended for illustra-

tive purposes only and is not meant to be comprehensive or to show all possible connections or components. Rather, it shows how a typical man-in-the-loop simulation might be constructed using the components and systems discussed in the previous sections and illustrates the interactions among the various elements and between the elements and the people involved.

The diagram is set up to flow from human operators (test conductors and the simulator pilot) to the Host Computer and back. Solid lines indicate the human-to-Host Computer path, and dashed lines, the Host Computer-to-human path.

The test conductors interact with the simulation system using the terminals in the VMS Lab and the switches on the SEP and PEP Panels. The terminals connect to the Host Computer through the Micom LAN, while the SEP and PEP Panels connect to it through the RIOU 0/CIOU pair to VMS SIO and the CIOU/CIOU pair to the Host Computer interface. In addition to the terminals and SEP
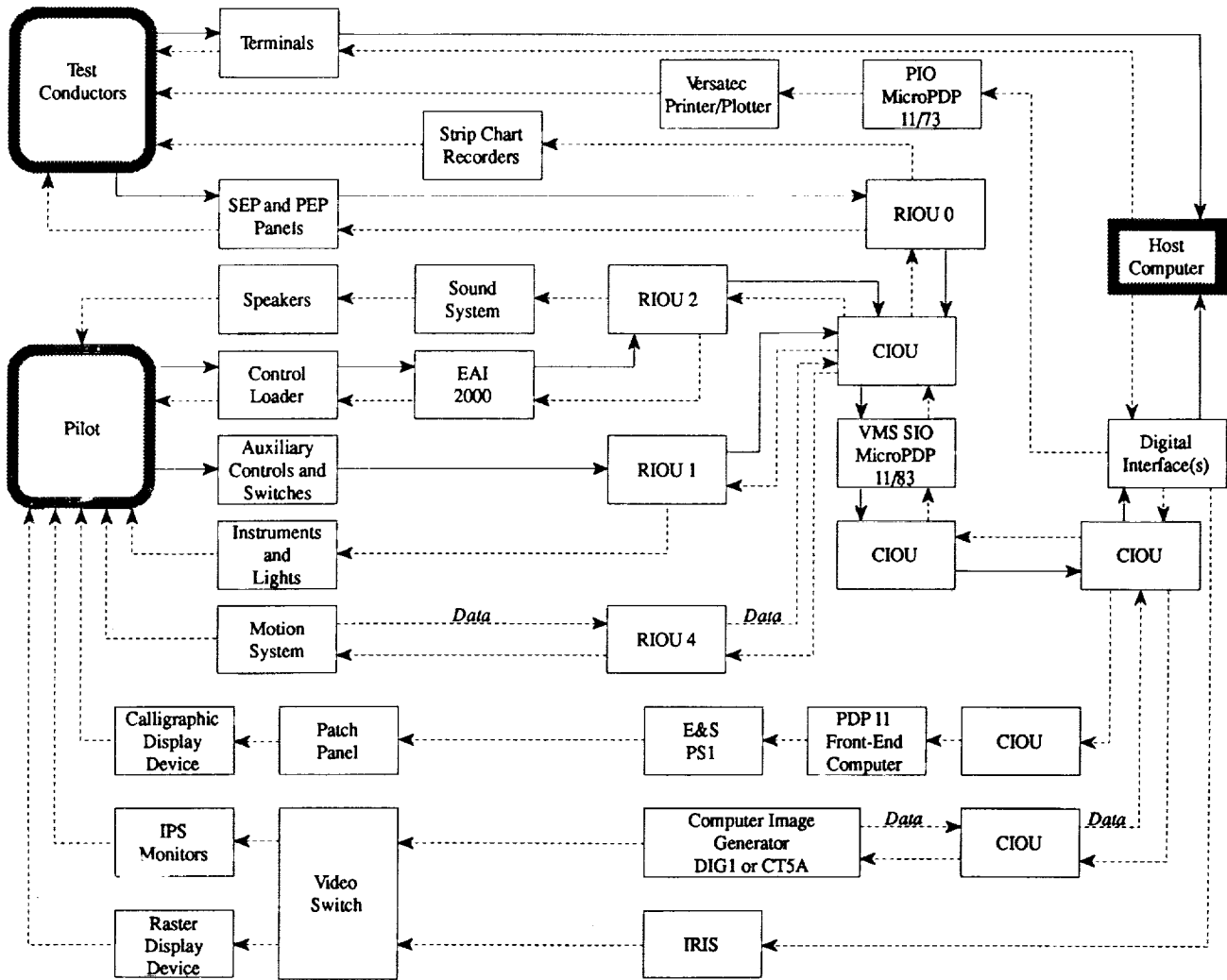
Figure 25. Example simulation system schematic.

and PEP Panels, the test conductors also receive information from the Host Computer on the Versatec printer/plotter and the strip-chart recorders. The Versatec is connected to the Host Computer interface through PIO and the strip-chart recorders through CIOU links, VMS SIO, and RIOU 0.

