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DEVELOPMENT AND VALIDATION OF THE CREW-STATION-SYSTEMS INTEGRATION RESEARCH FACILITY

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Ames Research Center

SUMMARY

This paper discusses the various issues associated with the use of integrated flight management systems in aircraft. To address these issues a fixed base IFR simulation of a helicopter has been developed to support experiments that contribute to the understanding of design criteria for rotorcraft cockpits incorporating advanced integrated flight management systems. A validation experiment has been conducted that demonstrates the main features of the facility and the capability to conduct crew/system integration research.

INTRODUCTION

Advanced avionics and integrated flight-management systems are becoming increasingly common in aircraft cockpits. The aim of these systems is to use shared controls, sensors, and programmable displays together with sophisticated data-processing capabilities to provide pilots with tools that extend mission capabilities while they enhance safety and decreasing work load.

A program has been conducted at NASA Ames Research Center that demonstrates the use of an advanced flight-management system in a general-aviation, twin-engine, light plane (fig. 1 a and b). In the Demonstration Advanced Avionics System (DAAS) program more than 100 guest pilots and observers have participated in over 60 flights. Oral debriefings and questionnaires have been obtained from all the participants and the summarized results have been published in references 1 and 2.

The DAAS program underscores three important issues associated with the use of advanced technologies and integrated flight-management systems. First, while such systems have the potential for extending the mission capabilities of aircraft, there is also the potential for producing unacceptable increases in the pilots's work load, both actual and perceived. That is, the pilot may not find it desirable to take advantage of the advanced features provided by the system because of difficulty in using them. Second, integrated flight-management systems have the potential for affecting safety both favorably and unfavorably. Positive effects come from capabilities such as sophisticated monitoring and warning systems, and moving map

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displays. These systems and displays can provide complete situational awareness. Yet these same capabilities encourage the pilots to become inattentive when they do not intervene during the long flights. On the other hand, high work loads can be imposed in such situations as making changes to the flight plan while en route or in the terminal area. In addition, keeping track of the actions and state of a complex system that is performing a complex task can itself impose a high work load. Advanced, integrated flight-management systems impose tremendous demands on the crews' training. Crews must now maintain sophisticated mental models of the system to effectively use its capabilities and maintain an awareness of the system's operating state. High demands are also placed on proficiency on flight procedures. The great variety in the details of functional implementation for various systems will require either restricting operations to the use of one type of system or crew familiarization with the various systems.

To address these issues the Digital Systems group at Ames Research Center is conducting a program to develop a research platform upon which to conduct experiments that can lead to the establishment of design criteria for crew stations using integrated flight-management systems. Because of the emphasis on rotorcraft at Ames Research Center, it has been decided that the research platform should be representative of a general-purpose helicopter with the flexibility to reconfigure the cockpit as necessary, and thus provide results which could validly be applied to all rotorcraft cockpits. The simulation includes an advanced flight-management system configured for rotorcraft. The system, Rotorcraft Digital Advanced Avionics System (RODAAS), is based on the DAAS mentioned earlier, modified as necessary to provide flight-management functions for rotorcraft.

The facility is called the Crew-Station-Systems-Integration Research Simulation. The intent of the facility is to provide a readily accessible platform upon which to conduct research on the way pilots interact with sophisticated electronics in modern rotorcraft cockpits. To provide this capability the facility must meet several criteria. (1) The system must be readily accessible and reasonably economical to operate, as the nature of the research being conducted requires numerous trials to develop a meaningful data base. (2) The simulation must include all of the features necessary to represent the rotorcraft cockpit environment with sufficient fidelity to support meaningful experiments in crew-system interaction. (3) The facility must be easily expandable and reconfigurable to accommodate the widely varying capabilities and different levels of automation and sophistication likely to be encountered in current and future rotorcraft cockpits.

The purpose of this paper is to describe the development and features of the Crew-Station Systems-Integration Research Simulation facility including: 1) general layout of the simulation cab; 2) computer hardware and software used to drive the simulation; 3) interchangeable instrument panel capability; 4) multipurpose graphics display; and 5) voice and data interface with the air-traffice-control (ATC) simulation. The paper concludes with a discussion of a validation experiment that demonstrates the main features of the Crew-Station Systems-Integration Research Simulation platform which provide the capability to address the issues confronting the use of advanced, integrated, flight-management systems.

SIMULATION CAB

The simulation cab is set up as an instrument-meteorological-conditions (IMC) cab on a fixed base, with a single seat, and housing conventional helicopter controls (fig. 2). The controls available are cyclic pitch and roll, rudders, and collective pitch with a throttle control available on the collective. Control position is sensed by linear variable differential transformers (LVDT) on each control axis. Throttle position is sensed by a potentiometer. Force feel is provided to the pilot by research magnetic brakes on the cyclic and rudder pedals. The pedals provide a centering force to a neutral point, unless the magnetic brakes are deenergized by depressing the trim/force button on the cyclic control grip (fig. 3). In this case the control can be moved freely. When the trim/free button is released, the control will again be provided with a restoring force to the new neutral point at which the trim/free button was released. Force feel for the collective is provided by an adjustable, variable-friction device. In addition to the magnetic-brake trim system, and continuous-"beeper" trim system is available for the cyclic roll and pitch control. When activated by a four-way switch on the pilot's cylic-control-grip, servo motors move the cyclic forward, back, left, or right, depending upon the direction in which the switch was activated. When the switch is released the cyclic remains in its new position. The cyclic control linkages are set up in such a way that when the beeper trim is activated the neutral point provided by the cyclic magnetic brakes moves with the cyclic stick. The speed at which the cyclic moves when the trim switch is activated can be varied continuously.

In addition to the trim/force and beeper-trim buttons, the other switches on the cyclic have also been interfaced to the simulation computers. The functions performed when the switches are activated depend on software and can be varied according to the needs of the researcher and the simulation configuration. Several switches on the collective grip have also been interfaced to the simulation computers and have functions dependent on software. The pedestal on the pilot's left (fig. 4) containes radio tuning heads, an autopilot-mode controller, and an intercom. The radio tuning heads are interfaced to the simulation computers and the frequency selection by the pilot is made available for use by appropriate software. As shown in figure 4, one communication, VOR, and transponder tuning head each are available with room to add more tuning heads should the need arise. Located directly above the radio tuning heads on the pedestal is an autopilot-mode controller. The autopilot-mode controller functions were designed with the RODAAS in mind and a description of the control laws used to implement those functions is available in reference 3. The RODAAS will be described in more detail later in this paper. The intercom located at the left rear of the pedestal enables communication between pilot and researcher, as well as allowing for simulating the helicopter noise environment, ATC communications, air-to-air communications, and so on. Flight conversation or pilot comments can also be recorded for subsequent analysis. The intercom is voice-activated and no action is required to converse with other stations of the intercom. A push-to-talk switch is available on the cyclic grip (fig. 3). This function is available when needed to simulate pilot transmissions with ATC or other aircraft. Considerable room for expansion is available on this pedestal to accommodate future research requirements. Three buttons are available in the pedestal to the pilot's right which control the execution of the simulation. Through these buttons the pilot can freeze the simulation (HOLD), continue (OP), or return to default initial conditions (IC). The instrument panel is designed to be interchangeable and readily reconfigurable. The configurations currently available will be discussed fully in a later section of this paper.

