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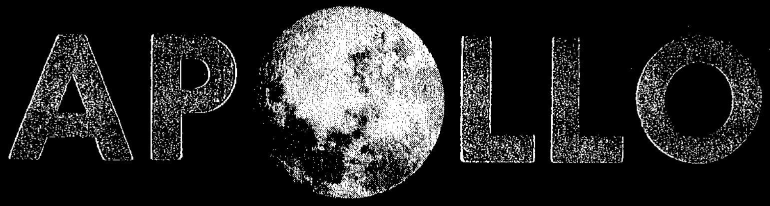

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HYBRID SIMULATION OF THE APOLLO GUIDANCE AND NAVIGATION SYSTEM

by
Madeline M. Sullivan
December 1965

MIT

CAMBRIDGE 39, MASSACHUSETTS

MASSACHUSETTS INSTITUTE

APOLLO

GUIDANCE AND NAVIGATION

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presented at the
1965 Fall Joint Computer Conference
Las Vegas, Nevada
December 2, 1965

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COPY # 135

ACKNOWLEDGEMENT

This report was prepared under DSR Project 55-238, sponsored by the Manned Spacecraft Center of the National Aeronautics and Space Administration through Contract NAS 9-4065.

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HYBRID SIMULATION OF THE APOLLO GUIDANCE AND NAVIGATION SYSTEM

ABSTRACT

A hybrid simulation of the guidance and navigation system of the Apollo spacecraft is underway at the Massachusetts Institute of Technology Instrumentation Laboratory. The Apollo Guidance and Navigation equipment is digital, electronic, and electromechanical, The G & N analog and digital hardware is combined in simulation with analog and digital computers so that the hardware will be subjectedto dynamic conditions approaching those found in a space environment.

The instrumentation of the Apollo Guidance and Navigation System is described as well as its adaptationto the hybrid simulation. Software models are discussed to indicate some of the varied problems considered. Digital procedures which are designed to support the operator and enhance the reliability of the simulation are described.

In conclusion, it becomes apparent that the judicious use of computers, together with G & N hardware and software, makes it possible to simulate in real time any part of the Apollo mission from lift-off to splash-down.

by Madeline M. Sullivan
December 1965

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

The problems encountered in a hybrid simulation are many and complex as any computer user will testify. Study of the elaborate conversion equipment used with commercial hybrid systems will illustrate the complexity of the task which permits analog and digital computers to operate compatibly. However, when the analog and digital computers are combined in simulation with analog and digital hardware, the engineer is faced with the added problem of building and debugging many of the interfaces himself, The variations can be very extensive and troublesome.

A hybrid simulation of the guidance and navigation equipment of the Apollo spacecraft is underway at the Massachusetts Institute of Technology Instrumentation Laboratory. The Apollo Guidance and Navigation equipment is digital, electronic, and electromechanical. The purpose of this paper is to describe:

1) the G&N system's function in flight,
2) how its equipment was made compatible with an analog computer in the laboratory,
3) how the analog computer simulates the Apollo spacecraft dynamics and control systems,
4) how a mockup of the Apollo Command Module provides facility for man-in-the-loop operation, and
5) how the entire simulation was designed to subject the G&N hardware to dynamic conditions approaching those found in a space environment.

Whatever software models are used, care is taken to ensure that they are calibrated to neither excel nor fall short of the performance of the hardware they represent.

A complex mathematical model is required to simulate the Apollo spacecraft and its control systems. Sophisticated techniques are necessary even to fit a problem of this magnitude onto a relatively small analog computer (two Beckman 2133's). Several procedures are described which enhance the reliability and versatility of system and make it tractable for a very small staff.

The result is an efficient hardworking simulation which can test G&N hardwareand software, train astronauts in the use of the G&N system, and provide a laboratory proving ground for scientists' ideas.

CHAPTER 2

INSTRUMENTATION OF
THE APOLLO GUIDANCE AND NAVIGATION SYSTEM

The Guidance and Navigation system is divided into three major subsystems: inertial, optical, and computer. The three subsystems, or combinations of subsystems, can perform the following functions:

1) Periodically establish an inertial reference which is used for measurements and computations.
2) Align the inertial reference by precise optical sightings.
3) Calculate the position and velocity of the spacecraft by optical navigation and inertial guidance,
4) Generate steering signals and thrust commands necessary to maintain the required spacecraft trajectory.
5) Provide the crew with a display of data which indicates the status of the guidance and navigation problem.

The following paragraphs present a brief functional description of the G&N system Block I series. Block I G&N equipment will be the first to fly. It will be replaced by the Block II equipment at approximately the same time that the Saturn C-5 replaces the Saturn C-IB as the first stage booster. The two configurations differ somewhat but the principles of the G&N system remain essentially the same for both series. The function interfaces of the Block I System are shown in Fig. 2. 1.

2.1 Inertial Subsystem

The inertial subsystem is used in the spacecraft guidance to determine the proper direction and magnitude of the required velocity corrections applied to the spacecraft.

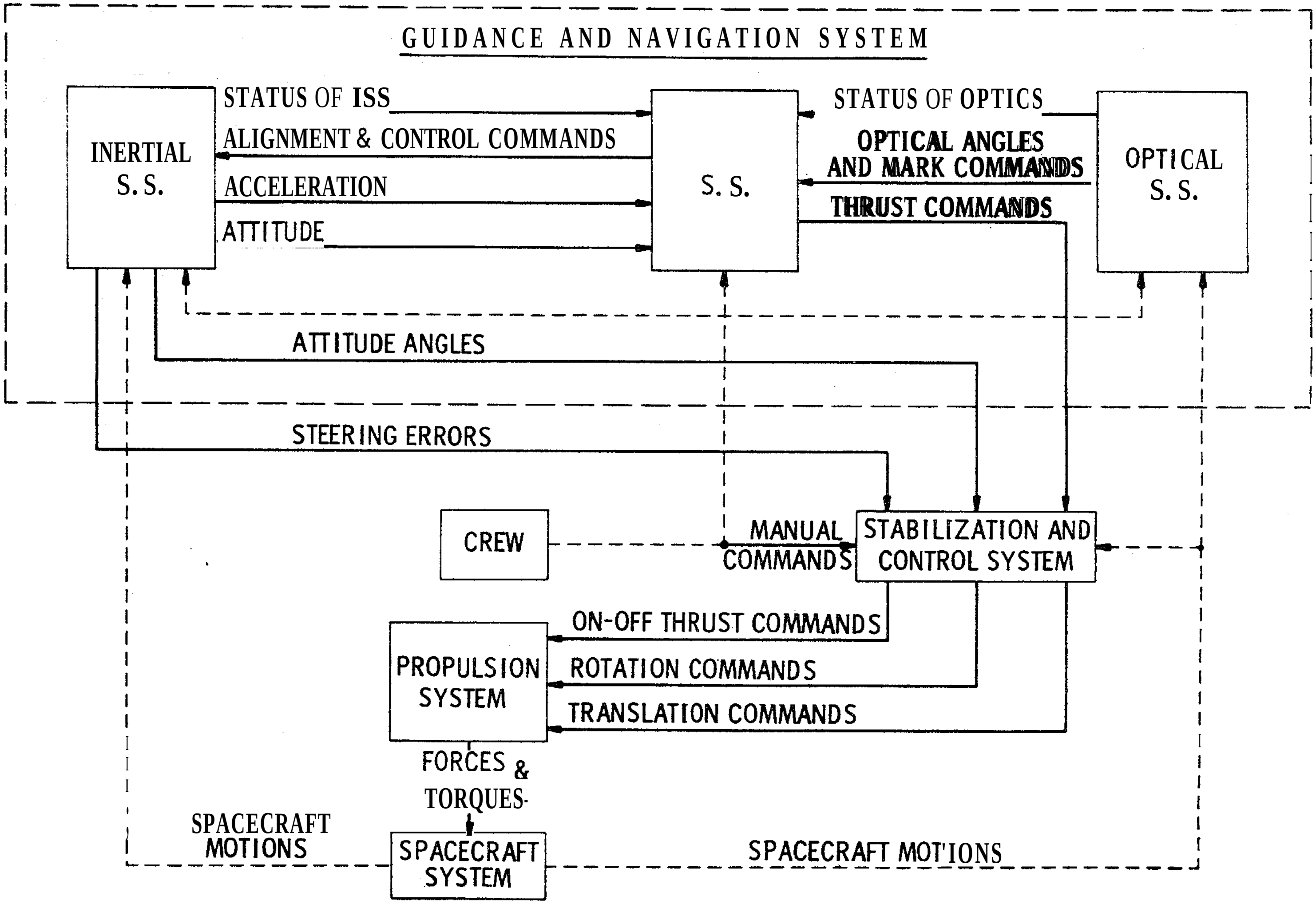


Fig. 2.1 Interfaces of the Guidance and Navigation Subsystem Block I

The inertial subsystem performs three major functions:

1) measures changes in spacecraft attitude,
2) assists in generating steering commands, and
3) measures spacecraft velocity changes due to thrust.

