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MORL CONTROL SYSTEM INTEGRATION

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SUMMARY

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General mission modes and orientations for the Manned Orbital Research Laboratory are presented, and an integrated control concept for these modes is discussed. Schematics of the baseline MORL control system and the primary subsystems are used to develop the control component functions during both zero-gravity and artificial-gravity operations. Emphasis is placed on the momentum storage and reaction control subsystems; and characteristic computer results are included to illustrate the control system performance during the orbital mission. These results consider centrifuge operations, aerodynamic and applied torques, CMG desaturation, maneuver capability, and wobble damping.

Author

INTRODUCTION

To understand the control philosophy for the Manned Orbital Research Laboratory, we must briefly review the laboratory mission and configuration. The MORL, shown in figure 1 during injection into orbit, is primarily a zero-gravity laboratory designed to support a crew of six in a 200-nautical-mile orbit for up to 5 years. After separation from its booster, the unmanned laboratory module is checked out and prepared for rendezvous and manning. A conical docking hangar allows crew transfer into the laboratory and a short-arm

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*This paper summarizes the results developed by Douglas Aircraft Company,[2,3] Bendix Eclipse Pioneer Division,[2] and NASA Langley Research Center in support of research on the stabilization and control problem for MORL.

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centrifuge is used for crew conditioning in the zero-gravity environment. Power for the laboratory is derived from a gimbaled solar cell array which must be continuously alined normal to the solar radiation.

If artificial-gravity capability is desired at some later date, the same basic module, together with a spinup section, is launched into orbit as shown in figure 2. The MORL module now remains attached to its booster, and the laboratory-booster combination rotates to produce the desired artificial-gravity field.

The function of the integrated control system for MORL is to orient or maneuver the laboratory as required by the experimental and operational mission while minimizing fixed system weight and propellant consumption. General accuracy and maneuver requirements for the laboratory mission are given in reference 1 and will not be repeated here.

MORL ORIENTATION

The primary orientations required during the mission are shown in figure 3. After injection, the unmanned laboratory is placed in a roll solar mode. For this mode the longitudinal or X-axis is pointed at the sun and the laboratory is rate stabilized about this axis. Reaction jets are used to maintain this sun alinement until rendezvous with the laboratory crew has been effected.

After manning, the laboratory will have three principal orientations. For approximately 70 percent of the time it will be in a roll solar mode for which the Y-axis is controlled to be in the orbit plane. This orientation results in cyclic gravity gradient torques and allows the use of fixed solar panels. For about 24 percent of the time, rendezvous, orbit keeping, and earth oriented experiments will require a belly-down mode. In this mode, the Y-axis is alined

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with the local vertical and the X-axis points along the orbital velocity vector. The gimbaled solar panels are now driven to maintain solar alinement. For the remaining 6 percent of the time the laboratory will be in an arbitrary inertial mode, for which any inertial or celestial orientation can be provided to meet the experimental requirements.

In the artificial gravity mode, the laboratory is deployed after manning and the minus Y-axis is then pointed at the sun. The solar panels remain fixed and the laboratory is precessed to maintain a solar orientation.

INTEGRATED CONTROL SYSTEM

A schematic of the integrated control system for MORL is shown in figure 4. The basic attitude reference elements are sun sensors, horizon sensors, and inertial rate integrating gyroscopes (IRIG). Signals generated by these elements are modified by the actuator selection logic for the specified modes and are used to actuate the momentum storage and reaction control systems.

The momentum storage system for zero-gravity operation consists of two double-gimbal control moment gyros (CMG's), alined with the laboratory X-axis and providing torques about the Y-axis and the Z-axis, and of two single-gimbal control moment gyros, alined with the Y-axis and providing torques about the X-axis. The CMG's compensate for the effects of cyclic aerodynamic and gravity gradient torques, and maintain the vehicle orientation during operation of the onboard centrifuge. In addition, these actuators are used for fine attitude control and maneuvering. For artificial-gravity operation, the single-gimbal CMG's are desaturated and locked into position and the double-gimbal CMG's are precessed to the Y-axis. These CMG's then act as wobble dampers and compensate for the effects of crew motions and other applied torques.

The reaction control actuators consist of four sets of 60-pound thrust engines which provide maneuver capability about all three axes of the laboratory and serve for desaturation of the CMG's. The reaction engines are also used for orbit keeping and for spin and precession control in the artificial-gravity mode.