COMPUTER HARDWARE

The simulation math model resides in the Digital Equipment Corporation (DEC) PDP11/23 microcomputer (fig. 5). The PDP11/23 is based on a 16-bit, high-performance microprocessor using MOS/LSI technology. Memory management is provided for 256K bytes of protected, multiuser, program space with parity-error detection. Memory is addressed in 16-bit words or 8-bit bytes and eight general-purpose registers are available for use as accumulators and for operand addressing. Stack processing is used for handling structured data, subroutines, and interrupts. An FPF11 floating-point processor hardware option is used with the PDP11 to increase the execution speed of floating-point instructions. The FPF11 uses 64-bit-wide data paths and a separate internal clock that generates variable-length microcycles to execute floating-point operations in a minimum amount of time. The widely used Whetstone benchmark was run on the PDP11/23 with the FPF11. The Whetstone benchmark is designed to test the overall capabilities of the processor, executing a variety of instructions typical of those found in scientific application programs, and contains a large number of floating-point operations. The Whetstone benchmark ran on the PDP11/23 at an average of 132,000 operations per second (KOPS). For comparison, a study conducted at Intel using the Whetstone benchmark listed the DEC PDP11/34 with a floating-point processor at 202 KOPS and the Intel 8086 microprocessor with the 8087 math coprocessor ran at 107 KOPS. The 8086/8087 is comparable in technology to the PDP11/23. The peripherals available for software development on the PDP11/23 include video terminals, high-speed line printer, and hard-disc mass storage with floppy diskettes available for backup.

All data input requirements are handled directly in the PDP11/23 with off-the-shelf technology. A 16-channel analog-to-digital (A/D) converter is used to read the control positions for use by the simulation math model. The RODAAS uses the A/D to send autopilot servo-command signals to the PDP11-23 math model which simulates the parallel and series servocontrol activators. The A/D is manufactured by DATEL and has 12 bits of resolution. Discrete signals are input to the PDP11/23 via two 16-bit, parallel-line, interface cards by MDB Systems, Inc. Discrete inputs to the PDP11/23 include the control-grip switches, simulation control, and radio tuning heads. The MDB cards also establish the data link between the PDP11/23 and the Z80 satellite processor. To relieve the processing load on the PDP11/23, a second satellite processor is used to control-data output. Output parameters are sent in digital format from the PDP11/23 to the satellite processor, which then performs the output through the necessary hardware. A variety of circuitry is needed to drive the simulation instruments and displays. Most of the required electronics was designed at Ames Research Center specifically for this simulation. The satellite processor complex is located in separate racks which contain the processor and related cards, the special-purpose interface electronics, and power supplies. The data-conversion requirements to drive the simulation cab are varied and include digital-to-analog, digital-to-syncro, and digital-to-resolver conversions. Breakout panels are provided for signal monitoring for use in troubleshooting or strip chart recording.

COMPUTER SOFTWARE

The operating system used for program development and execution is RSX11M. The RSX11M is a hard-disk-based, multiuser, multitasking, real-time operating system. As currently configured in the Systems Integration Research laboratory, RSX11M can support up to eight users simultaneously. The RSX11M is also a multitask system; that is, it can support several different programs executing simultaneously and provides interprogram communication and control over program execution. A clock is used to provide real-time control of programs. Programs for the crew-station simulation are written using DEC's FORTRAN 77 or MACRO-11. DEC's FORTRAN 77 is superset of the ANSI standard and makes full use of the hardware floating-point capability of the FPF11 floating-point processor. MACRO-11 is a symbolic assembly language which is used only when required for primitive input/output operations. Although not used in the simulation, compilers are available for the PASCAL and C programming languages.

The simulation software is divided into three main sections. These are the executive model, aircraft math model, and navigation model. The executive controls the initialization and executive of the simulation. During initialization various parameters can be modified by the operator to control the execution of the simulation. These parameters include the initial aircraft state, wind parameters, navigation setup, and so on. At any time the simulation may be interrupted and control transferred back to the initialization routines to alter any parameters. During simulation the execution controls software module execution. The operator's console is also continuously updated with information on the simulation's progress and is continuously monitored for inputs from the operator. This monitoring allows the operator full control of the simulation and the ability to change simulation execution in real time as well as to monitor or record simulation data.

The executive controls loop timing using a line time clock and RSX11M-system timing routines. The basic simulation loop executes at a 20-Hz rate (50-msec period). Other timed loops run at slower rates, including software that is less time critical. The entire simulation uses about half of the available cycle time to complete its run, leaving room for future expansion.

The executive is responsible for controlling the flow of data to and from the simulation cab and the RODAAS. Data from the cab and the RODAAS is read into the PDP11/23 directly (fig. 6), data from the PDP11/23 to the cab and the RODAAS is sent to the Z80 satellite processor in digital form. The software then channels the data through the appropriate output converters for the simulation instruments and displays. Data are input and output once for each basic simulation loop, that is, at 20 Hz. Most of the software used in performing data input and output is written in assembly code to ensure high speed and because of the machine-dependent nature of the functions being performed. These routines rarely require substantial alterations, except when there are changes to the hardware. It is our philosophy to avoid the use of assembly or machine-level programming to the greatest extent possible. Except for the data input and output routines, the balance of the simulation software is written in high-level language.