To accomplish these functions, the inertial measurement unit, (IMU), provides an inertial reference consisting of a stable member gimballed in three degrees of freedom and stabilized by three integrating gyros. The schematic of the IMU appears in Fig. 2.2. Each time the inertial subsystem is energized the stable member must be aligned with respect to a predetermined reference by sighting the optical instruments on target during preflight preparations and on celestial objects during flight,

Once the inertial subsystem is energized and aligned, any rotational motion of the spacecraft will be about the gimballed stable member, which remains fixed in space. Resolvers, mounted on the gimbal axes, act as angular sensing devices and measure the attitude of the spacecraft with respect to the stable member. These angular measurements are sent to electromechanical motor/shaft devices called Coupling Data Units (CDU's). Within the CDU's the IMU gimbal angles are compared with those commanded by the Apollo Guidance Computer (AGC). Any difference between the actual and commanded angles results in a steering error signal being generated in the CDU's. The error signal is sent to the stabilization and control system (SCS) to correct the spacecraft attitude.

Acceleration of the spacecraft is sensed by three pulsed integrating pendulous accelerometers (PIPA's) mounted orthogonally on the stable member. The signals from the accelerometers are sent to the AGC which then calculates the total velocity.

The modes of operation of the inertial subsystem are initiated automatically by either the AGC or ground control or manually by the crew.

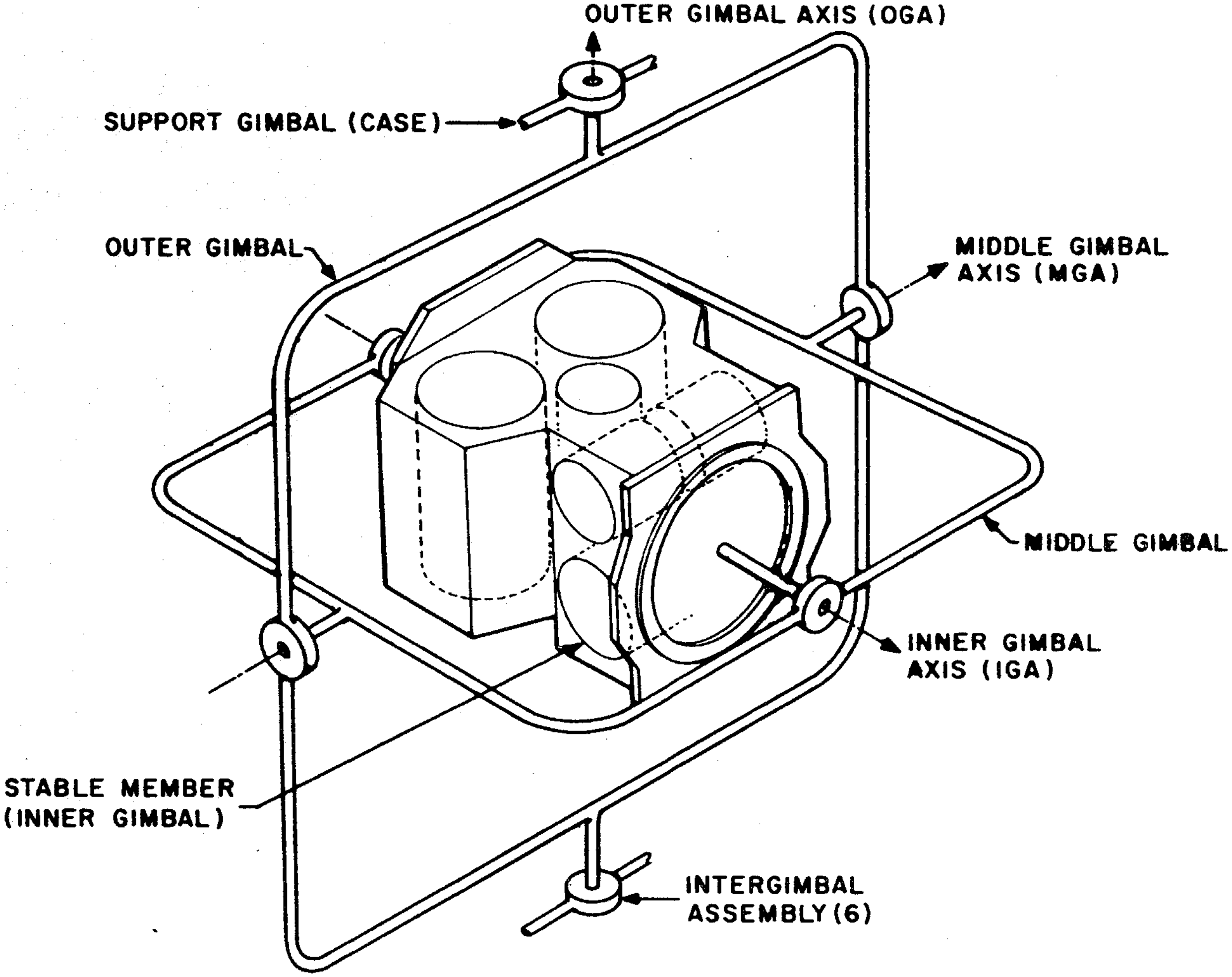


Fig. 2.2 Schematic of the Inertial Measurement Unit

The status or mode of operation is displayed on the control panel and supplied to the computer.

2.2 The Optical Subsystem

The optical subsystem is used to determine the position and orientation of the spacecraft in space. This is accomplished utilizing a catalog of stars stored in the *RGC* and celestial measurements which are made by the navigator. The identity of celestial objects and optimum schedule of measurements is determined before launch.

The optical subsystem performs three major functions:

1) provides the *AGC* with data obtained from measuring angles between lines of sight to celestial objects,
2) provides measurements for establishing the inertial reference, and
3) tracks a star or horizon automatically.

The optical subsystem contains a sextant and a telescope, shown schematically in Figs. 2.3 and 2.4 respectively. The sextant is a dual-line-of-sight deviceused for precisionangular measurements. The sextant can be equipped with a special device which provides automatic tracking capability. The telescope has one line of sight and is used for coarse acquisition or orbital tracking of landmarks.

The modes of operation of the optical subsystem are indicated on the display and keyboard panel (DSKY) and are supplied to the AGC.

