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HYBRID SIMULATION OF THE
APOLLO GUIDANCE NAVIGATION
AND CONTROL SYSTEM

Philip G. Falleman
December 1966

MIT INSTRUMENTATION
LABORATORY

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APOLLO

GUIDANCE, NAVIGATION AND CONTROL

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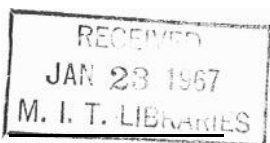
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HYBRID SIMULATION OF THE APOLLO GUIDANCE NAVIGATION AND CONTROL SYSTEM

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ABSTRACT

The MIT Instrumentation Laboratory has the responsibility for the design of the Guidance and Navigation System for the Block I Apollo Spacecraft and the further responsibility of the design of the primary control system for the Block II spacecraft and LEM. This results in both a hardware design and on-board computer programs for each mission. The purpose of this hybrid simulation laboratory is to verify these programs in a real-time simulation which utilizes G&N flight hardware. With these simulators, crew procedures are examined and programs can be modified to allow a better interface between the flight crew and the G&N system. The simulator also becomes a part task trainer with the addition of a cockpit mockup.

The facility uses an analog/digital general-purpose computer, flight hardware such as the on-board computer, coupling data units, and special purpose simulators for the inertial measurement unit and accelerometers. The facility is designed to allow rapid changeover from Block I to Block II simulations.

I. Introduction

The hybrid simulation of the Apollo Guidance, Navigation and Control System described in this paper was conceived of as a validation tool for certain of the on-board computer programs developed at MIT. The simulation was first used for testing the AS-202 program for the first guided unmanned Apollo flight. Subsequently, the simulator was enlarged to incorporate a partial command module cockpit mockup in order to test programs for AS-204, the first manned orbital flight of Apollo. This simulation proved extremely valuable for testing the man-machine interface with the on-board computer programs and was used as a training device for the flight crew. This simulation was essentially an analog computer representation of the spacecraft tied to certain of the flight hardware. A general purpose digital computer was used to initialize the analog computer as well as the flight computer. An entry simulation was also performed utilizing, in addition to the above mentioned equipment, the general-purpose digital computer to perform atmospheric and geometric calculations. As a result of the experience gained during the Block I simulation activity, it was decided to expand the capability of the hybrid facility for Block II work in order to provide diagnostics during the period when the flight programs are being written. The primary verification tool for the on-board programs has been the all-digital simulation which contains a bit-by-bit simulation of the AGC (Apollo Guidance Computer). The hybrid facility offers certain advantages over this all-digital simulation; primarily: a) real-time

operation, b) ability to allow manual access to the AGC during the simulation, and c) on-line monitoring of the progress of the simulation. The main disadvantage of the hybrid simulation is its limited capability to examine the step-by-step operation of the AGC i.e. to trace a computation procedure.

II. Block I Configuration

The details of the simulator configuration for the Block I work have been described by Sullivan. Two separate simulations were conducted, one from SIM separation to CM/SM separation and the second from CM/SM separation through entry to 50,000 feet altitude. Block diagrams of these are shown in Figure 1 and Figure 2. Figure 3 shows certain of the flight hardware and special simulators used for the Block I simulations.

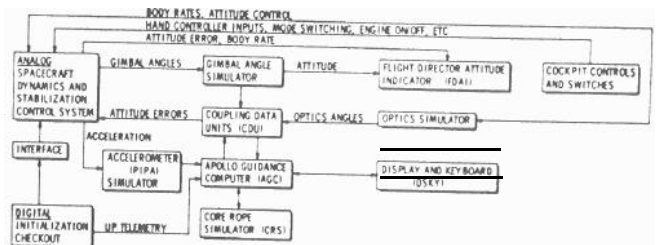


Fig. 1 AS-204 Command/Service Module Simulator

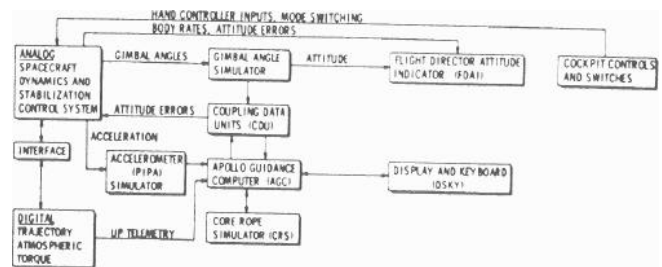


Fig. 2 AS-204 Command Module Entry Simulator

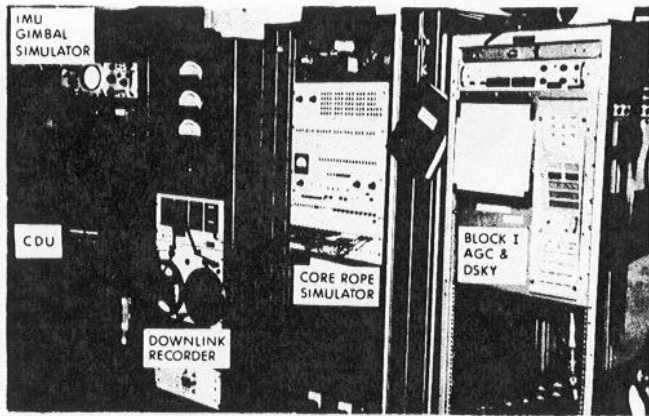


Fig. 3 Flight Hardware Simulation Equipment.