The aircraft math model is isolated in a separte routine. Changes can thus be made to the math model without signficantly affecting the bulk of the simulation software. It is also possible to incorporate a completely new aircraft model by replacing the existing module with a new one. The current model represents the dynamics of a UH1H helicopter. The model employs a quasi-static main-rotor representation; a uniform inflow over the rotor disc; and simple expressions for the contributions of the tail rotor, fuselage, and empennage. No interference effects between components are modeled. The development of the model is documented in reference 4, which presents the equations of motion. Step inputs to the simulation model are compared with flight data, and pilot evaluations are given for fixed- and moving-base simulations. Above 60 knots the simulation provides a reasonable match with flight data. At slower speeds and hover the model is usable, but less realistic. In addition to the helicopter dynamics, a simple, steady-wind model has been incorporated into the simulation. The primary reason for the incorporation is to introduce the need for holding a wind correction angle when navigating by reference to navigation aids.

The third major component of the simulation software is the navigation scenario. The scenario is a flat-Earth representation of an approximately 50-mi^2 area centered on the San Francisco Bay. Simple representations of all VOR navigation radio aids are included as are representations of most of the ILSs at the major airports in the area. Navigation aids can be selected by the pilot via radio tuning heads located in the avionics pedestal, which were described previously in this paper. The navigation scenario software has been written so as to make additional navigation aids or other features easy to add.

INSTRUMENT PANEL

The crew-station research cab incorporates an interchangeable instrument panel. The panel is divided into several sections, each of which can be individually removed and replaced with alternate sections or covered with a blank panel section. Two instrument panel configurationa have been developed. The first configuration is representative of a conventional helicopter panel equipped for flight in instrument meteorological conditions. This setup includes the conventional "T" configuration: airspeed, artificial horizon/flight director, barometric altimeter, horizontal situation indicator, trim coordinator, and vertical speed. Auxiliary instruments that are also included are a radio magnetic indicator, radar altimeter, marker beacon indicator, and conventional engine instruments. The second configuration incorporates the RODAAS displays and switches (fig. 7). The RODAAS is an advanced, integrated, flight-management system that makes use of shared controls, displays and sensors, a common data bus, and distributed processing with failure-mode-reconfiguration capability (fig. 8 a & b). The RODAAS functions and its operation are documented fully in reference 3. In this version of the instrument panel, the right-center section has been replaced. The new section includes the same altimeter, vertical speed indicator, and marker beacon indicators as previously mentioned, but the mechanical-artificial-horizon and horizontal-situation indicators have been replaced with their RODAAS counterparts. Also appearing on the panel are the switches that control the electronic display for the horizontal situation indicator, the warning/caution lights, and an autopilot-mode annunciation panel, as well as displays for selected flight-path angle and altitude. The left-center panel is unchanged, except that the previously unused digital display functions as an indicated-airspeed-select display. The previously blank far left panel now houses the control and display unit with which the pilot interacts with the RODAAS.

The crew-station simulator incorporates a color-graphics system. A second monitor is shown installed in the far right panel of the simulator cab (fig. 7). The Cromenco system provides the capability to display color graphics with high speed and resolution. The first planned use of the system is as a display device for a workload metric experiment described in a paper by Jim Phillips of Ames (unpublished). Other potential uses include a terrain-map presentation for obstruction avoidance, collision avoidance, and traffic situation display; an electronic chart presentation for long range navigation planning; and so on.

ATC SIMULATION INTERFACE

The Aircraft Guidance and Navigation Branch at Ames Research Center has an ongoing research effort in ATC issues. Most recently the mixing of conventionally vectored aircraft with those using precise four-dimensional navigational techniques has been explored (ref. 5). This techniques involves simulating the ATC environment, including the participating aircraft. Incorporating piloted simulations with the ATC simulation has been proven useful to validate the algorithms being developed for ATC (ref. 6). To provide a permanent, piloted, simulation capability the crew-station simulation has been linked to the ATC simulation. This link requires data and voice channels, both of which have ben established. The capability of "flying" the Crew-Station Systems-Integration Research Simulation in the simulated ATC environment enhances both facilities as it provides a realistic environment for concepts researching crew-station integration as well as valuable feedback to the ATC researchers by pilots on the acceptance of the research techniques.

VALIDATION EXPERIMENT

To exercise the capabilities of the Crew-Station Systems-Integration Research Simulation platform, a validation experiment has been conducted. The validation is divided into two segments. The first segment is a representation of an IFR commuter-mission scenario flown from Moffett Field Naval Air Station to Salinas and return (fig. 9). The flight includes an instrument approach at Salinas, followed by a missed approach, and an RNAV approach at Moffett Field. The scenario is identical to that flown with the DAAS and allows a comparison of the uses and merits of integrated flight-management systems for fixed-wing aircraft versus rotorcraft. A research test pilot has flown the scenario and provided subjective comments on the simulation.

In carrying out the conversion of the DAAS for use with rotorcraft, it has been clear that certain differences must exist between flight-management systems intended for fixed-wing aircraft and those systems intended for rotorcraft. Functions that must be modified include the autopilot, weight and balance, performance, checklists, flight status, and warning. It has been found that, in general, these functions can be incorporated without altering the structure of the system and that the same control and display devices are adequate. The test pilot feels that using the RODAAS with the autopilot fully functioning allows flying the Salinas scenario with "very low workload and lots of time available for flight planning." Few differences exist in using this flight-management system with rotorcraft versus fixed-wing aircraft for the IFR commuter mission.

The design of both the DAAS and the RODAAS is predicated on the assumption that the availability of an autopilot is crucial to the safe, effective use of flight-management systems. A preliminary attempt has been made to quantify the effects of loss of the autopilot on the use of RODAAS during the approach and missed-approach segments of the commuter mission. These segments have been flown first making full use of the autopilot, and then reflown without the autopilot. Based on pilot comments, it is apparent that there is some difficulty experienced while trying to control the helicopter and at the same time making use of the more advanced features of the flight-management system (such as map editing and waypoint generation). In these cases the pilot reverts to using the system in its most basic mode. The pilot comments that the "task of flight planning while manually flying the displays is unacceptable for normal operations." However, even though the flight planning features were not usable in the absence of the autopilot, other features such as the map display, flight status, and warning annunciation continue to provide useful assistance during high-workload periods.

The second segment of the validation incorporates the link with the ATC simulation. In this experiment the pilot is vectored in an ATC environment, which includes other aircraft of various capabilities, to intercept an instrument final-approach course. The approach is continued to the missed-approach point, at which time either a missed approach is flown or the piloted simulator is removed from the ATC simulation and the flight terminates. Results of this segment indicate that the

ATC simulation link with the crew-station research simulation is a valuable addition to both facilities.