A functional block diagram of the integrated control system is shown in figure 5. Solar detectors are used to acquire the sun and the laboratory attitude is then monitored by means of both wide and narrow angle sun sensors. Earth horizon scanners provide a local vertical reference and these signals, together with IRIG signals, are used to select the appropriate actuator logic for the momentum storage and reaction control systems. The momentum storage system uses ON-OFF or proportional gimbal torque commands based on the vehicle attitude and rate during the nonspinning mode and proportional gimbal rate commands based on the vehicle rate and off-axis rate integral during the spinning mode. The reaction control system provides for rate-limited, fuel optimal ON-OFF control during the nonspinning mode and uses a masked sun sensor to generate control commands for precession control during the spinning mode.

Attitude and rate signals are also displayed on a laboratory control console and the control maneuvers may be performed manually, semiautomatically, or automatically. For manual control, the pilot commands direct torques from the CMG's or reaction engines by means of a three-axis control stick; and for semiautomatic control, the pilot selects a desired rate about a laboratory axis by rotating a PROGRAMED RATE knob.

A schematic of the reaction control system is shown in figure 6. The system uses earth storable hypergolic bipropellants, N_2O_4/MMH, which are fed to the radiation-cooled engines from metal bellows positive expulsion tanks. The propellant and pressurant storage and control systems are located in an unpressurized area within the laboratory. All pressurant bottles are interconnected so that any bottle can supply gas to the propellant tank through the parallel regulator system. Ambient nitrogen is controlled normally by one side of the parallel regulator while the other side serves as an inactive backup. In case of malfunction, the backup is automatically selected by pressure switch rating elements. Burst disks, backed by relief valves, guard against propellant tank overpressure. This method eliminates leakage until the disk is ruptured, and the relief valve prevents additional loss of propellants. Propellant and gas fill, drain and vent systems can be controlled remotely; and protection against leakage and guaranteed shutoff is provided by two solenoid valve seats installed in series in each line.

ZERO GRAVITY CONTROL

Disturbance Torques

The primary disturbance torques during zero-gravity operation arise from aerodynamic moments, gravity gradients, and centrifuge operation. A characteristic aerodynamic and gravity gradient torque profile for the roll solar mode is illustrated in figure 8. In this orientation, the iso-density contours with their diurnal bulge produce a biased aerodynamic torque. The corresponding Z-axis components of the aerodynamic and gravity gradient moments are given at the left of the figure. The torque, plotted against position in orbit, reaches a maximum of about 1.33 ft-lb. Corresponding laboratory attitude errors were determined with both proportional and ON-OFF control for the momentum storage system. The attitude error ψ with the proportional control commands was found to be as high as 10°, while the ON-OFF control scheme held the attitude error to less than 0.1°.

Proportional control also resulted in somewhat higher gimbal angles θ_G and correspondingly less efficient use of the CMG's than the ON-OFF control. Addition of an attitude integral feedback loop to the proportional commands may be as effective as ON-OFF control, though, and performance studies between these two control schemes are currently under way.

The disturbance torques produced by the onboard centrifuge are cyclic and are illustrated in figure 9. The centrifuge, shown at the right of the figure, is operated three times per day to produce a 1 g level in the Y-Z plane. Each operation requires 15 minutes to attain the 1 g level and 5 minutes continuous operation for view conditioning at this level. The resultant spinup torque about the X-axis is given at the left of the figure and must be counteracted by the momentum storage system. Two control schemes to compensate for this torque were again analyzed and the corresponding laboratory response is presented in the figure. Control for the MORL with proportional commands was found to be inadequate and resulted in maximum attitude errors of about 4.1°. Control with ON-OFF commands essentially eliminated these errors for the centrifuge spinup operation.

Differential Desaturation

In the event that the momentum storage system becomes saturated and must be unloaded to maintain the required position accuracy for the laboratory, the reaction engines are used for desaturation of the control moment gyros. A functional schematic of the unload logic for the momentum storage system is shown in figure 9. A signal voltage, whose amplitude is a function of the gimbal angle and rate is transmitted to the unload logic through two Schmitt triggers. The stop unload Schmitt level is set to the gimbal angle to which it is desired to unload and the commence unload Schmitt level is set to coincide with the maximum gimbal angle allowed. Both of these triggers must fire to initiate the unloading sequence. The CMG gimbals are then torqued toward their neutral position by applying a bias command input to the gimbal torquer power amplifiers. Simultaneously, the reaction jets fire for a preselected pulse interval. When the gimbal angle reaches the desired unload gimbal angle, the Schmitt triggers are reset and the unloading sequence is complete. Similar circuitry is provided for the other gimbal axes.