The manual stick in front of the control panel is used by the astronaut to position the optical lines of sight. Since the optical instruments' fields of view are limited, controls are also provided by which the astronaut can maneuver the entire spacecraft thus pointing the optical instruments in any

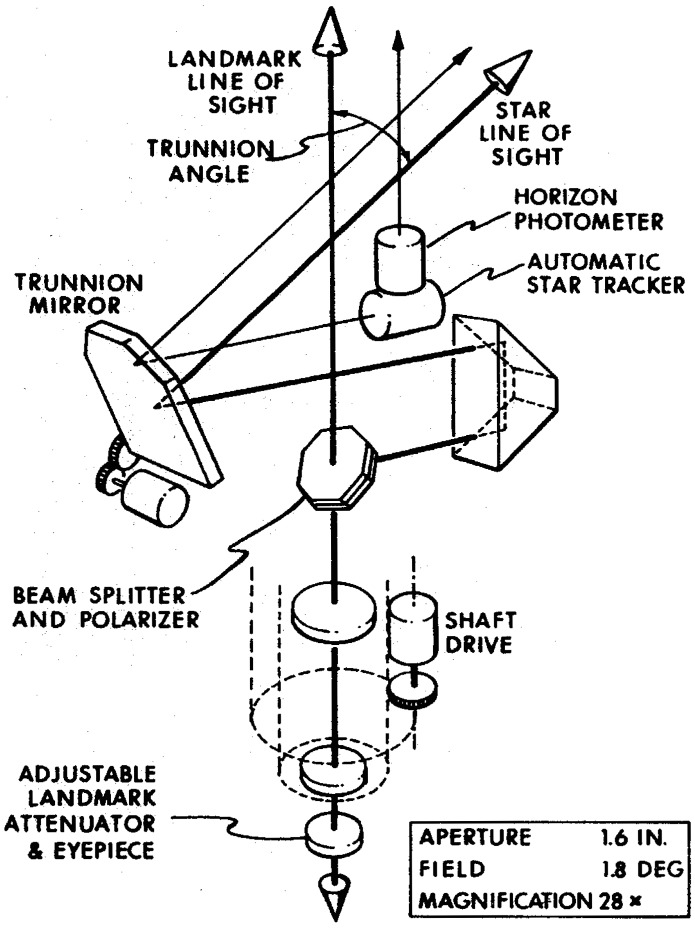


Fig. 2.3 Sextant Schematic

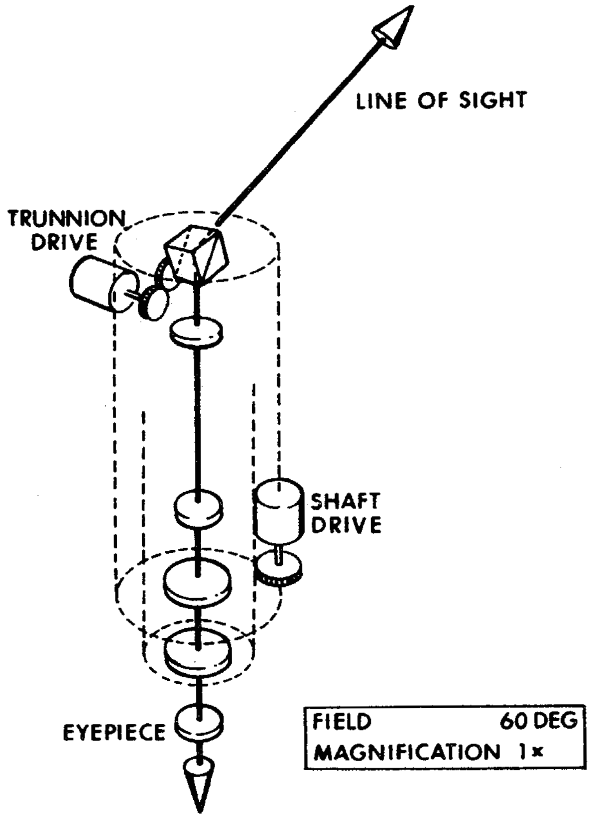


Fig. 2.4 Scanning Telescope Schematic

desired direction. The astronaut initiates a timing mark which causes the AGC to record the trunnion and shaft angles and the time at the instant the sextant is properly pointed for measurement.

2.3 The Computer Subsystem

The computer subsystem is used to perform space-flight data handling and computation.

The AGC is a general purpose digital computer employing a core memory, parallel operation, and a built-in self-check capability. Programs are stored in the AGC and selected to control and solve flight equations. The selection of programs can be'controlled either manually by the astronaut or by automatic sequencing.

The display and control panels (DSKY's) are consoles which provide access via a keyboard to both the AGC and the inertial subsystem. Together they comprise a computer subsystem which has five major functions:

1) process navigation data to maintain knowledge of the actual trajectory,
2) calculate steering signals and engine discretes necessary to keep the spacecraft on the required trajectory,
3) position the stable member in the IMU to a coordinate system defined by precise optical measurements,
4) conduct limited malfunction isolation of the G&N system by monitoring the level and rate of system signals, and
5) supply pertinent spacecraft condition information to the DSKY.

Using information from navigation fixes, the AGC computes deviations from the required trajectory and calculates the necessary corrective attitude and thrust commands. The velocity corrections are measured by the inertial subsystem and controlled by the computer subsystem, Velocity corrections are not made continuously, but rather are initiated at discrete check points in the flight. The technique of check-point velocity corrections reduces fuel consumption since the engines are used only when a significant correction in velocity is required.

The AGC uses information from celestial measurements to align the stable member of the IMU to a defined coordinate system.

Lamps on the DSKY indicate the program being solved by the AGC or the results of such calculations. Selection of the computer program or insertion of data into the AGC is done by the astronaut with the keyboard on the DSKY.

CHAPTER 3

HYBRID SIMULATION DESCRIPTION

The Apollo flight schedule progresses from unmanned suborbital flights to manned lunar landings. The goals for each flight will expand continuously to test every requirement of the Apollo program. The guidance and navigation hardware and software will also develop with mission expansion. For example, the guidance and navigation information programs stored in the AGC will be optimized to meet each flight's requirements.

Each AGC program is designed and tested on a three-dimensional all-digital simulation of the Apollo spacecraft and its designated mission. The digital simulation provides a proving ground for painstaking step-by-step analysis of each program. However, in practice its use is generally restricted to low frequencies if the solution time is to be at all reasonable, Digital simulation of hardware must be idealized - mostly because hardware idiosyncrasies are virtually impossible to describe analytically.

The G&N hardware is tested in the laboratory where the procedures are limited by the lack of a closed loop with a spacecraft and crew.

A practical solution to the aforementioned limitations is to join the G&N system hardware and software to a real-time three-dimensional analog-digital simulation of the Apollo spacecraft. Idealization can then be kept to a minimum. Sometimes a problem may appear either because it had been masked or because the circumstances which led to its existence had been impossible to predict. Should such a problem appear, it can be corrected in the laboratory by making whatever changes are necessary.

If the G&N system continues to function well under all of the conditions finally imposed on it by this hybrid simulation, the level of confidence is thereby greatly enhanced.

The hybrid simulation must be flexible enough to provide environments for flights varying from the early unmanned missions of the Command and Service Module (CSM) to the manned flights when the Lunar Excursion Module (LEM) is attached to the CSM, and later to lunar orbits and landings.