CONCLUSION

Various issues associated with the use of integrated flight-management systems in aircraft exist which pose questions in the area of design criteria for crew-station-systems integration. To address these issues as they pertain to rotorcraft cockpits, a fixed-base IFR simulation of a helicopter has been developed to support experiments that contribute to the understanding of design criteria for rotorcraft cockpits incorporating advanced, integrated, flight-management systems. A validation experiment has been conducted that demonstrates the main features of the facility. This facility will allow future research in crew/station integration in rotorcraft cockpits as well as other flight vehicles and systems.

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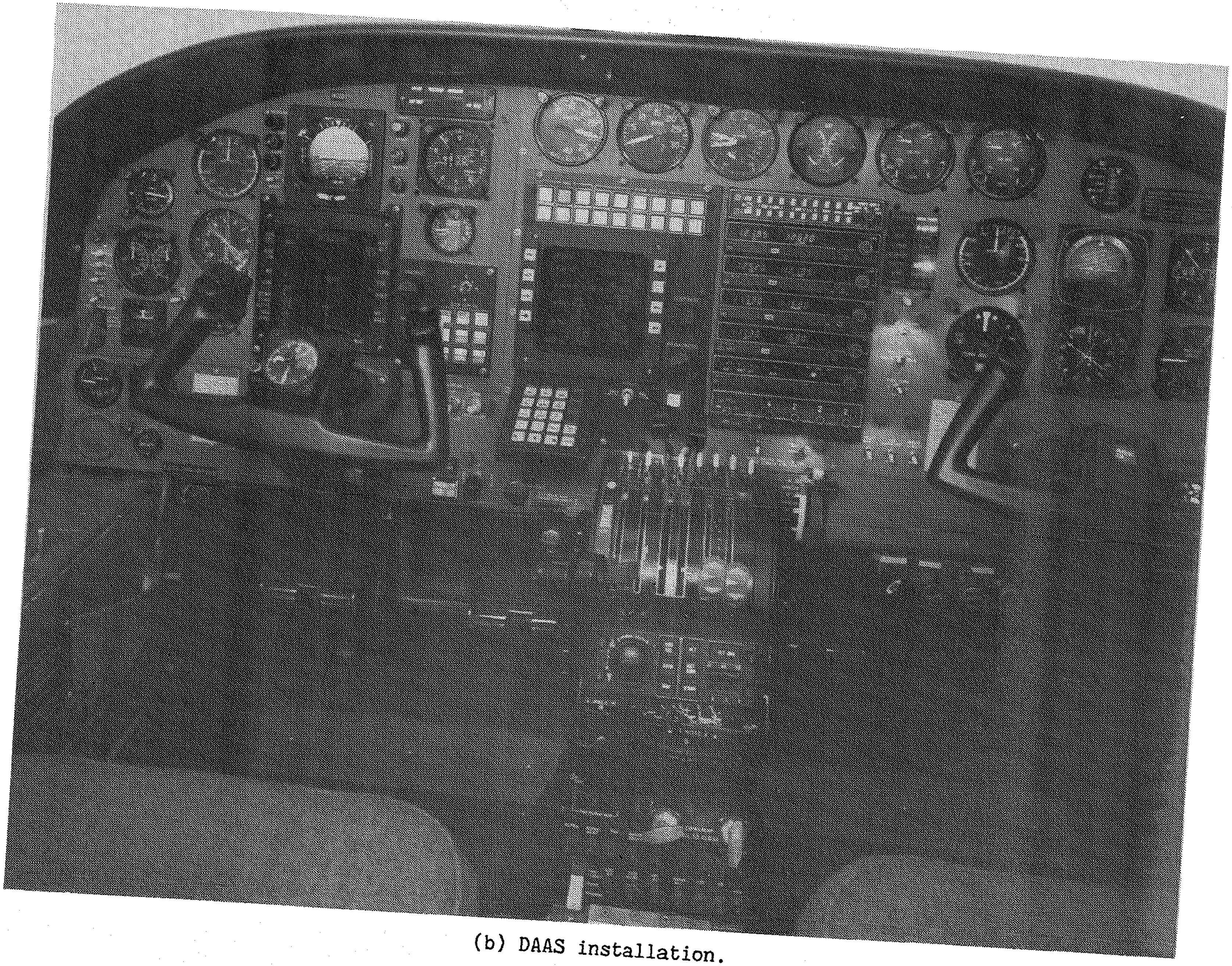
(a) Aircraft used in DAAS flight test.

Figure 1.- Cessna 402B Businessliner.



(b) DAAS installation.

Figure 1.- Concluded.