The Pilot interacts with the simulation system mainly through the control loader, auxiliary controls, and other devices such as switches and buttons. The control loader is unique because it acts both as an input device and a cueing system. When the pilot moves any of the control loader axes, the resulting displacement signals are transmitted to the EAI 2000 in the VMS Lab, then to VMS SIO through the RIOU 2/CIOU link, and finally to the Host Computer interface through the CIOU/CIOU link. Inputs from the auxiliary controls and switches are transmitted to the Host Computer through RIOU 2 in the

cab and the VMS SIO link. The control inputs are processed by the Host Computer to produce appropriate changes in the kinematic states of the simulated vehicle and, based on these changes, corresponding drive signals for the various cueing systems are computed.

The drive signals are transmitted to the different cueing devices through the Host Computer interface and three CIOU/CIOU links. The first of these connects to VMS SIO, which, in turn, connects to RIOU 1, RIOU 2, and RIOU 4. RIOU 1 provides drive signals for the simulated flight instruments and other indicators such as lights in the cab. RIOU 2 transmits drive signals to the Sound System in the VMS Lab, which produces sound cues through the speakers in the cab. It also transmits signals to the EAI 2000 that are used to modify control loader force-feel characteristics. RIOU 4 transmits drive signals to the VMS Motion System that result in the motion cues felt by

44

the pilot in the cab. There is also a data-feedback link through RIOU 4 and VMS SIO that transmits analog information such as displacement, velocity, and acceleration sensor measurements to the host, where it can be processed and displayed in the VMS Lab.

The remaining CIOU/CIOU links transmit digital drive signals to the Computer Image Generator and the PS1 auxiliary display generator. The Computer Image Generator's front-end processor connects to one CIOU/CIOU link, and its video outputs are sent to the Video Switch, which, in turn, directs them to the appropriate Image Presentation System monitors in the cab. There is also a data-feedback link through this CIOU pair that allows information originating in the Image Generator to be transmitted to the host computer.

The PS1 auxiliary display generator is connected to the other CIOU/CIOU link through its PDP 11 front-end computer. PS1 output is directed to calligraphic auxiliary display devices in the cab through the special-purpose patch panel. Similarly, the IRIS auxiliary display generator is connected to the Host Computer via the Ethernet LAN. The video output of the IRIS is sent to the Video Switch, which directs it to a raster-type display device in the cab.

Appendix

Glossary

Specialized Terms, Abbreviations, and Acronyms

AD 100 • A digital computer produced by Applied Dynamics, International; one of SimLab's host computers.

AD Real-Time Input/Output System • A custom input/output system that is one of the major subsystems of the AD 100.

ADC • Analog-to-Digital Converter.

ADDEV • Familiar name given to one of SimLab's MicroVAX systems.

ADRIO • AD Real-Time Input/Output System.

ADVAX • Familiar name given to one of SimLab's MicroVAX systems (the AD 100 front-end processor).

ADWS • Familiar name given to one of SimLab's MicroVAX systems.

Aircraft state • See *State*.

Aliasing • The generation of spurious results (signals) caused by sampling a process (signal) at too low a rate.

ALU • Arithmetic Logic Unit.

Analog signal • A nominally continuous electrical signal that varies in amplitude or frequency in response to changes in some physical parameter.

Analog-to-digital converter • A device that translates (converts) continuous analog signals into proportional, discrete digital signals.

Anti-aliasing • Pertaining to a process or feature that prevents aliasing or ameliorates its effects.

Arithmetic Logic Unit Processor • A processor that is part of the AD 100; it performs arithmetic logic operations.

Auxiliary control • Any of a group of aircraft or flight vehicle control devices that are not one of the primary controls.

Auxiliary Display Generator • A device used to generate the display (electronically "draw the picture") for one of the Auxiliary Electronic Displays.

Auxiliary Electronic Display • Any cockpit-mounted electronic display used to provide information to the pilot. For the purposes of this document, an Auxiliary Electronic Display is composed of an Auxiliary Display Generator and an Auxiliary Display Device.

Background • An environment in which a computer is performing lower priority functions because resources are not required for higher priority functions.

Backplane • A wiring board, usually constructed as a printed circuit, used in minicomputers to provide the required connections between logic, memory, and input/output modules.

Baud • A unit of signaling speed equal to the number of discrete conditions or signal events per second, usually expressed as bits per second.