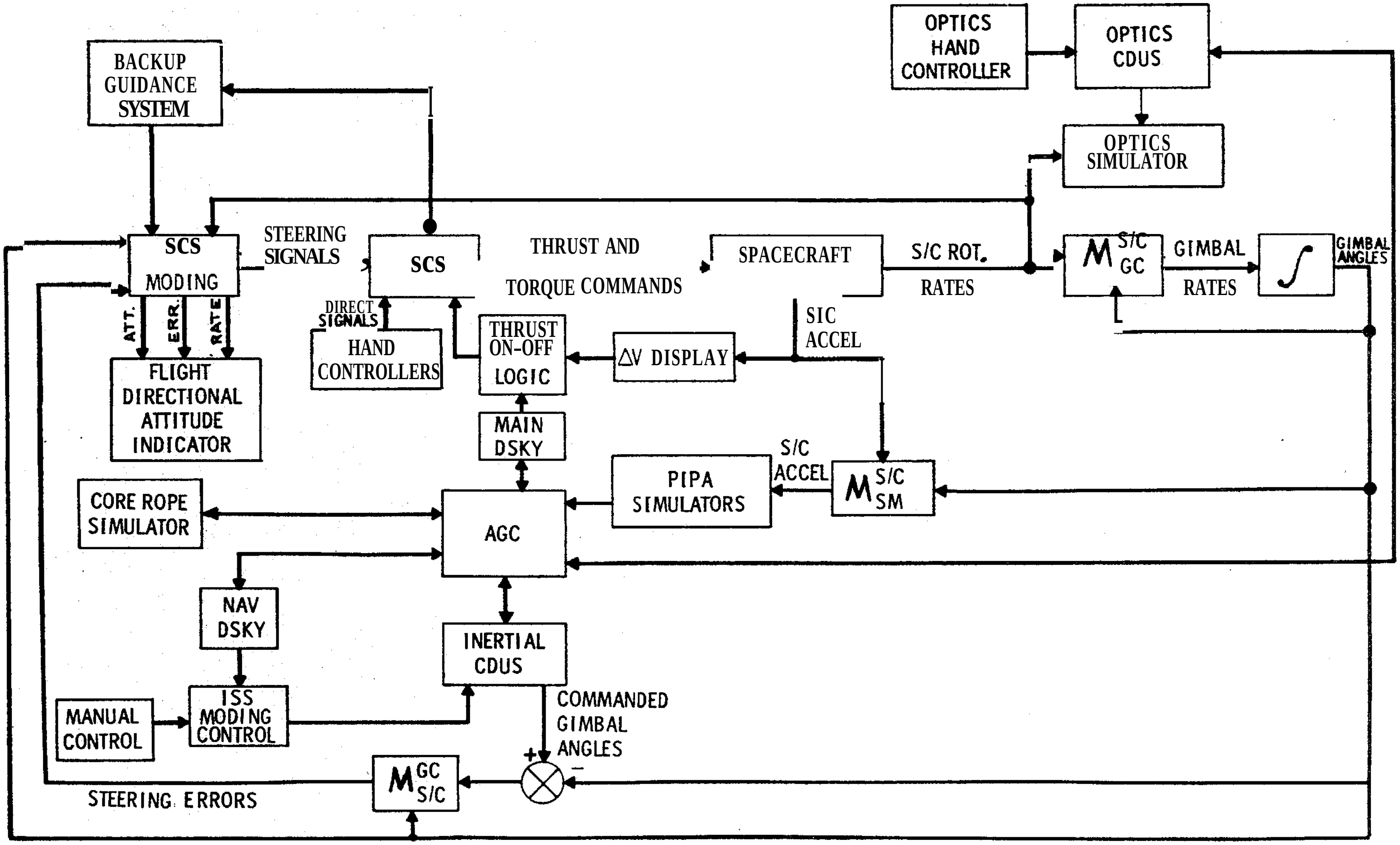
Actual G&N system hardware is used wherever possible. Exceptions are those sensing devices, attitude and rate gyros, accelerometers, etc., which will not perform in the laboratory's 1-g field as they will in a variable g-field, and the optical subsystem which must be simulated to reproduce a space orientation. The mechanization of the manned hybrid simulation is shown in Fig. 3.1.

3.1 Analog Simulation of the Mathematical Model

At the heart of the hybrid simulation is the analog simulation of the Apollo spacecraft - its dynamics and control systems. Some applications of the hybrid simulation, such as program verification or astronaut training, require a relatively unsophisticated mathematical model of the spacecraft. However, other applications, for example, stability analysis, permit few simplifications because virtually every force we can predict does under some circumstances become significant.

For example, much of the Command and Service Module's mass consists of propellants which not only slosh, contributing destabilizing forces which must be controlled, but which also are consumed, thus varying spacecraft inertias, c.g. location and mass. As they are consumed each propellant's own sloshing mass, location, frequency, and compliance change. Complete histories of all of these quantities then must be provided as functions of total vehicle mass.

The attitude of the Command and Service Module is controlled by the stabilization and control system (SCS). The SCS consists of two major subsystems: 1) the reaction control system (RCS) and 2) the thrust vector control system (TVC). The RCS controls the attitude of the spacecraft using



*NO ATMOSPHERE

Fig. 3.1 Mechanization of the Manned Hybrid Simulation of the Apollo G&N System* four clusters of four jets each - mounted symmetrically around the longitudinal axis. The TVC system controls the attitude of the spacecraft with a large gimballed engine mounted on the rear of the spacecraft. During a TVC maneuver the roll jets remain activated to provide roll stabilization. The RCS jets and gimballed main engine are shown in Fig, 3.2.

The use of jets or of the main engine depends on the particular maneuver selected by the AGC. For example, in a zero-g field, the propellant could be anywhere in the tanks. The firing of a selected group of jets can accomplish an ullage maneuver, pushing all of the fuel to the bottom of the tanks where it should be prior to the firing of the main engine. Three autopilots (one for each axis) and a jet-select logic system control the behavior of the jets,.

Large maneuvers of the spacecraft, such as midcourse corrections and orbit changes, are accomplished using the main engine. The main engine is gimballed in pitch and yaw and is controlled by two associated autopilots. The main engine deflection is limited in both position and rate.

Forces created by gimballing the main engine, sloshing propellants, and thrusting through a misaligned center of gravity result in bending moments which can be very significant. This is especially noticeable at the docking collar when the LEM is attached to the CSM. Bending effects then are reflected throughout the system and can become especially troublesome but interesting in a simulation where the ultimate control is in a digital computer (the AGC) with fixed sampling rates and quantum levels.

In one case quantization within the AGC excited the bending modes of the spacecraft. A redesign of the digital portion of the system resulted in thoroughly acceptable performance,

Before entry the Service Module is jettisoned and the Command Module is controlled by guidance system commands to 12 reaction jets on the command module surface as illustrated in Fig. 3.3. During this phase the

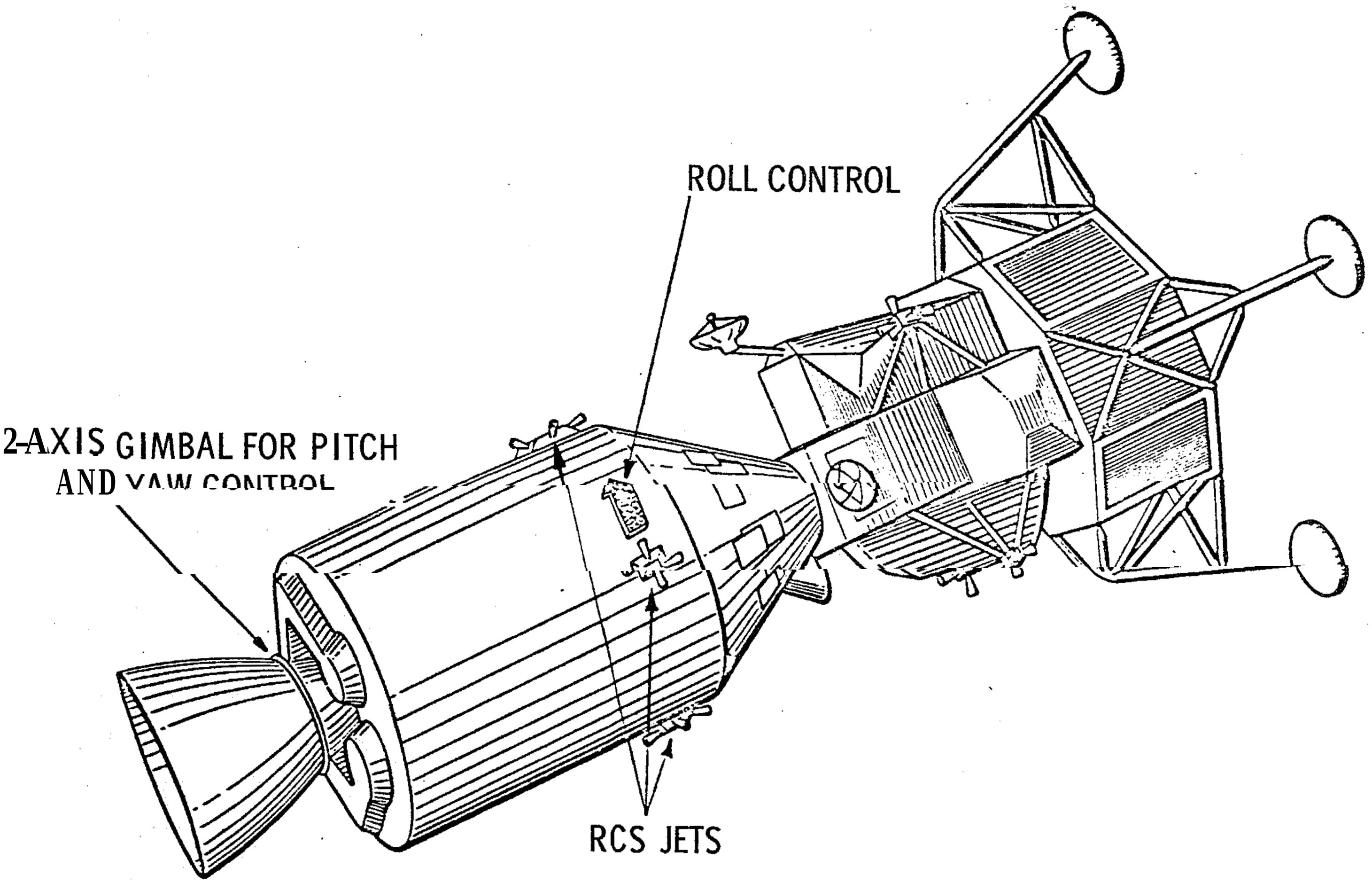


Fig. 3.2 Apollo Spacecraft Configuration Showing RCS Jet Locations and Gimballed Main Engine

effects due to bending and slosh are negligible but the aerodynamic forces and moments become significant.