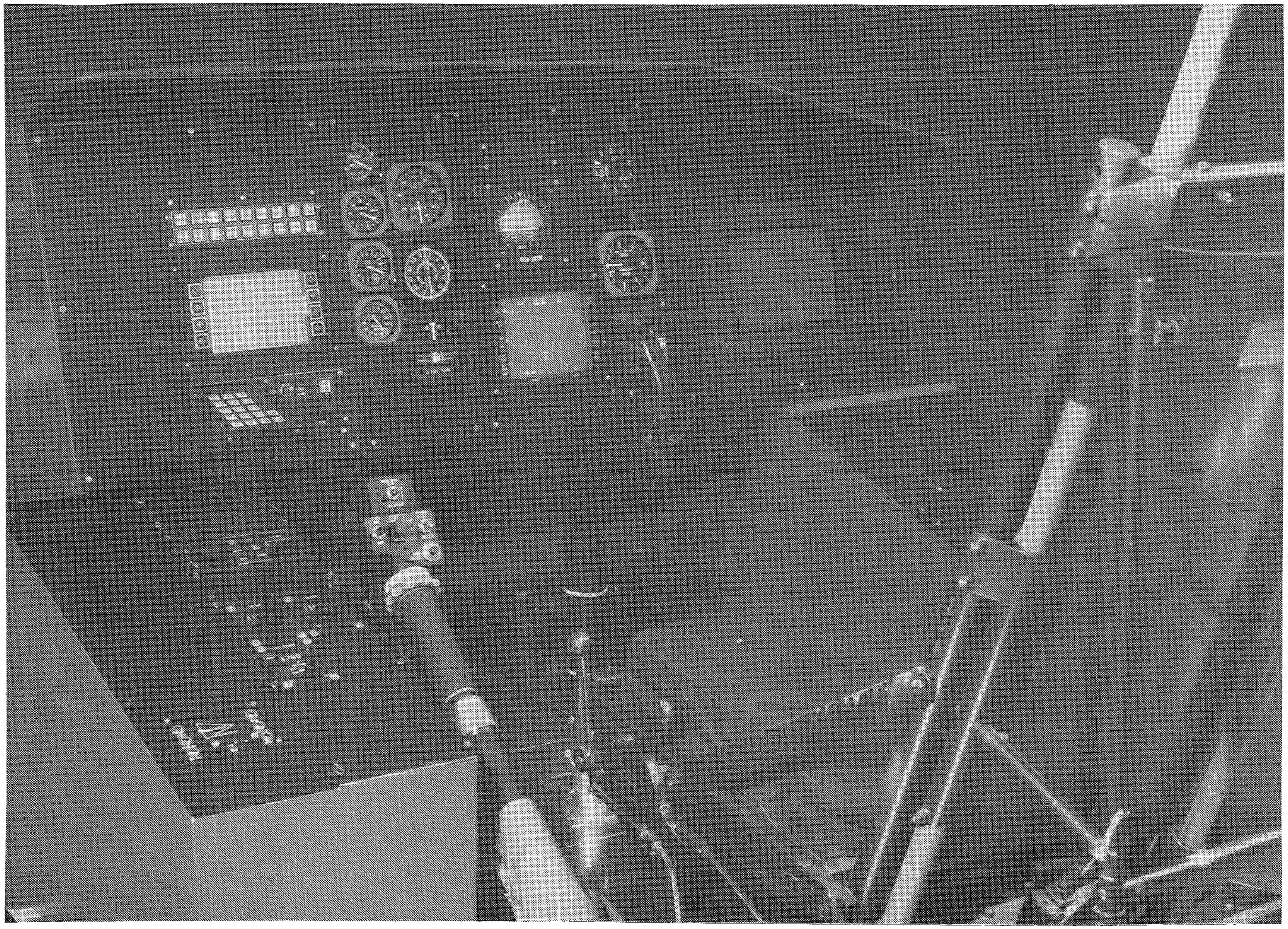


Figure 2.- Simulation cab.

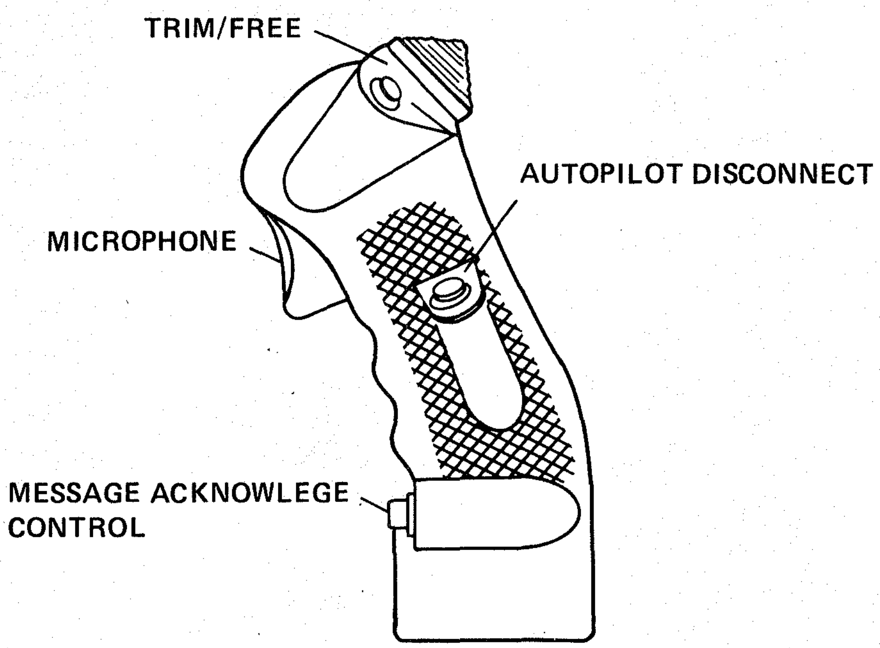


Figure 3.- Cyclic grip.