Beam splitter • A partially reflective optical element that reflects part of the beam of light falling on it and transmits part; similar in function to an *optical combiner*.

BI bus • A computer bus that is part of the SimLab VAX 9000 architecture that provides for connecting a CIOU to the XMI bus.

Bias • A static offset applied to or inherent in a dynamically variable parameter.

Boot • From "bootstrap;" a technique, device, or part of a computer program that is designed to bring itself into a desired state by means of its own action.

Boresight • Alignment of an optical axis with a reference axis.

Boresight Reticle Unit • A part of the IHADSS that provides a collimated target reticle used as a visual reference when boresighting the system.

Bus • A set of conductors in a computer used to transmit information from any of several sources to any of several destinations.

Byte • A sequence of adjacent binary digits (bits) operated upon as a unit in a computer; typically shorter than the computer word for the particular system, so that a word is composed of some number of bytes.

C • A computer programming language.

Cache • A small, fast storage buffer integrated in the central processing unit of some computers.

Calligraphic display • A display device in which the display elements of a display image may be generated in any program-controlled sequence; synonymous with stroke display and directed-beam display.

Catenary • An articulated cable tray used to carry electrical cables and hydraulic lines between the VMS tower walls and the lateral carriage of the motion system.

Center of rotation • A point about which a set of rotational motions occur. See also *Gimbal*.

Center Position • One of the five defined modes of operation of the VMS motion system. The motion system is stationary with all degrees of freedom at their center of travel. Also, the position of the motion system when this mode is in effect.

Central processing unit • The part of a computer containing the circuits required to interpret and execute instructions.

Central Processor Unit • One of the major subsystems composing the VAX 9000 host computer; the part containing the central processing unit and closely related systems.

Channel • 1. A path along which information may flow within a computer or between systems. 2. Designating one of several distinct viewing areas for which imagery can be generated and displayed in a visual display system.

Channel Processor • One of the major subsystems of the CT5A computer image generator.

Character Generator • One of the major subsystems of the PS1 auxiliary display generator.

Chin window • A helicopter or aircraft window located on the bottom forward end of the fuselage.

Chip • An integrated circuit on a piece of semiconductive material, usually capable of performing a large number of functions.

CIG • Computer Image Generator.

CIOU • Computer Input/Output Unit.

CLR • Control Line Register.

CMOS • Complementary metal oxide semiconductor.

Cockpit Cueing Device • A catchall term denoting any of a number of cueing systems located primarily in the simulator cockpit.

Collimated • Designating a beam of light for which all rays are parallel.

Collision volume • A specially defined portion of a CIG database which designates the three-dimensional region for which collisions with the ownship can occur.

COM • Communication and Control Processor.

Communication and Control Processor • A processor that is part of the AD 100; it controls all the computer's resources at run time and provides the interface to the input/output system.

Compiler • A computer program that translates a higher level language into machine language that can be linked and executed by the computer.

Computer Image Generator or image generator • A system of computers and special-purpose components that calculates and generates, in real time, electronic signals representative of dynamic real-world imagery as would be viewed by a pilot flying an airplane. The composition of the imagery (landscape features, buildings, vehicles, etc.) is stored in a database, and the output signals feed a display device that turns them into visible pictures.

Computer Input/Output Unit • A special-purpose data transmission device that provides communication between two digital systems.

Control Line Register • One of the components of the AD 100 input/output system; a Discrete Output device.

Control loader • A servosystem that can provide realistic force-feel cues over a range of conditions.

Control surface • A movable airfoil on a flight vehicle used to guide or control the vehicle's motion through the air.

Controller • A name given to the general-purpose computer that is part of the DIG1 computer image generator.

Coprocessor • A processor that is designed to function in conjunction with or in support of another (usually main) processor.

CPU • Central Processing Unit or Central Processor Unit.

CPU Subsystem • One of the major subsystems of an IRIS System.

Crew station • That portion or area of a vehicle where the crew members perform their tasks and functions.

CT5A • A Computer Image Generator produced by Evans and Sutherland Corporation.

Cueing System • Any system designed specifically to provide cues to the pilot or other personnel in a simulator.

Cycle time • The time elapsed between the start of a given host computer's computational cycle and the succeeding one.

DAC • Digital-to-Analog Converter.

Deflection Amplifier Unit • One of the major subsystems of the FDI HUD; the part containing the deflection amplifiers and related items.

Degree of freedom • Generally, any one of a number of ways in which the configuration of a system can change; in kinematics, each degree of freedom corresponds to one of the spatial coordinates of the *coordinate system* used to describe motions.

Describing function • A function used to represent a non-linear transfer function by an approximately equivalent linear transfer function; specifically, the ratio of the phasor representing the fundamental component of the output of the system under consideration (determined by Fourier analysis) to the phasor representing a sinusoidal input signal.