III. Block II Configuration

In order to accommodate the requirements of AGC program diagnostics and to provide the capability of the more complicated dynamic problems of the Block II missions, a reconfiguration of the simulator was required. First, the general purpose digital computer was changed from an SDS 930 to an SDS 9300 with high-speed magnetic tape units and more memory capacity. Additional A/D and D/A interface was acquired and a special unit was designed to enable SDS processing of the downlink telemetry of the AGC. The original design of the simulator was planned to allow rapid change-over from Block I to Block II configuration by means of cable connections, since certain of the equipment was common to both configurations. This capability was achieved during the time period when both Block I and Block II simulations were being performed and it was possible to have all the peripheral hardware converted by the time the analog/digital programs were set-up and checked out. This capability extends now to the Block II system for change-over between CSM and LM simulations. During early 1967, a second hybrid facility is being acquired which will allow parallel operation for simulating CSM and LM. This second facility will be configured to handle LM problems and the first will be used exclusively for CSM. Each of these facilities is essentially equivalent with the only major differences those of the special purpose simulators for LM and CSM. Figure 4 and 5 show general block diagrams of these simulator configurations.

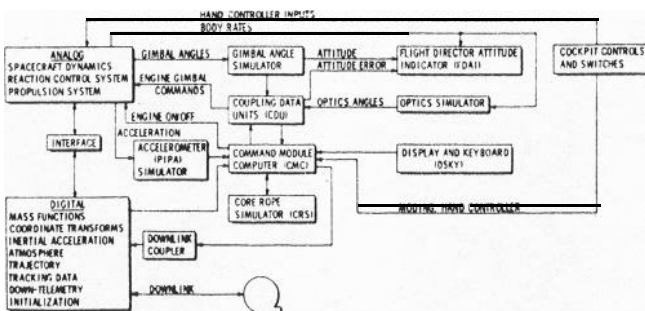


Fig. 4 Block II Command/Service Module Simulator

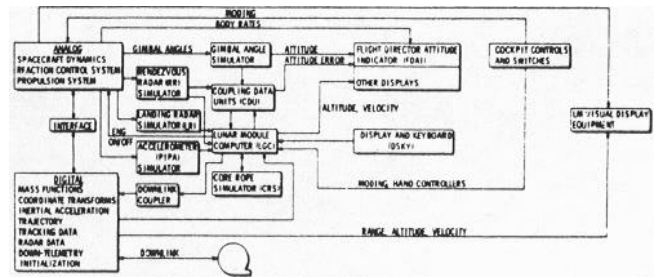


Fig. 5 Lunar Module Simulator

IV. Command/Service Module Simulator

The CSM simulator consists of a general-purpose digital computer (SDS 9300) with 32K words of memory, two analog computer consoles (Beckman 2133), interface equipment (40 A/D, 56 D/A channels) and a complement of flight hardware (real and special-purpose simulators). The heart of the flight hardware is the on-board guidance computer (CMC) which contains the programs for guidance, navigation, and control of the spacecraft. In the simulator, a real CMC is used, but the fixed memory is replaced by a core rope simulator (which operates with the CMC and has all erasable memory). This allows modification of the flight programs before they are manufactured into modules. The entire contents of the fixed memory is recorded onto magnetic tape and can be loaded into the core rope simulator in a few minutes. Individual memory locations may be altered or monitored as well. This simulator also allows control of the CMC, by providing address stop, step-by-step operation, etc. The inertial measurement unit (IMU) is simulated by two devices, the gimbal angle simulator and the accelerometer simulator (PIPA simulator). The gimbal angle simulator accepts three dc inputs corresponding to the three gimbal angles (which relate the inertial axes to spacecraft orientation) and by means of three servos, positions the gimbal resolvers. These resolvers are interfaced to the coupling data units (CDU), as in the flight system, which digitize the gimbal angle information for the CMC. Each CDU also has a D/A section for converting CMC output to either 800-cps or dc voltages for use in the system, e.g. to position the SPS engine, display attitude errors, position optics, etc. The accelerometers are simulated by a special-purpose device which generates pulses to the CMC as a function of the applied input voltage (dc). This device interfaces directly with the CMC.

The down-telemetry output and up-telemetry input of the CMC are interfaced through special-purpose devices to the SDS 9300. For downlink telemetry, the device converts serial data to the parallel format which is acceptable to the SDS and these data are stored for later processing. The up-telemetry is generated in the SDS and serial pulses are sent to the CMC in the appropriate format. The uplink is used to initialize the CMC prior to a simulation.