Simulation of the reentry phase requires the addition of a digital computer (SDS 930) which will provide trajectory information and aerodynamic forces and moments.

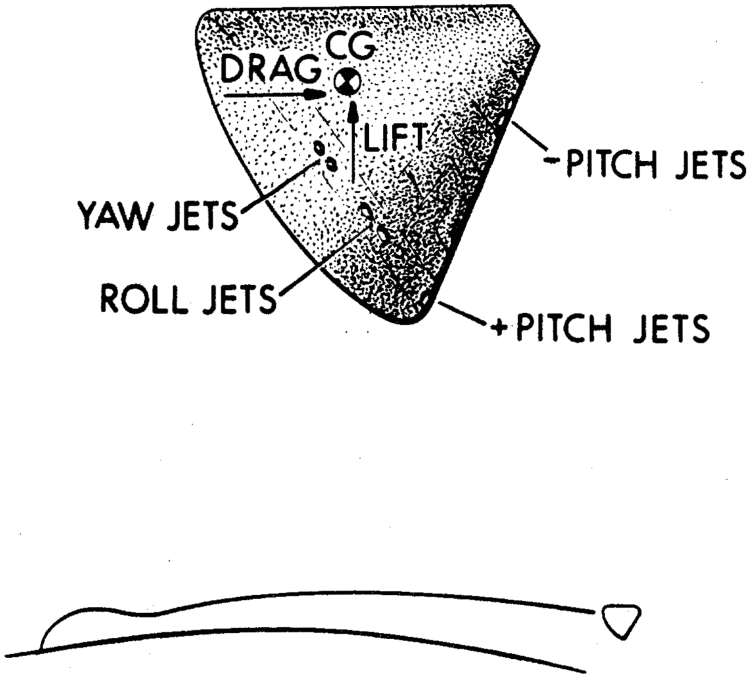


Fig. 3.3 Earth Atmospheric Entry

3.2 Inertial Subsystem Simulation

The inertial subsystem simulation includes three CDU's and an analog simulation of the gimballed stable member, In a spacecraft environment, the spacecraft attitude, attitude rate, and lateral acceleration would be supplied by resolvers, gyros, and accelerometers mounted on the gimbals. In the laboratory, the spacecraft attitude, attitude rate, and acceleration are obtained from the analog simulation of the spacecraft. The analog signals (direct current) are then converted to alternating current or pulse trains to complete the appropriate interfaces with the G&N subsystems hardware.

3.3 Command Module Simulation

A full-size interior mockup of the command module is completely equipped with all of the controls and displays associated with the G&N system. The cockpit contains all physical objects which might aid or hinder the crew's operation of the G&N system. These include provisions for crew operation wearing space suits.

3.4 Optical Subsystem Simulation

The mockup is also equipped with an optical subsystem simulator which reproduces as closely as possible the accuracy of the flight optics. The sextant simulator consists of a telescope, mirrors, a beam splitter, a sensitive dual-axis refractosyn, and two collimators. (Fig. 3.4)

The mirrors reflect the star and landmark images onto the objective of the telescope. They are mounted to rotate about two orthogonal axes, Both lines of sight are combined by the beam splitter. The two-axis refractosyn precisely determines the position of mirror 2 from a reference position, The reference position is selected *so* that the refractosyn output is nulled when the star and landmark are superimposed. Hand controllers in the cockpit send spacecraft commands to the stabilization and control system and to the optics servo drives. The apparent motion of the star and of the landmark is simulated by moving the mirrors. Spacecraft motion is simulated by movement of mirror 1. Optical instrument motion is simulated by movement of mirror 2.

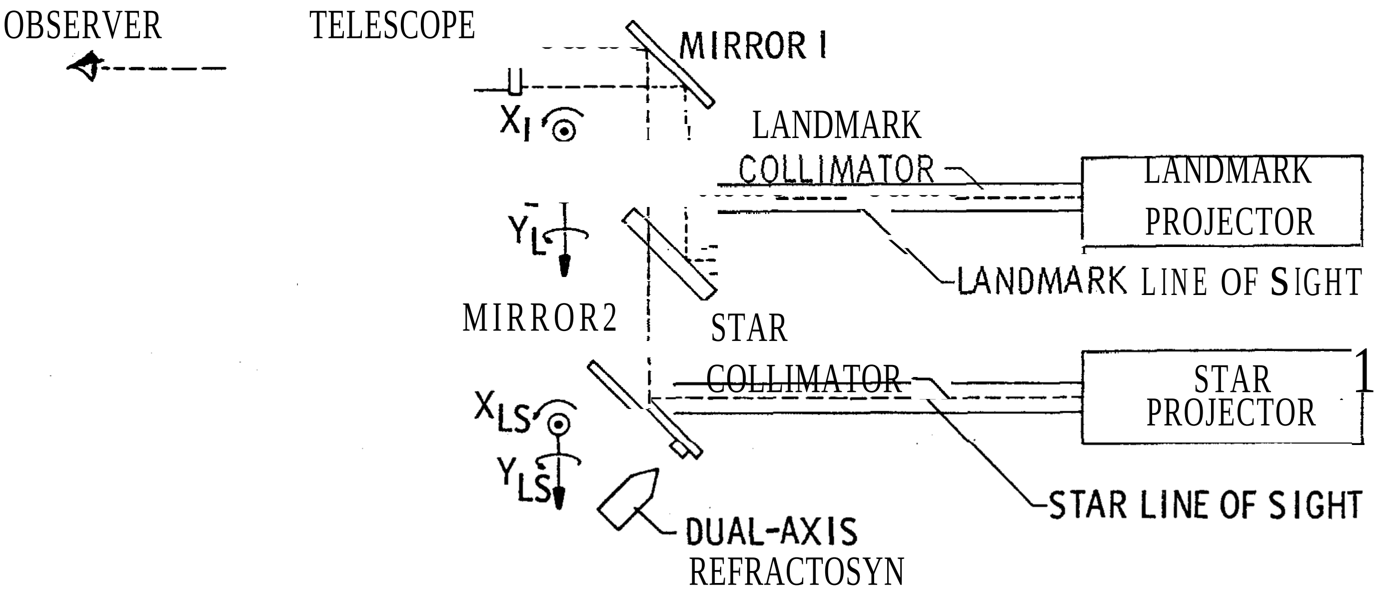


Fig. 3.4 The Sextant Simulator

The scanning telescope simulator consists of 1) a hemisphere on which stars are reproduced in magnitude and color and onto which slides of the Earth and Moon can be projected and 2) a telescope. Figure 3.5 is a schematic of the scanning telescope simulator,

The telescope actually consists of two back-to-back telescopes separated with a single dove prism, A rotating double dove prism is mounted *so* that its trunnion axis (TA) is orthogonal to the shaft axis (SA) of the telescope. Consequently, the astronaut can point to any part of the hemisphere by rotating the double dove about its trunnion axis and the telescope about its shaft axis.