Design eyepoint • The eyepoint used as the basis for designing or specifying optical systems; the eyepoint at which a system is designed to function optimally.

DI • Discrete Input.

DIG1 • A Computer Image Generator produced by the Singer Link Company.

Digital signal • An electrical signal that is both discrete and quantized and whose magnitude varies in response to changes in some physical parameter.

Digital-to-analog converter • A device that translates (converts) discrete digital signals into proportional continuous analog signals.

Digital-to-synchro converter • A device that translates (converts) discrete digital signals into synchro signals.

Discrete Input • A converter device that translates discrete-level voltage signals into corresponding on/off-type digital signals.

Discrete Output • A converter device that translates on/off-type digital signals into discrete-level voltage signals.

Display Processor • One of the major subsystems of the CT5A computer image generator.

Display Subsystem • One of the major subsystems of an IRIS System.

Dither • The application of an input of controlled amplitude and frequency to a servosystem so that the device experiences constant small-amplitude sinusoidal motion and therefore cannot stick in its null position.

DO • Discrete Output.

Dock Position • One of the five defined modes of operation of the VMS motion system. The rest state of the motion system wherein all inputs are disconnected and the servos are locked in a position such that the cab aligns with the boarding ramp. Also, the position of the motion system when this mode is in effect.

DPM • Dual-port Memory Unit.

DR11 • A general-purpose direct memory access device for interfacing computers and other types of digital systems.

Drive signal • An electrical signal used to excite or command a system to produce a desired response.

DSC • Digital-to-Synchro Converter.

Dual-Port Memory Unit • An element in the AD 100 input/output system that provides a communications path to an external digital system.

EAI 2000 • An analog computer produced by Electronic Associates, Incorporated.

Edge • The primitive from which imagery is constructed in a DIG1 computer image generator.

Equilibrator • A pneumatic force-producing mechanism, a pair of which are used to balance the static weight of the VMS motion generator and its payload.

Event marker • A special type of pen on a strip chart recorder that can be moved between discrete positions to record discrete events.

EXP • Expansion assembly, used to indicate slots on the AD 100 buses that are unused and available for expansion.

Eyepoint • A point in space used to represent the theoretical location of an observer's eye.

FCAB • One of the four Interchangeable Cabs.

Feed-forward compensation • An element used for process control in which changes are detected at the process input and an anticipating correction is generated before the process output is affected.

Feedback • Pertaining to the control of a system's input as a function of its output by means of returning some portion or function of the output to the input.

Field • One of the equal parts into which a frame is divided in an interlaced, scanning raster-type display device; a field includes one complete scanning operation from the beginning to the end of the picture and back again.

Field rate • The number of fields produced per second by a raster-type display device, expressed in Hertz.

Field of view • The area or solid angle over which a display provides a picture.

Flight instrument • A gauge or other type of instrumentation used to display information pertaining to a flight vehicle, its systems, its flight path, and its environment.

FLIR • Forward-Looking Infrared.

Floating point • A number system in which the location of the decimal point does not remain fixed with respect to one end of the string of numerals.

FMU • Function Memory Unit.

Footlambert • A unit of luminance (photometric brightness) equal to the uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of 1 lumen per square foot.

Foreground • An environment in which a computer is performing higher priority functions.

FORTRAN • A family of procedure-oriented computer languages used mostly for scientific or algebraic applications.

Forward-Looking Infrared • Pertaining to an infrared device that employs an optomechanical system to make a two-dimensional scan and produce a visible image corresponding to the spatial distribution of infrared radiation.

Frame Calculator • One of the major subsystems of the DIG1 computer image generator.

Frame • One complete scan of the image area of a raster-type display device by the electron beam; a frame may be composed of several *fields*.

Frame rate • The number of frames produced per second by a raster-type display device, expressed in Hertz.

Function Memory Unit Processor • A processor that is part of the AD 100; it provides extra data memory.

Geometric distortion • An aberration in an optical system in which magnification varies with distance from the optical axis, causing straight lines to appear curved.

Geometric Processor • One of the major subsystems of the CT5A computer image generator.

Geometry Subsystem • One of the major subsystems of an IRIS System.

Gimbal • A device with two or more independent axes of rotation, thus providing free angular movement around each axis; the axes are typically mutually perpendicular and intersecting, with the intersection point termed the *center of rotation.*

Graphics Subsystem • One of the major subsystems of an IRIS System.

Hammer Chart • A chart or graph presenting field-of-view information using the Hammer equal-area projection method.