Both the flight hardware and the hybrid computer are interfaced with a cockpit mockup which contains displays and controls. Many of the discrete

input signals to the CMC originate in the cockpit, e.g. mode control, attitude and translation control, etc. In addition, the lower equipment bay of the cockpit contains the optics simulators and controls which provide star fields for navigation and alignment of the TMU. These optics simulators interface with the CMC through the CDU's.

V. Lunar Module Simulator

The Lunar Module (LM) simulator consists of essentially the same complement of equipment with certain other special-purpose devices added and the deletion of the optics simulator. In particular, rendezvous radar and landing radar simulators are used to generate radar data to the guidance computer (LGC) with the rendezvous radar angle data interfacing through the CDU. There is also a LM Visual Display device which projects a lunar landscape to the left window or the LM cockpit and which is driven by the SDS/Beckman computer. This device allows simulation of a manually controlled lunar landing maneuver with a realistic display of the scene as would be seen from the vehicle.

VI. Simulation Software

The CSM and LM simulations are run under an executive control program contained in the SDS which initializes the problem for both the hybrid and flight computers, synchronizes a real-time SDS clock with the guidance computer clock, calls the various dynamic, real-time subprograms which are used, calls the subprograms which maintain knowledge of vehicle position and velocity, calls programs necessary to generate tracking data and calls programs to record and process down-telemetry.

Following each simulation run, the recorded down-telemetry data and SDS data can be processed to provide comparison of AGC and SDS parameters (e.g. position, velocity, attitude, etc.) A variable format edit program allows this processing for specified time intervals or for an entire simulation run. It is through this medium that program diagnostics are accomplished.

For the CSM simulation, the basic computation rate is 10 milliseconds for the dynamics updating program. This program computes the orientation of the spacecraft in inertial coordinates by converting body rate to gimbal angle rate and then integrating. It also computes the acceleration in inertial coordinates for use by the accelerometer simulator. At one-second intervals, the acceleration is integrated to provide velocity and position information. The spacecraft model is programmed as follows:

- a) on the analog computer; the propulsion system actuator dynamics, reaction control system, and dynamic spacecraft equations including three linear accelerations, three rotational accelerations, two nozzle equations, six bending equations, four service module slosh equations, and four LM slosh equations;
- b) on the digital computer; coordinate transforms, including generation of gimbal angles with bending effects, mass-dependent functions, eg. inertias and center-of-gravity locations, linear acceleration in the inertial reference system, nonlinear reaction torques, and slosh forcing functions. Four spacecraft configurations are simulated; 1) command module (CM), 2) command module and service module (CSM), 3) Command/ service

module with full LM (CSMLM), and 4) command/service module with empty LM ascent stage. In addition to the basic dynamics equations, the digital computer (SDS) calculates position and velocity each second while in free-fall and while in thrusting flight. During free-fall modes of operation, the position and the velocity of LM are also computed in order to generate tracking data for driving the optics simulator. During the simulation of entry, atmospheric torques and forces are generated by an SDS program as functions of position and velocity.

For the LM simulation, a similar organization of digital/analog programming exists although the details of the dynamics are considerably different. There are only two spacecraft configurations to be simulated, namely ascent stage and ascent + descent stage. The SDS generates the signals to drive the LM Visual Display equipment for the lunar landing simulation under its own executive control, and also generates the data for driving the two radar simulators. For LM simulations, fuel and oxidizer slosh are included in the mode but no bending is considered.

VII. Guidance Computer Diagnostics

In order to evaluate the performance of the AGC programs, it is necessary to perform a certain amount of parallel computation for comparison. Therefore, trajectory data (position and velocity) are continuously computed in the SDS and are recorded along with AGC trajectory data (transmitted via the down-telemetry). Other variables of interest are also recorded in the same manner and at the end of a simulation, these recorded variables can be processed to provide the data comparison.

In developing the AGC programs, simulations using small program sections will be run first; then, as the program reaches higher levels of confidence, entire mission segments will be simulated. In order to exercise the flight programs extensively, a flexible initialization program has been written which will allow specification of vehicle configuration, position and velocity, attitude, elapsed time from launch, and all other necessary parameters. This initialization can be accomplished through either the computer typewriter or card reader, and successive runs may vary either some, all, or none of these parameters at the operators choice. This program is used also to initialize the analog computer (eg. by setting potentiometers), and the AGC through the up-telemetry channel. It also synchronizes the SDS clock to the AGC.

VIII. Summary

In summary, the hybrid simulation of the Apollo Guidance Navigation and Control System provides a useful tool for real-time flight program checkout and debugging and performs a vital function in the verification of these programs prior to flight. The simulator also is utilized to develop the programs for the man-machine interface which is so essential to manned space flight and, moreover, the simulator can serve as a training or familiarization device for the guidance navigation and control system.

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1. Sullivan M. M., Hybrid Simulation of the Apollo Guidance and Navigation System, Simulation, Vol 7 No 1 July 1966.

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