The gimbal angle response for this differential desaturation scheme is sketched in figure 10. Here, the upper Schmitt trigger has been set at 60° and the lower Schmitt trigger fires at 50°. The disturbance corresponds to a typical gravity gradient and aerodynamic torque acting on the vehicle in the roll solar mode. As the biased applied torque causes the gimbal angle to exceed its upper limit of 60°, the gimbal torquers are actuated and the reaction engines are fired to oppose the gimbal torques and stabilize the laboratory during desaturation. When the gimbal angle has decreased to the stop unload level, the torquers are shut off and the gimbal angle is again allowed to increase. The desaturation process then continues until the disturbance torque decreases.

Maneuver Mode

The reaction engines are used to maneuver the laboratory as required for the experimental mission. Position or rate commands are generated as biased input signals to the rate-limited control logic, which then actuates the appropriate reaction engines. Results for a typical maneuver are given in figure 11. The commanded maneuver is a 10° rotation with a 0.5° per second rate limit about all three vehicle axes, and the figure illustrates the laboratory attitude and control torque time history. It can be seen that the new attitude is achieved in approximately 24 seconds with a fuel consumption of 16 pounds for the 60-pound thrusters.

The reaction engines also serve as backup for the momentum storage system and provide control during the initial unmanned mode.

ARTIFICIAL GRAVITY MODE

Spinup Operation

For an artificial gravity launch, the MORL is stabilized by jets in a nonspinning solar orientation mode until manning of the laboratory has been completed. The laboratory module and booster combination are then spun up to produce the desired artificial-gravity level. A functional diagram of the spinup operation is presented in figure 12. The spinup jets are turned on to begin rotation of the MORL about the -Y-axis. Roll attitude control is maintained throughout the maneuver, and the laboratory and booster are given an initial separation rate by means of separation struts. The cables connecting the booster and laboratory are then extended at a nominal rate of 0.1 ft/sec and the MORL spin rate is held to small perturbations about a nominal rate of 0.1 rad/sec. The spinup jets are actuated whenever the spin rate deviation due to cable extension exceeds the preset perturbation deadband. The resulting torque then increased the spin rate until the upper deadband limit is reached and the jets are turned off. This process is continued until the final cable extension is reached. The laboratory is then spun up to the desired angular rate. Despin is accomplished by reversing the order of this sequence.

Precession Control and Wobble Damping

The solar orientation during spinning operation will be maintained by the reaction engines which precess the laboratory to compensate for gravity gradients and orbital regression. The control torque for determining thrust pulses is essentially inherent in a masked sun sensor. Precession thrust corrections are applied when the sensed sun angle exceeds a nominal threshold and the sun is detected in one of the unmasked sensor areas. Thrust commands are stopped when the sensed sun angle is less than a built-in hysteresis cutoff threshold.

Internal disturbance torques, such as crew motions and cargo transfer, and external moments, such as docking impulses, produce nutation or wobbling motions of the laboratory in the artificial-gravity mode. Damping and control of these motions is accomplished by one of the two double-gimbal CMG's comprising the momentum storage system. The other double-gimbal CMG is used as a backup in case of failure of the primary damper.

Characteristic results for MORL control with the momentum storage system are illustrated in figure 13. The disturbance here corresponds to an extreme case for which all crew members suddenly migrate to one corner of the laboratory. The associated motion is shown by time histories of the MORL laboratory solar sensor outputs. The laboratory attitude errors produced by the crew motion are reduced to approximately zero in 12 spin cycles and are held at zero by the gyroscopic torque resulting from precession of the deflected CMG. Removal of the disturbance causes the CMG to return to its neutral position.

CONCLUDING REMARKS

The integrated control system and the function of the various components of this system in stabilizing the MORL have been discussed. The system presented here forms a baseline for current studies aimed at optimizing the subsystem logic and gain factors for laboratory control. These studies incorporate the accuracy and orientation requirements developed by concurrent research to define the MORL experimental program and will evaluate the effectiveness of this system in meeting the experimental requirements.