Hammer equal-area projection • A method for depicting field-of-view information that employs a mapping function to generate a grid of curved lines that constitute the projection of the complete surface of a sphere onto a planar surface. A notable feature is that equal areas on the two-dimensional projection represent equal areas on the spherical surface.

Hand Controller • A class of auxiliary control device that is operated manually. For the purposes of this document, this class is further subdivided into *Joysticks* and *Sidearm Controllers.*

HDD • Head Down Display.

HDU • Helmet Display Unit.

Head Down Display • A class of auxiliary electronic display for which the viewing area is positioned outside a crew member's normal external (out-the-window) field of view; it is typically located in a forward panel.

Head Up Display • A class of auxiliary electronic display for which the viewing area is positioned directly within a crew member's normal external (out-the-window) field of view.

Helmet Display Unit • The part of the IHADSS that contains the actual viewing area and display generator; it is mounted on the right side of the special pilot helmet.

Helmet Mounted Display • A class of auxiliary electronic display for which the display device is attached to a crew member's helmet. Also, one of the major subsystems of the IHADSS.

Helmet Mounted Sight • One of the major subsystems of the IHADSS; it measures the line-of-sight angles that determine where the helmet is pointing.

HMD • Helmet Mounted Display.

HMS • Helmet Mounted Sight.

Holographic • Pertaining to a technique used for three-dimensional optical image formation based on recording, then reconstructing amplitude and phase distributions of a wave disturbance.

Host Computer • A large digital computer that is the nucleus of a simulation system; it solves the equations that represent the mathematical model of the flight vehicle and its related systems and performs all the computations required to command and control the other parts of the simulation system.

HUD • Head Up Display

Hydraulic actuator • A cylinder- or fluid-powered motor that converts hydraulic power into mechanical motion.

I/O • Input/Output.

ICAB • Interchangeable Cab.

IHADSS • Integrated Helmet and Display Sighting System.

IHU • Integrated Helmet Unit.

Image Presentation System • That portion or subsystem of a Visual Display System that presents imagery in a form visible to the human eye.

Image Processor • The major subsystem of the CT5A computer image generator; the portion consisting of all the special-purpose hardware.

Initial Position • One of the five defined modes of operation of the VMS motion system. The motion system is stationary, but each degree of freedom may be displaced from the center of travel to suit test requirements. This is the only mode from which the system can transition into full dynamic operation. Also, the position of the motion system when this mode is in effect.

Input/Output Control Processor • A processor that is part of the AD 100; it controls input/output operations.

Integrated Helmet and Display Sighting System • A production helmet-mounted display with an integrated head-tracking capability.

Integrated Helmet Unit • The part of the IHADSS that is the actual flightworthy pilot helmet.

Interchangeable Cab • A specially designed and constructed structure used to simulate the cockpit/crew station for VMS simulations and to support and house additional simulation-related equipment.

Intercom • Abbreviation of intercommunication system. A two-way audio communication system having a microphone and speaker at each of a number of distinct stations and designed to provide communication over a limited area.

Interface • 1. A shared boundary (possibly a hardware device) defined by functional characteristics, common physical interconnection characteristics, signal characteristics, and other characteristics as appropriate. 2. Some form of electronic device that enables one piece of gear to communicate with or control another. 3. A device that serves as a link between two otherwise incompatible devices.

Interface Device • A special-purpose item designed to provide communications between specific types of electronic equipment. For the purposes of this document these include Computer Input/Output Units and Remote Input/Output Units.

Interlacing • A scanning process in raster-type display devices in which the distance from center to center of successively scanned lines is two or more times the nominal line width, so that adjacent lines belong to different fields. *See also* Field.

IOCP • Input/Output Control Processor.

IPS • Image Presentation System.

IRIS System • A type of computer graphics system produced by Silicon Graphics, Incorporated; used at SimLab primarily as an Auxiliary Display Generator.

Joystick • A subclass of hand controllers that provides a minimum of functions, typically only one or two control outputs.

KB • Abbreviation of Kilobyte.

Kilobyte • One thousand bytes.

LAN • Local Area Network.

Lateral carriage • That portion of the VMS motion system that provides translational motion along the length of the vertical platform, which is nominally the lateral degree of freedom.

Limiter • A device, circuit, or algorithm that serves to prevent a physical state or electrical signal from exceeding a specified level.

Local Area Network • A communications network connecting various hardware devices.

Longitudinal carriage • That portion of the VMS motion system that provides translational motion perpendicular to the vertical platform, which is nominally the longitudinal degree of freedom.

Main Memory Subsystem • One of the major subsystems of the VAX 9000 host computer; the part containing the working storage used by the central processing unit.

Man-in-the-loop • Pertaining to a simulation that includes a human as a controlling element.