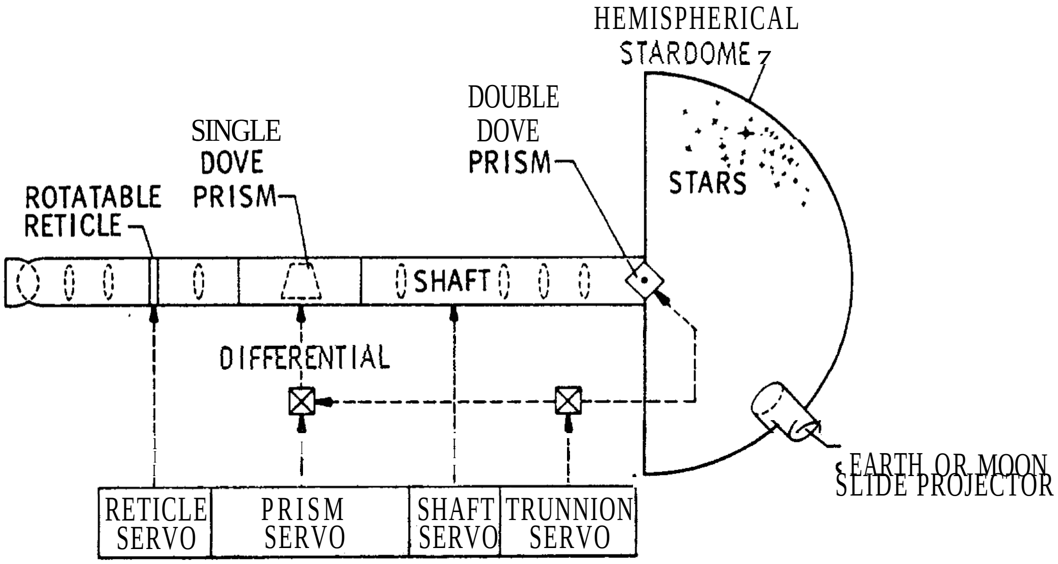


Fig. 3.5 The Telescope Simulator

Rotations of the single dove prism, the eyepiece reticle, the telescope shaft, and the double dove prism are used to optically simulate spacecraft motion.

3.5 Computer Subsystem Simulation

The computer subsystem simulation is made up almost entirely of flight hardware. It consists of display and control panels, both in the cockpit and in the laboratory and the Apollo Guidance Computer (AGC). Figure 3.6 shows a mock-up of the display and control panels.

In flight the AGC fixed memory is stored on core-rope modules which provides absolute security of information, true random access, and a high degree of coincidental current selection which permits simple addressing circuitry. In the laboratory the fixed memory is replaced by a core-rope simulator (CRS) of the type shown in Fig. 3.7.

The core-rope simulator supplies a facility with which programs can be checked prior to committing them to rope hardware. The simulator has a control panel which permits access to any part of the program. There is complete read and write capability via magnetic and paper tapes. The read and write formats are compatible thus enabling loading of previously used programs without reassembly. The time required to load a 24,000-word assembly via magnetic tape is 4.8 minutes. The magnetic tape also has a trace feature which can provide a continuous record of the contents of any register in the CRS.

3.6 Simulation of the Gimballed Engine

The analog program of the spacecraft dynamics and control system is relatively straightforward to an experienced programmer. However, there is one analog simulation which is the object of considerable interest by analog devotees - the rate- and position-limited engine. This particular engine has snubbed limits and was simulated with the circuit in Fig. 3.8. For expediency, analysis of the circuit will not be included here; however, a brief description of its operation is as follows,