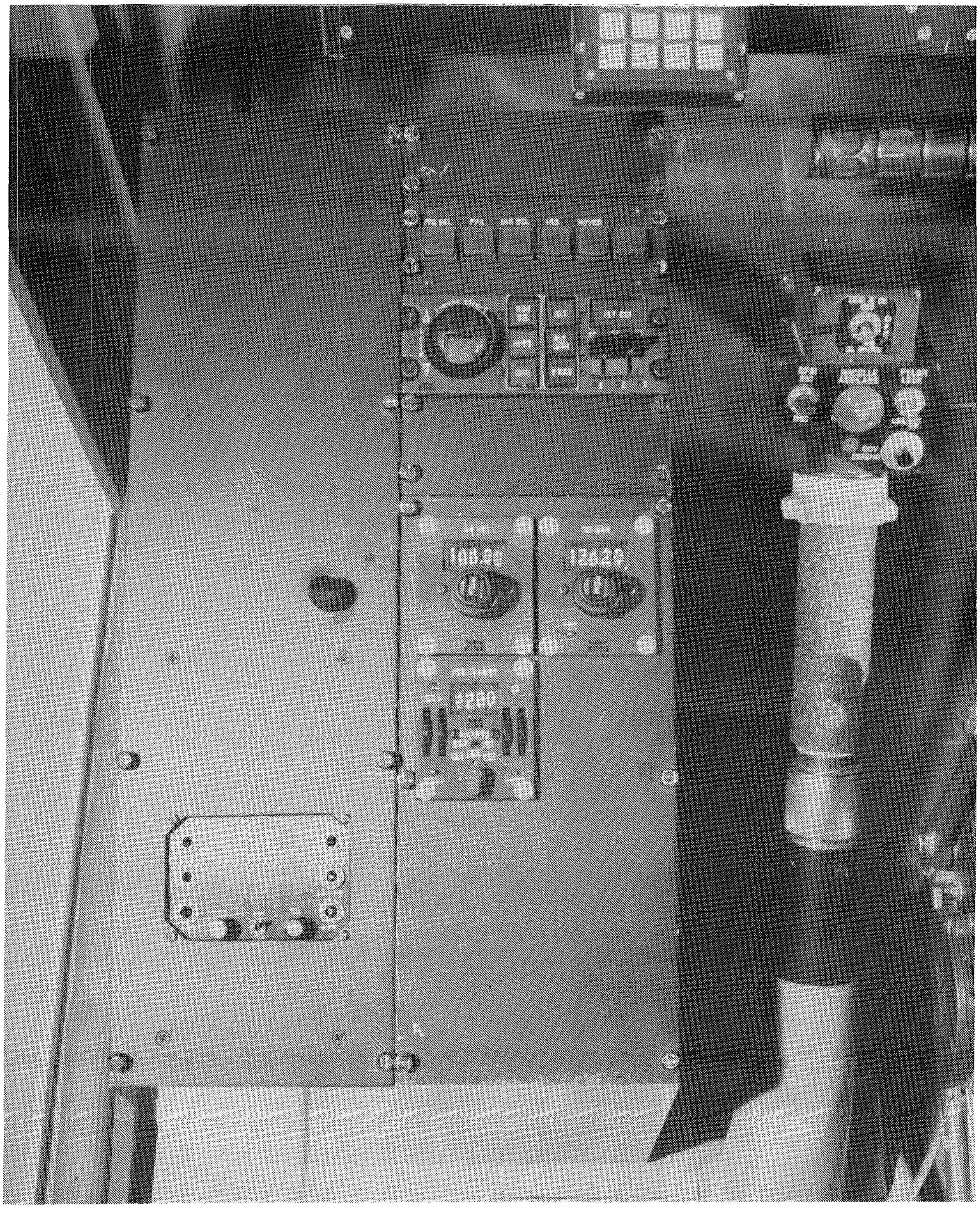


Figure 4.- Left-hand pedestal.

Figure 5.- Digital Equipment Corporation microcomputer used for this simulation math model.

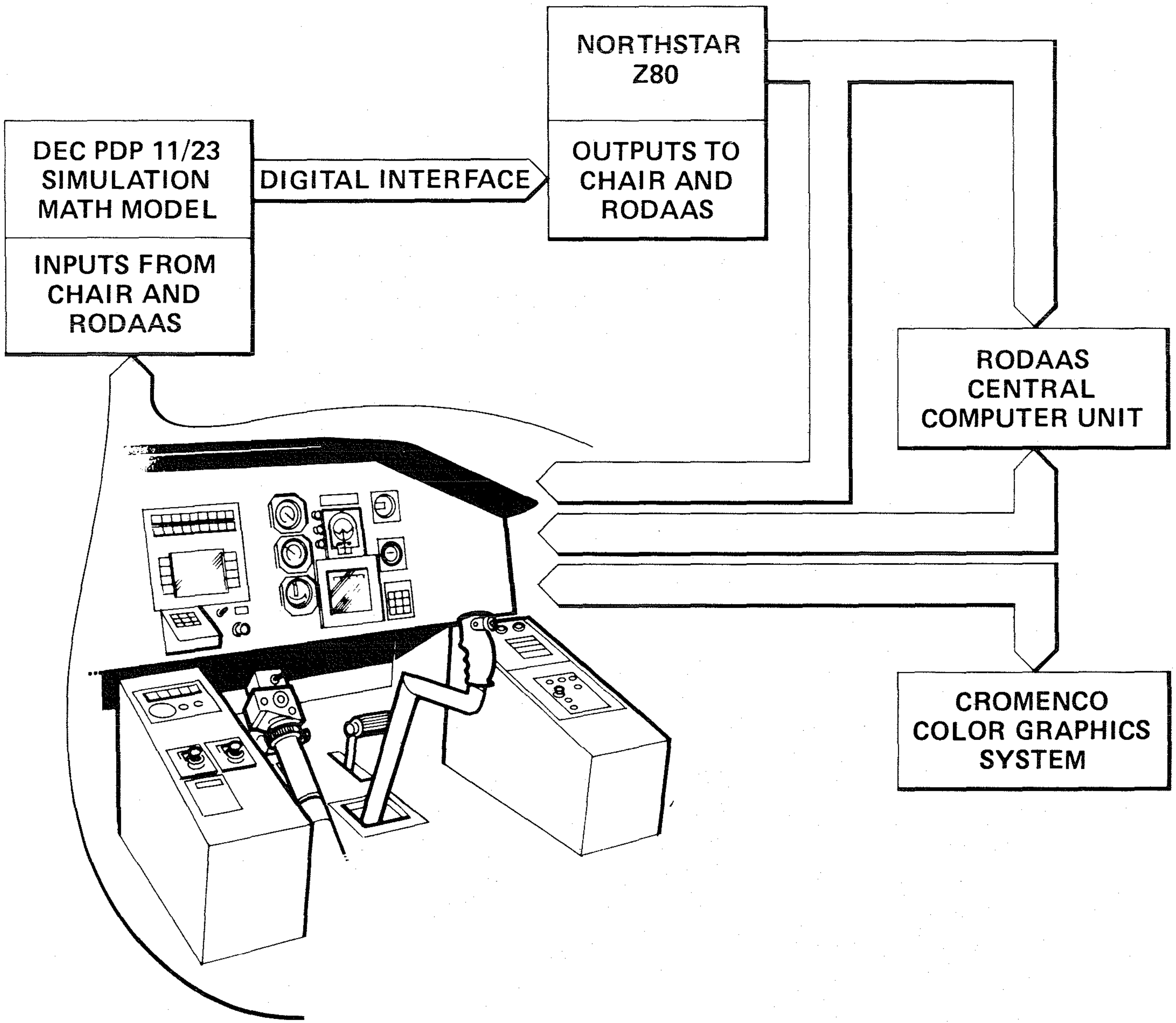


Figure 6.- Data input schematic.