Man-rated • Designating a system or piece of equipment that has been certified to comply with established man-rating standards. In general this means that the item has been thoroughly reviewed and found to be safe for human occupation and/or operation.

Mathematical model • A mathematical representation of a process, device, or concept by means of a number of variables defined to represent its inputs, outputs, and internal states, along with a set of equations and inequalities describing the interaction of these variables.

MB • Abbreviation of Megabyte.

MCU • Mode Control Unit.

Megabit • One million bits (binary digits).

Megabyte • One million bytes.

Micro600 Port Selector • The major hardware component of the Micom Local Area Network.

Microprocessor • A single silicon chip on which, for example, the arithmetic and logic functions of a computer are placed.

MicroVAX • A product line of digital computers produced by Digital Equipment Corporation.

MIPS • Million Instructions Per Second, a measure of digital computer operating speed.

Mode Control Unit • A special-purpose electronics device that serves as the primary interface between drive signals from the host computer and the VMS motion system servos.

Monochrome • Having only a single chromaticity (color).

Motherboard • A common pathway over which information is transmitted between the hardware devices in a microcomputer.

Motion base or motion generator • That portion of a motion system that actually moves or imparts movement to the payload.

Motion Control Room • A special control room for the VMS motion system.

Moving model • An object in a computer image generator database that is controlled dynamically so that it appears to move relative to the background scene, for example, a car traveling down a road.

MUL • Multiplier Processor.

Multiplexing • Pertaining to the combining of two or more signals or parameters onto a single display channel.

Multiplier Processor • A processor that is part of the AD 100; it performs multiplication operations.

Nanosecond • One one-billionth of a second.

Nap-of-the-earth flight • Designating flying or a flight path that closely follows the local terrain at extremely low (the lowest possible) altitude, including flying around objects rather than over them so that vegetation and terrain contours can be used to mask the vehicle.

NCAB • One of the four Interchangeable Cabs.

NTSC • National Television Systems Committee, a group impaneled to set standards for commercial television in the United States.

Object Manager • One of the major subsystems of the CT5A computer image generator.

Occulting • Pertaining to the masking of imagery in any part of a display system.

Operate Mode • One of the five defined modes of operation of the VMS motion system. The only mode for which full dynamic operation is possible and for which the motion system is under the control of the host computer.

Operational limit • A value for a parameter that represents the maximum level usable or attainable under *normal operating conditions*. For the VMS motion system, an operational limit includes the effects of all the limiters in the system (both hardware and software) and may be less than the corresponding system limit.

Optical combiner • A partially reflective optical element that reflects part of the beam of light falling on it and transmits part; similar in function to a *beam splitter*.

Overhead Display Unit • One of the major subsystems of the FDI HUD.

Ownship • The simulated vehicle that the simulator pilot is "flying."

Parabolic limiter • A form of limiter for which a plot of limiting displacement versus limiting velocity takes the form of a parabola that is a line of constant acceleration.

PDP-11 • A product line of digital computers produced by Digital Equipment Corporation.

PEP • Project Engineer's Panel.

PEP Station • A work station/control station in the VMS Lab that provides a central control and communications facility for test operations.

Picture Controller • One of the major subsystems of a PS1 line-drawing system.

Picture Generator • One of the major subsystems of a PS1 line-drawing system.

Picture Processor • One of the major subsystems of a PS1 line-drawing system.

Pilot Display Unit • The name given to a Head Up Display developed for the Space Shuttle.

PIO • Printer Input/Output.

Pitch • One of the rotational degrees of freedom, representing angular displacement about the lateral axis; the nose-up/nose-down motion.

Pixel • Abbreviation of picture element; the smallest addressable element in an electronic display.

PLUSBUS • The main bus in the AD 100 host computer.

Polygon • The primitive from which imagery is constructed in a CT5A computer image generator.

Polygon Manager • One of the major subsystems of the CT5A computer image generator.

Potentiometer • A resistor having a sliding contact that is continuously adjustable over a range and generally mounted on a rotating shaft; used chiefly as a voltage divider.

Power controller • A device used to control a vehicle's powerplant.

Power management console • A control console used in certain types of flight vehicles, used to control the powerplant as well as other related functions.

Pre-Dock Position • One of the five defined modes of operation of the VMS motion system. A reference mode that, for safety considerations, is a required precondition for docking. This is the only mode from which the system can transition into Dock Position. Also, the position of the motion system when this mode is in effect.

Primary control • One of the classic aircraft or helicopter control devices. For the purposes of this document these include: control stick, wheel and column, rudder pedals, and collective stick.

Project Engineer's Panel • A control panel, located in the PEP Station, that contains switches and indicators used to control a simulation.