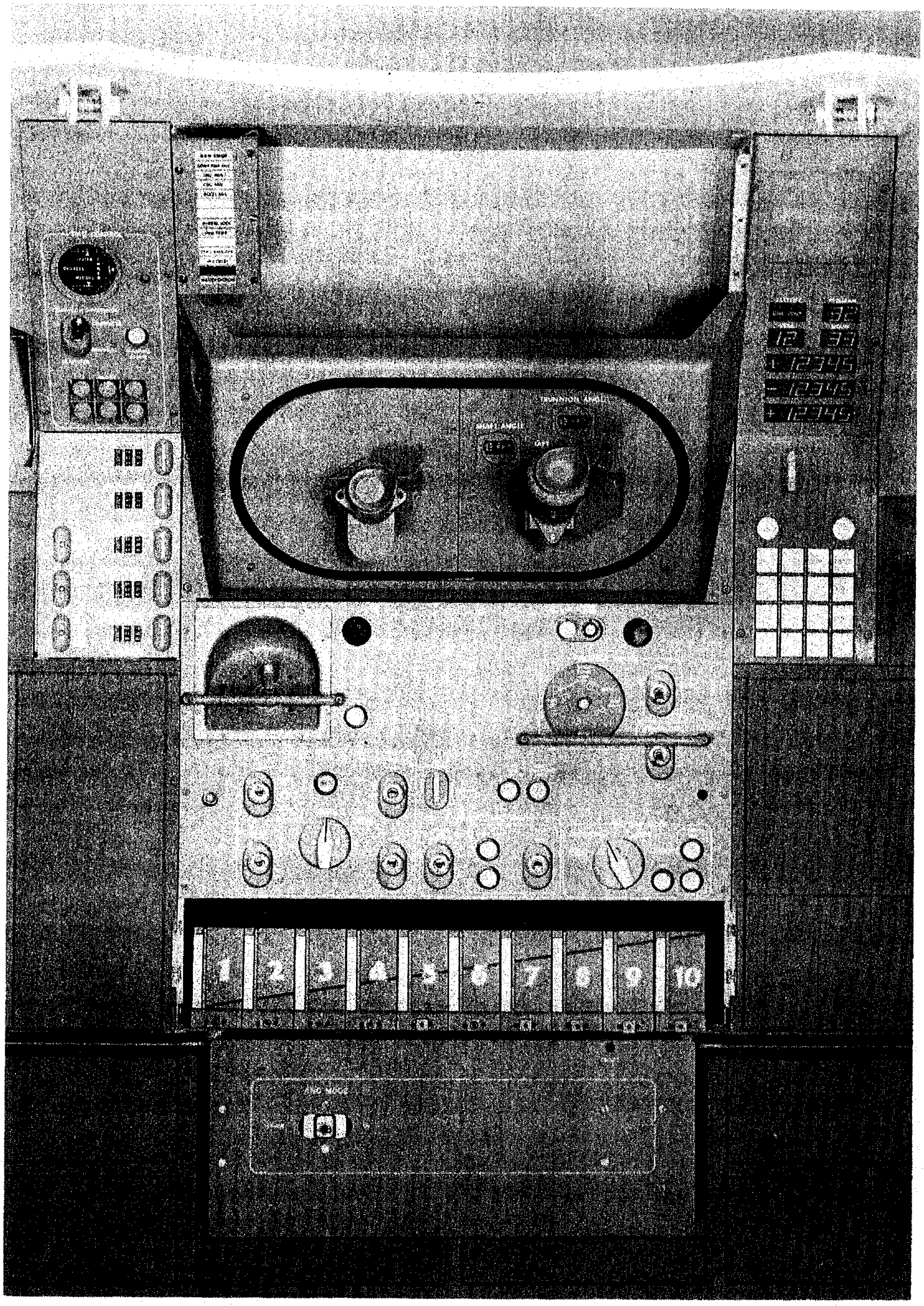


Fig. 3.6 Mock-up of the Display and Control Panels

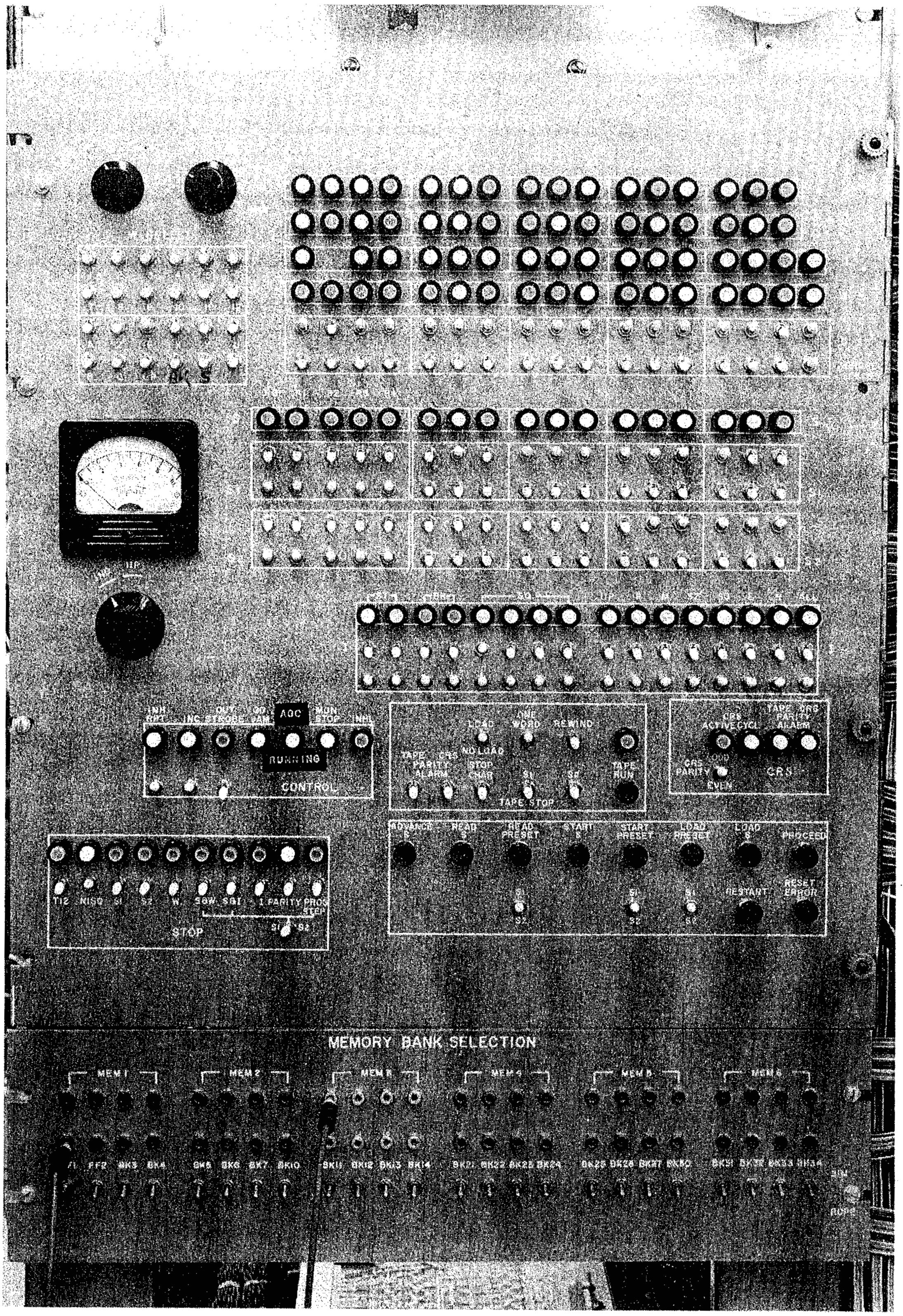


Fig. 3.7 Core-Rope Simulator

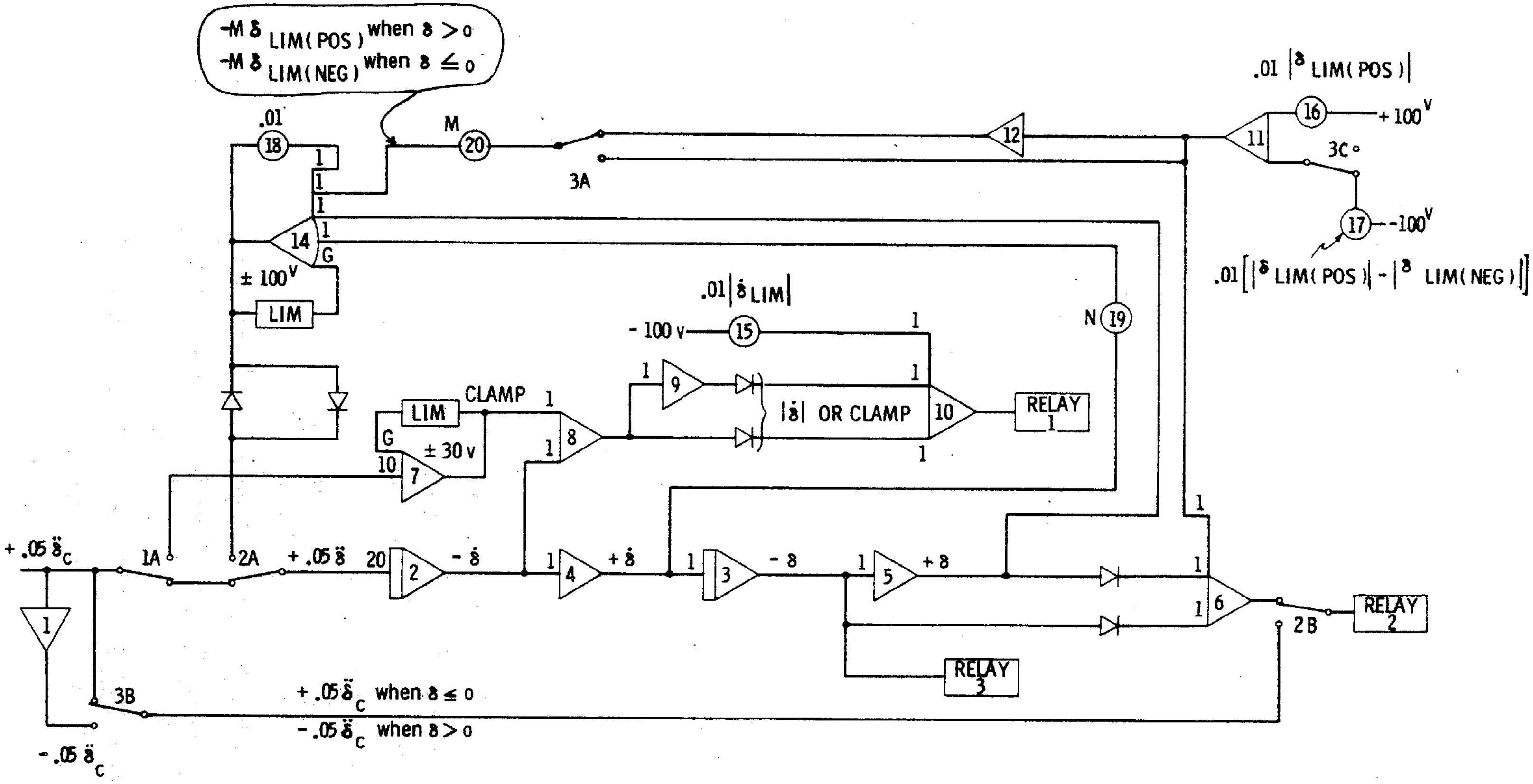


Fig. 3.8 Analog Program of a Rate- and Position-Limited Gimballed Engine

The circuit as shown is operating in its linear region. Amplifier 7 has no input and amplifier 10 has a dc voltage output equal to $|\delta_{LIM}| - |\delta|$. Relay 3 will energize whenever $\delta > 0$ permitting:

1) asymmetrical position limits on the arm of relay contacts 3A,
2) amplifier 14 to have input equal to $N\dot{\delta} + \delta - M\delta_{LIM}$ (Pos. or Neg.), where M and N are calibrated pot settings, and
3) relay 3B arm to equal plus-or-minus $\ddot{\delta}_C$.

When $\dot{\delta}$ hits its limit, relay 1 is energized thus redirecting the command, $\ddot{\delta}_C$, from the input of integrator 2 to the input of amplifier 7 which now acts as a clamp. Engine acceleration, $\ddot{\delta}$, is now zero and rate, $\dot{\delta}$, is constant. Relay 1 will continue to be energized until the clamping voltage goes to zero, i.e., when $\ddot{\delta}_c$ changes sign.