Work on the mechanization of the control system is also underway. Primary efforts in this area include the development of a Control Flight Test Simulator,[4] which will be capable of evaluating the performance of both scaled and full-scale integrated control system hardware for MORL and simulation studies of the efficiency of pilot control[5] for the laboratory.

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3. Douglas Aircraft Company, Inc.: Optimization of a MORL System Concept. Douglas Report SM-46043, Confidential, Contract NAS1-3612, 1964.
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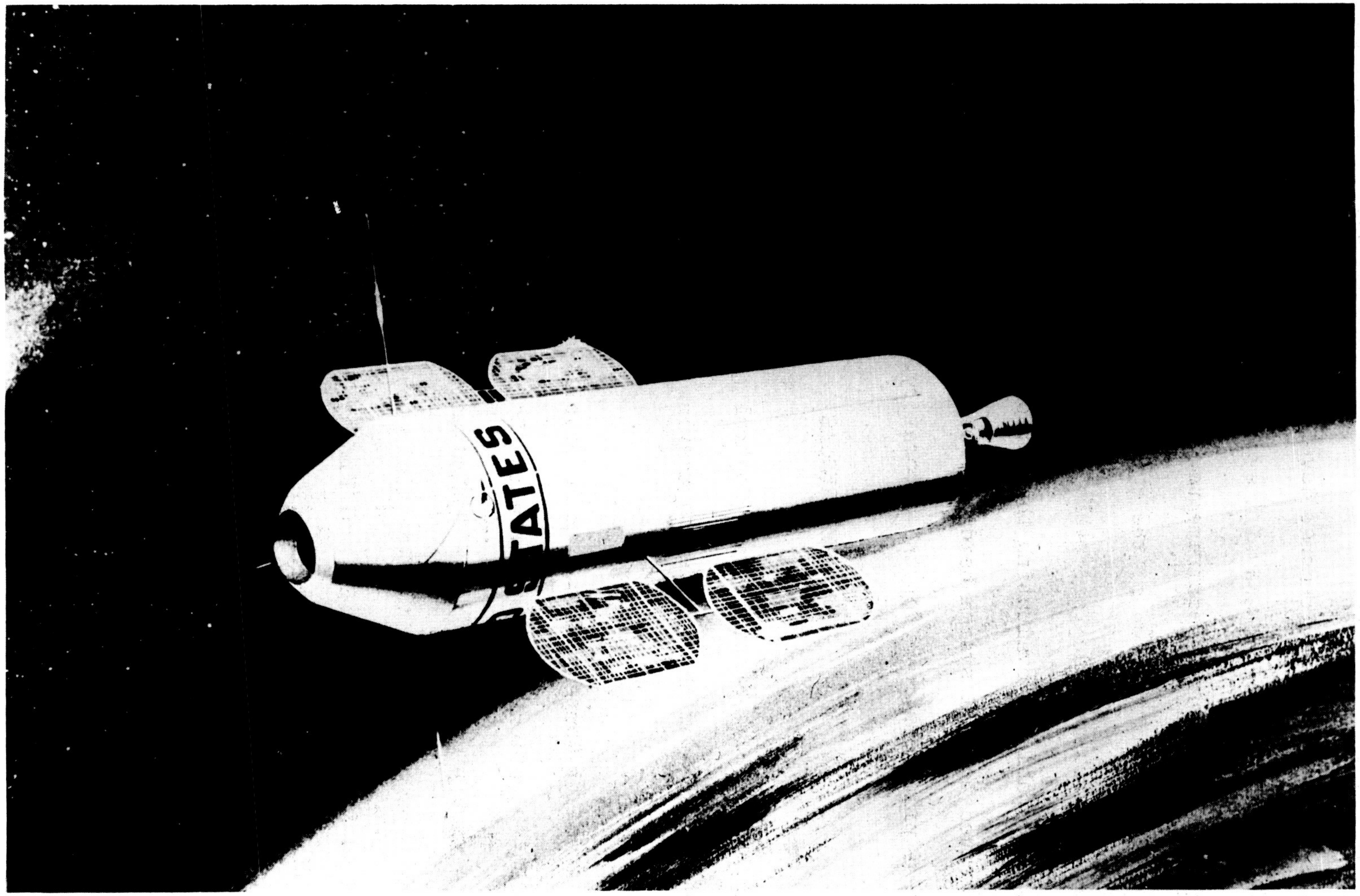

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Figure 1.- MORL in zero-gravity mode.