PS1 • A calligraphic computer graphics system produced by Evans and Sutherland, Incorporated; used at SimLab primarily as an Auxiliary Display Generator.

Q-Bus • The main bus employed in a several computer product lines produced by Digital Equipment Corporation.

Radar altitude • The altitude of an aircraft above the local terrain as measured by a radar altimeter, determined by measuring the time for a radar pulse to be reflected from the ground.

Raster • A predetermined pattern of scanning lines that provides substantially uniform coverage of an area.

Raster Subsystem • One of the major subsystems of an IRIS System.

RCAB • One of the four Interchangeable Cabs.

Read-only memory • A device for storing data in permanent or nonerasable form.

Real image • An optical image that can be projected on a screen; one formed by the meeting of converging rays of light.

Real time • Pertaining to the actual time during which a physical process transpires, e.g., the performance of a computation during the actual time that the related physical process transpires, in order that the results of the computation can be used in guiding the process.

Real-time simulation • The operation of a simulator such that the time-scale factor is equal to unity for both the physical time specified by the system being simulated and the corresponding computer time of the simulator.

Recirculating ball-bearing assembly • A type of ball-bearing assembly used for translational motion applications in which the balls can circulate in a closed path.

Reduced Instruction Set Computer • A computer design that provides enhanced performance by limiting the number of executable instructions.

Refresh Buffer • One of the major subsystems of a PS1 line-drawing system.

Relay lens • A lens or lens system used to transfer an image from one part of an optical path to another.

Remote Input/Output Unit • A special-purpose data transmission device that provides communication between a digital system and an analog system.

Reticle • An image placed in the focal plane of the eyepiece of an optical device to aid in the positioning of the field of view or for direct observation of the apparent size of an item viewed through the device.

RIOU • Remote Input/Output Unit.

RISC • Reduced Instruction Set Computer.

Roll • One of the rotational degrees of freedom, representing angular displacement about the longitudinal axis; the wing-tip-up/wing-tip-down motion.

Rotational degrees of freedom • The three degrees of freedom that represent angular or rotary motions.

Safety interlock system • A system that prevents activation of a piece of equipment when certain predetermined unsafe conditions exist.

SCAB • One of the four Interchangeable Cabs.

Scan Conversion Subsystem • One of the major subsystems of an IRIS System.

Scanline • The path traced by a single scan in a raster-type display device.

Scanline Computer • One of the major subsystems of the DIG1 computer image generator.

SCSI • Small Computer System Interface.

SCU • System Control Unit.

53

Sense Line Register • One of the components of the AD 100 input/output system; it receives discrete inputs.

Sensitivity • The ratio of the response to a stimulus; the ratio of change induced in the output to a change applied at the input.

SEP • Simulation Engineer's Panel.

SEP Station • A work station/control station in the VMS Lab that provides a central control and communications facility for test operations.

Server • A device that is part of a network that connects to and interacts with a certain class of equipment.

Service Processor and Scan Subsystem • One of the major subsystems of the VAX 9000 host computer; the part containing the operator's console.

Servo system • An automatic feedback control system for mechanical motion; the controlled quantity or output is mechanical displacement or one of its derivatives.

Servo valve • A valve that controls the flow to a hydraulic actuator and is an integral part of a hydraulic servosystem.

Sidearm controller • A subclass of hand controllers that includes a contoured handgrip and provides one or more control outputs and additional control functions using buttons and switches.

SIMDEV • Familiar name given to one of SimLab's MicroVAX systems.

SimLab • The collection of flight simulators and related simulation components, support facilities, and support equipment located in the Flight and Guidance Simulation Laboratory and nearby buildings at Ames Research Center.

Simulation Engineer's Panel • A control panel located in the SEP Station that contains switches and indicators used to control a simulation.

SIMVAX • Familiar name given to one of SimLab's MicroVAX systems.

SIO • Simulation Input/Output, a computer used as an interface between the host computer and a number of RIOUs.

SLR • Sense Line Register.

Small Computer System Interface • An interface standard designed for microcomputers.

Smooth shading • Adjustments made to the color and intensity levels of the elements used to make up an object in a computer-generated image to give the object the appearance of being rounded or curved.

Span processing • A processing technique used in the CT5A that operates on rectangular areas of the display field and thereby avoids aliasing problems associated with scanline processing.

Spherical aberration • An aberration in an optical system that arises from the fact that rays that are initially at different distances *from* the optical axis come to a focus at different distances *along* the axis.

Staircasing • A slang term used to describe quantization or quantization effects.

STARVAX • Familiar name given to one of SimLab's MicroVAX systems.

State • A minimum set of numbers representing kinematic parameters that contain enough information about a system's history to enable its future behavior to be computed.