When δ hits its limit, relay 2 is energized resulting in integrator 2 being driven to zero, and integrator 3 being held to the position limit value by'the addition of a highly damped second-order feedback. In the limit, relay 2 is energized by $+\ddot{\delta}_c$ when $\delta \leq 0$ or by $-\ddot{\delta}_c$ when $\delta > 0$. Consequently, δ will come out of its limit when $\ddot{\delta}_c$ changes sign.

3.7 Interfaces

The Apollo hardware has interfaces whose requirements vary from pulse bursts to pulse trains to ac to simple relay closures. These interfaces must be made compatible with each other and with the analog computer which produces dc voltages.

Interfaces which actually exist in the flight hardware, say between the AGC and the CDU, form an integral part of the hardware itself. In this case the AGC transmits to the CDU pulse bursts at 3200 pps which are converted by a DAC to an 800-cps signal which is then used to drive the CDU shaft. Each pulse transmitted by the AGC is approximately equal to 39.5 seconds of arc. The CDU shaft position is encoded and sent back to the AGC.

In the laboratory a linear potentiometer is mounted on the CDU shaft and is excited by dc voltages from the analog computer. The output of the potentiometer is a dc voltage proportional to the CDU shaft angle. This angle is compared with the IMU angle - and the difference becomes a steering signal to drive the simulated SCS.

The difference is also modulated back to 800 cps to provide null which is used by the CDU during its fine-align mode. The modulation of the 800-cps CDU power signal is accomplished using a quarter square multiplier on the analog computer,

Care must be taken to ensure that the CDU shaft does not rotate through the discontinuous portions of the linear potentiometer. This is possible only when the total excursion of the shaft is less than 360°. It can be accomplished by manually rotating the linear potentiometer on the CDU shaft such that its center is at the mean of its expected excursion. An easier way is to drive the CDU's with a bias angle, $\theta - \alpha$, whose mean excursion can be expected to be zero. The CDU registers in the AGC can be set to the correct value of the angle and will subsequently respond to relative changes in $8 - \alpha$ which are equivalent to changes in an unbiased θ. The IMU angle generated in the analog computer can be similarly biased. The effect of the bias is cancelled out when the two angles are compared to produce a steering signal for the simulated SCS.

Lateral acceleration of the spacecraft is computed on the analog computer and is measured in Vdc. The dc voltage is converted to a pulse train whose frequency is proportional to the magnitude of the input voltage. The pulse is then sent to a'counter within the AGC.

A survey of the commercial market yielded a converter with almost identical characteristics as the PIPA's. The only alteration required was that its output pulses had to be separated into positive and negative trains and shaped to make them compatible with the AGC interface. Signal conditioning is accomplished using a simple transistor circuit (see Fig. 3.9).

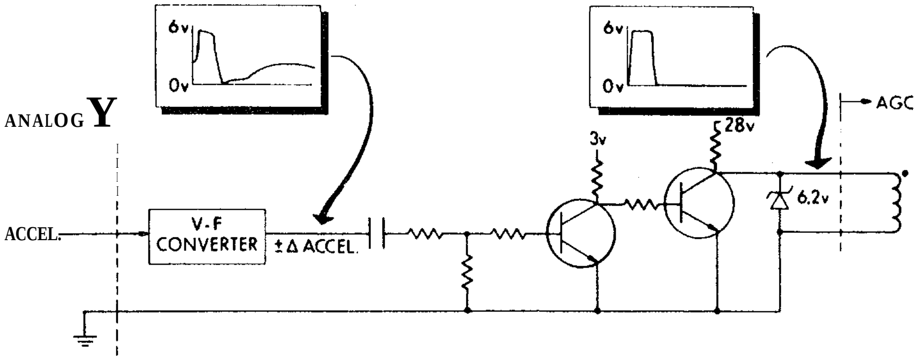


Fig. 3.9 PIPA Simulator Pulse Shaping

Discretes from the AGC to the spacecraft are converted to Vdc by a simple RC network, transistor and zener diode. The RC network (see Fig, 3.10) has a time constant just longer than the decay time between pulses, Consequently, the presence of a pulse train turns on the transistor, shorting the collector to the grounded emitter. In the absence of a pulse train the lag will go to zero, shutting off the transistor. The collector will return to **28** Vdc but the zener will clamp the output to *6* Vdc. These voltage level changes are used to change relay states which control the moding of the analog program.

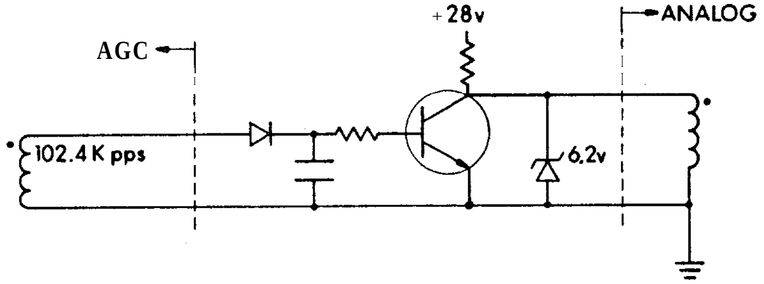


Fig. 3.10 AGC Pulse Train Conversion

Similar circuits are internal to the DSKY *so* that whenever discretes are present, relays are energized within the DSKY and in turn energize relays elsewhere in the system.

The AGC must be continuously informed of all events taking place. This even includes commands which originate within the AGC but which affect other hardware external to it. An example of such an event is the SIVB separate signal which can originate in the SIVB, the AGC, or from ground control, depending upon existing conditions. In any case, the AGC must receive confirmation that the separation has indeed occurred if it is not to produce a program alarm. Corroboration of events may be a simple relay closure to ground or the presence of a 102.4 K pps pulse train which, when sensed by the AGC, results in the proper record.

3.8 Digital Computer Support

Liberal use of the digital computer, in this case the Honeywell H-200 and H-1800, greatly improves the flexibility of the analog program.

The parameter variation with propellant usage was analyzed, computed, and curve-fitted digitally.

All of the potentiometer settings are recorded on 80-column cards. The cards are then processed into a punched paper tape with a format compatible with the analog computer's automatic input system which in turn servo-sets the potentiometers. There are nearly 300 potentiometers in the simulation and the entire process from cards to settings can be completed in approximately 30 minutes.

Setup, shut down, and calibration procedures have been written for all of the hardware and software. They have been punched on 80-column cards which are printed out on an IBM 407. This method of recording procedures permits:

1) rapid orientation of new operators,
2) flexibility which allows for expansion and program changes, and

3) reliability which is especially appreciated when the facility is operated by a small staff - say one person.

A rigorous static check of the analog program is achieved using a special-purpose digital program. False initial conditions are chosen to energize every component in the system simultaneously. The digital program uses the same false initial conditions and computes what the outputs of every amplifier, integrator summing junction, potentiometer, multiplier, resolver and trunk connections should be. The analog computer components are automatically scanned and should identically match the digital answers. This static check is a very powerful tool and provides a complete check of the analog computer for wiring errors or machine malfunctions.

CHAPTER 4

SUMMARY

Judicious use of analog and digital computers, together with the analog and digital G&N hardware and software, make it possible to simulate in a small laboratory any part of an Apollo mission from lift-off to splash-down.

Spacecraft dynamics can be simulated on an analog computer even including forces due to bending, to slosh, and to c.g. movement caused by propellant usage, Trajectory information and aerodynamic forces due to atmosphere can be simulated on a digital computer and combined with the analog simulation.

Wherever possible, flight hardware can be and is used, Actually, those components which are the major contributors to system performance are all included. The computer subsystem is complete. The inertial subsystem omits only those sensors that would not perform similarly in the laboratory as they would in a variable-g field. The optical subsystem has been entirely simulated by other hardware which has nearly identical performance characteristics. The optical subsystem simulates in the laboratory a moving spacecraft in a celestial field.

The entire mission program, including all of the guidance and navigation functions of the AGC, can be loaded into the core-rope simulator (CRS). The CRS can also be provided with a special program which allows the operator to control. the entire simulation from the AGC console (DSKY).

R-525
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