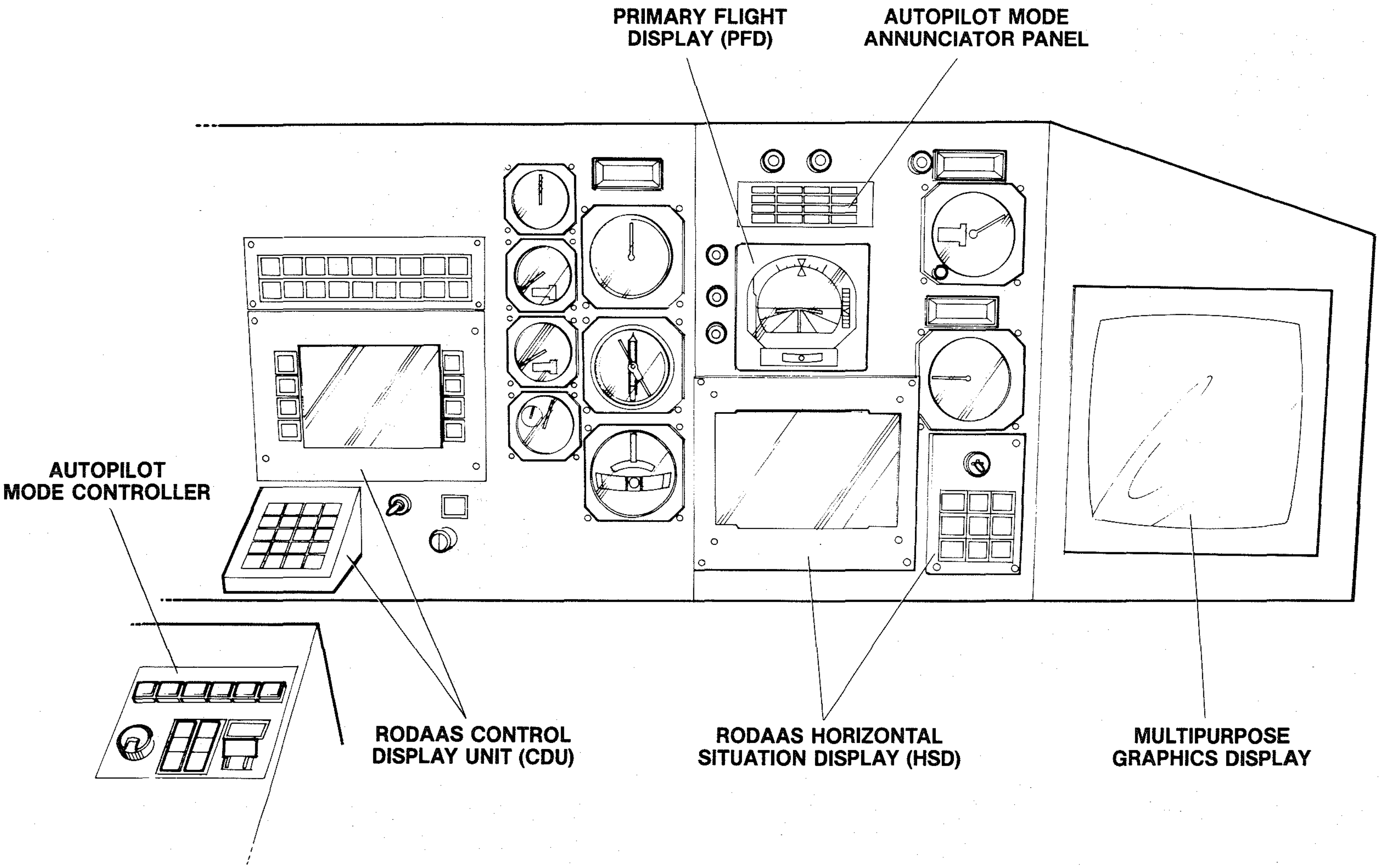
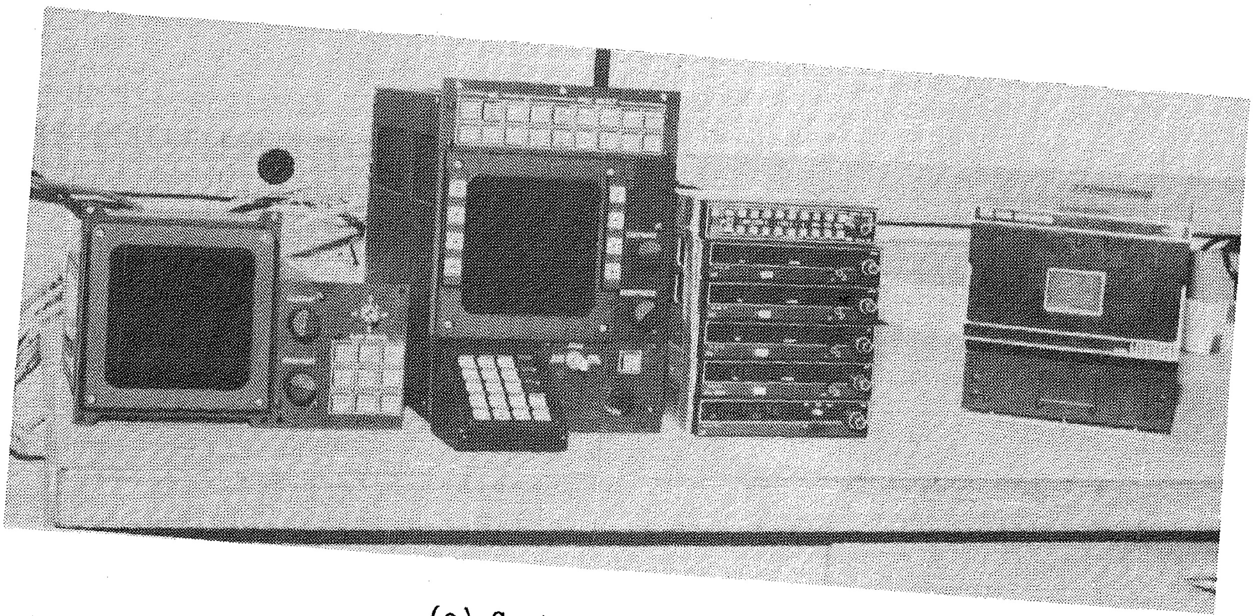