STO • Storage Processor.

Storage Processor • A processor that is part of the AD 100; it provides limited high-speed data storage for program variables and coefficients.

Strip chart recorder • A data recording device that operates by drawing chart paper at a controlled rate under a series of pressurized ink pens that deflect perpendicular to the direction of paper motion in response to input voltages.

SUP • Supervisor.

Supervisor • A processor that is part of the AD 100; it provides the interface path between the main bus and the front-end computer.

System 21 • A commercial microprocessor-controlled matrix-routing switcher produced by DYNAIR Electronics, Incorporated, and used at SimLab as a video switcher.

System Control Unit • One of the major subsystems of the VAX 9000 host computer; the part that manages the data flow among all the other subsystems.

System limit • A value for a parameter that represents the maximum level attainable under *controlled conditions*, but not necessarily normal operating conditions. For the VMS motion system, a system limit does not include the effects of software limiters and may be greater than the corresponding operational limit.

Throttle quadrant • A device that contains a set of power control levers that are used to control a vehicle's powerplant.

Thyristor controller • A type of controller used in the electrical drives of the VMS motion system that employs a certain type of transistor (a thyristor) that provides a high-speed triggering action.

Time delay • The time required for a signal to pass through a device or series of devices.

Translational degrees of freedom • The three degrees of freedom that represent motion from one point in space to another.

U-matic • A commercial standard for video tape recording.

UNIBUS • The main bus employed in a several computer product lines produced by Digital Equipment Corporation.

UNIX • Operating system software developed at Bell Laboratories.

V/STOL • Vertical/Short Takeoff and Landing.

VAX • A product line of digital computers produced by Digital Equipment Corporation.

VAX Unit of Processing • A parameter used to designate the performance level of VAX computers; defined as the performance equivalent of one VAX 11/780 system and roughly equal to 1 *MIPS.*

VAXlab • A work station built around one of the various MicroVAX systems; it typically includes a video display monitor, extra memory, and an Ethernet interface.

VAXStation • A work station built around one of the various MicroVAX systems and primarily oriented to real-time operations; typical features are a real-time clock/counter, special termination/connector panels, and a special software library.

Vertical platform • An extremely large beam structure that can translate vertically and upon which are mounted the cab and virtually all the moving parts of the VMS motion system.

Vibration generator • A cueing system that provides high-frequency, low-amplitude acceleration cues to the pilot.

Video switch • A device used to switch and route video signals from a number of sources to desired destinations.

Viewing volume • That region of space from within which a display produces no or, at a minimum, acceptable, degradation.

Viewpoint Processor • One of the major subsystems of the CT5A computer image generator.

Viewport • A predefined region in a display area.

Virtual image • An optical image that cannot be projected on a screen; an image from which rays of light only appear to diverge without actually being focused there.

Visual database • A database in which is stored all the information necessary to produce the imagery in a computer image generator.

Visual Display System • An arrangement of computer, video, and optical equipment that generates and presents imagery representing the view of the outside world to the crew members of a simulator.

VLSI • Very Large Scale Integration; a technique in which a large number of microcircuits are integrated in a single chip.

VME • A commercial computer interface standard.

VMS • Vertical Motion Simulator, the subject of this document.

VMS Lab • A control room that serves as both the work area and focal point for the personnel who conduct and direct VMS simulations. It also contains operating consoles and control consoles as well as test support and monitoring equipment.

VT320 • A model of computer terminal produced by Digital Equipment Corporation.

VUP • VAX Unit of Processing.

Window • An arrangement of a display device (monitor) and optical elements by means of which a crew member can view one channel of the Visual Display System in the cab; a part of the Image Presentation System.

Work station • 1. A set of equipment arranged to provide convenient operation of a computer or computer-based system. 2. A set of equipment consisting of a computer along with compatible software and communications, display, and interface hardware marketed as a package by a computer manufacturer.

XMI bus • The main bus in the VAX 9000 host computer.

Yaw • One of the rotational degrees of freedom, representing angular displacement about the vertical axis; the nose-left/nose-right motion.

4D • A model designation for a class of IRIS System.

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13. ABSTRACT *(Maximum 200 words)*

The Vertical Motion Simulator Familiarization Guide provides a synoptic description of the Vertical Motion Simulator (VMS) and descriptions of the various simulation components and systems. The intended audience is the community of scientists and engineers who employ the VMS for research and development. The concept of a research simulator system is introduced and the building block nature of the VMS is emphasized. Individual sections describe all the hardware elements in terms of general properties and capabilities. Also included are an example of a typical VMS simulation which graphically illustrates the composition of the system and shows the signal flow among the elements and a glossary of specialized terms, abbreviations, and acronyms.

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