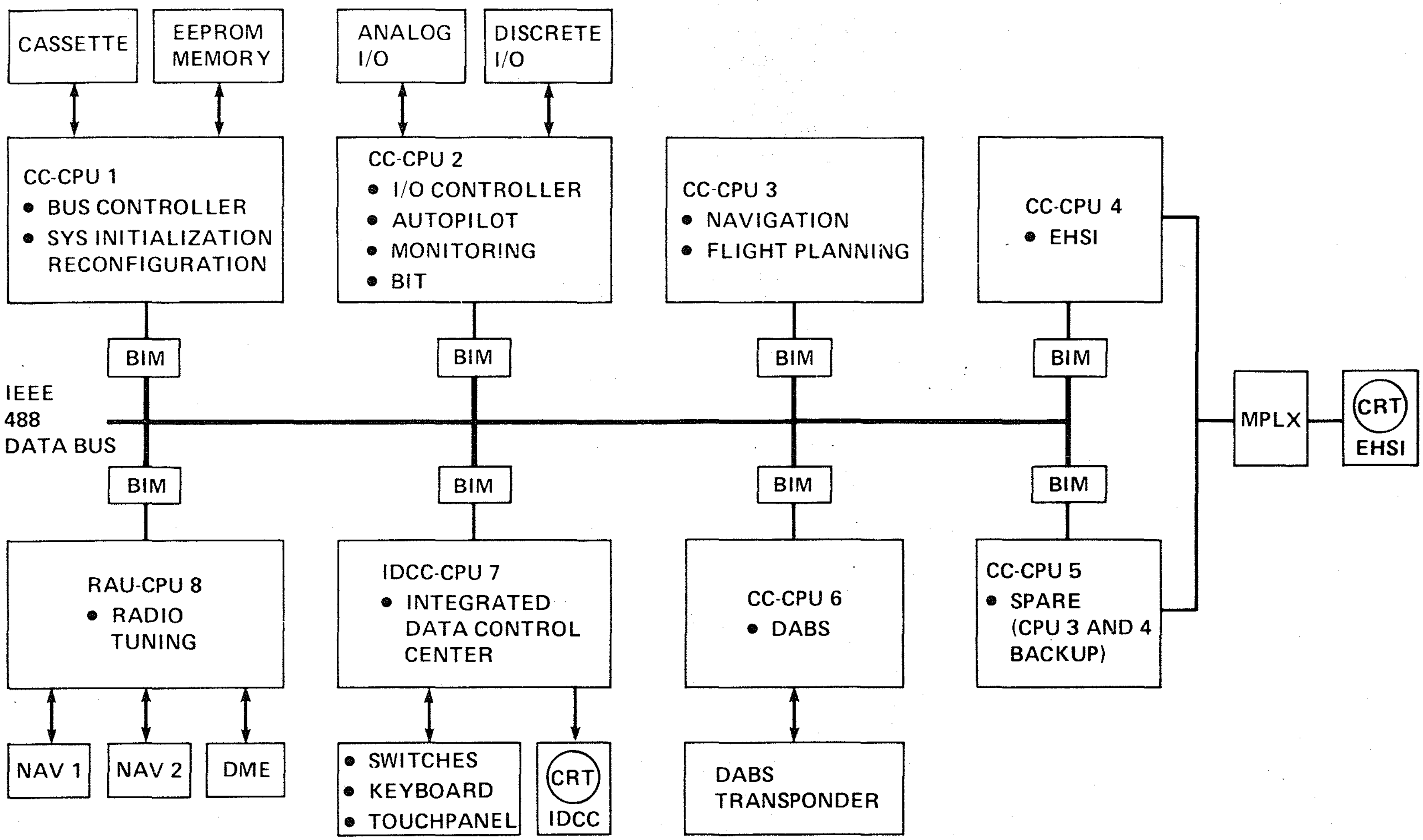
Figure 7.- RODAAS panel configuration.



(a) System components.

Figure 8.- RODAAS.

DAAS ARCHITECTURE



(b) System architecture.

Figure 8.- Concluded.

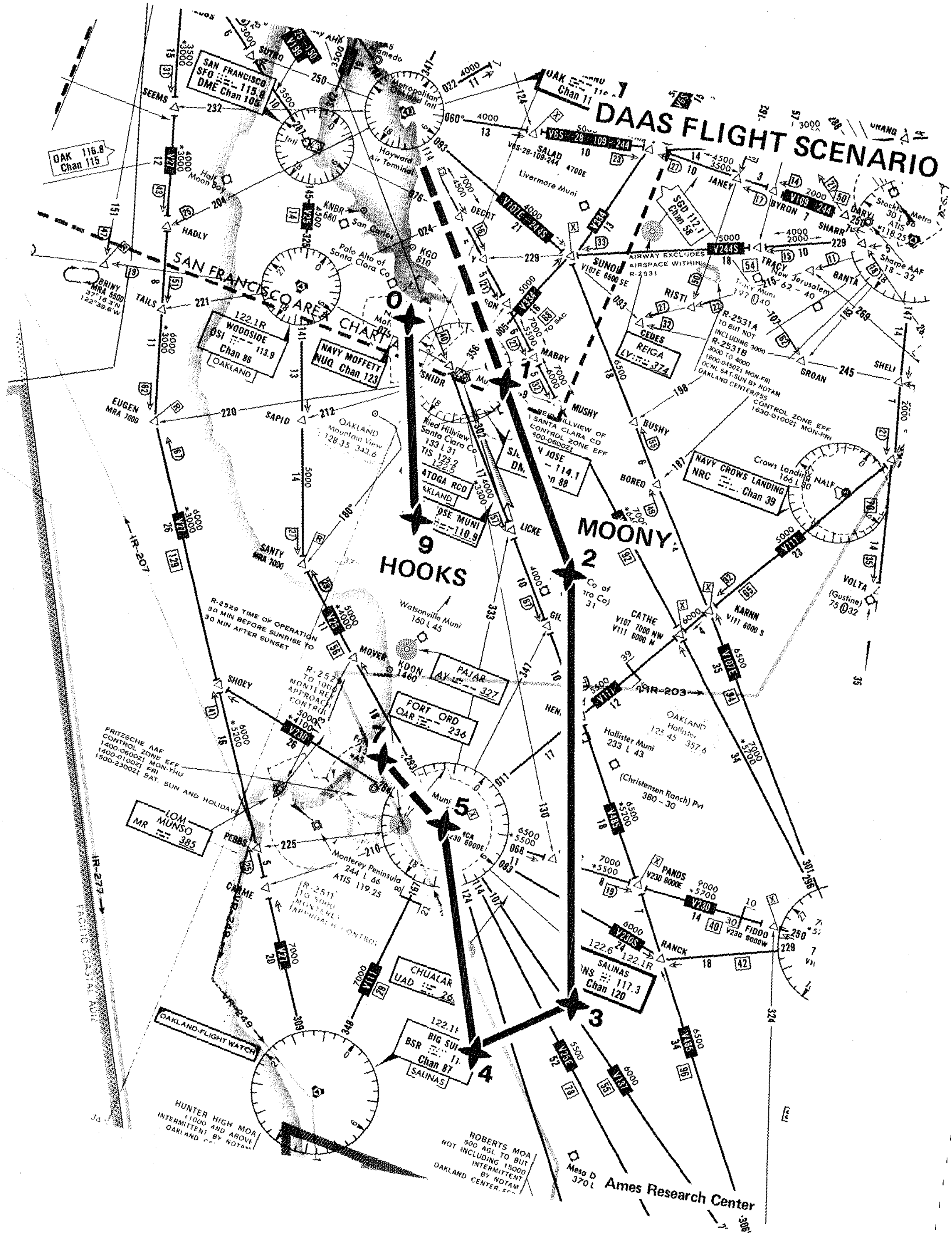


Figure 9.- Validation flight scenario.

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15. Supplementary Notes

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16. Abstract

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