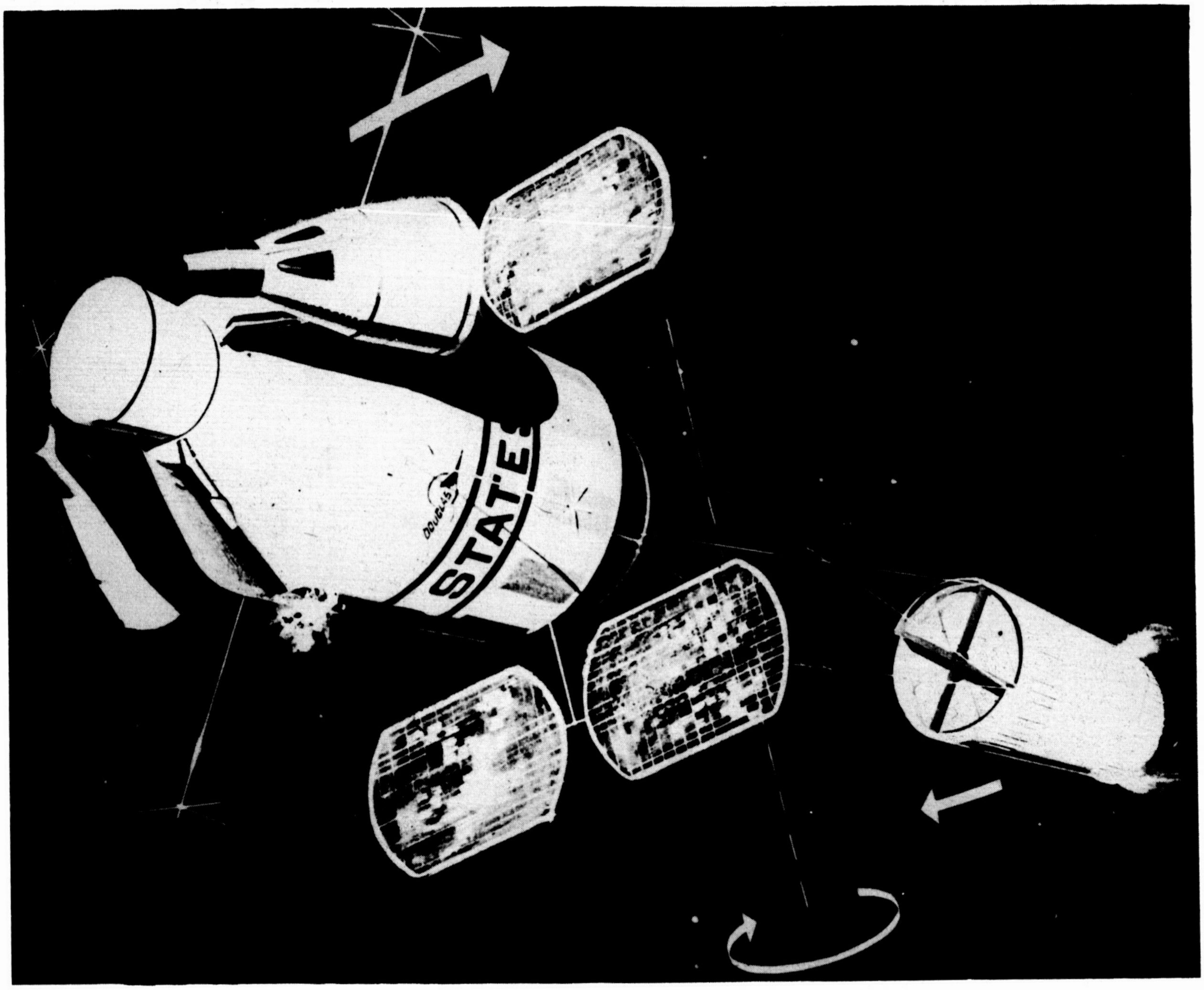

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Figure 2.- MORL in artificial-gravity mode.

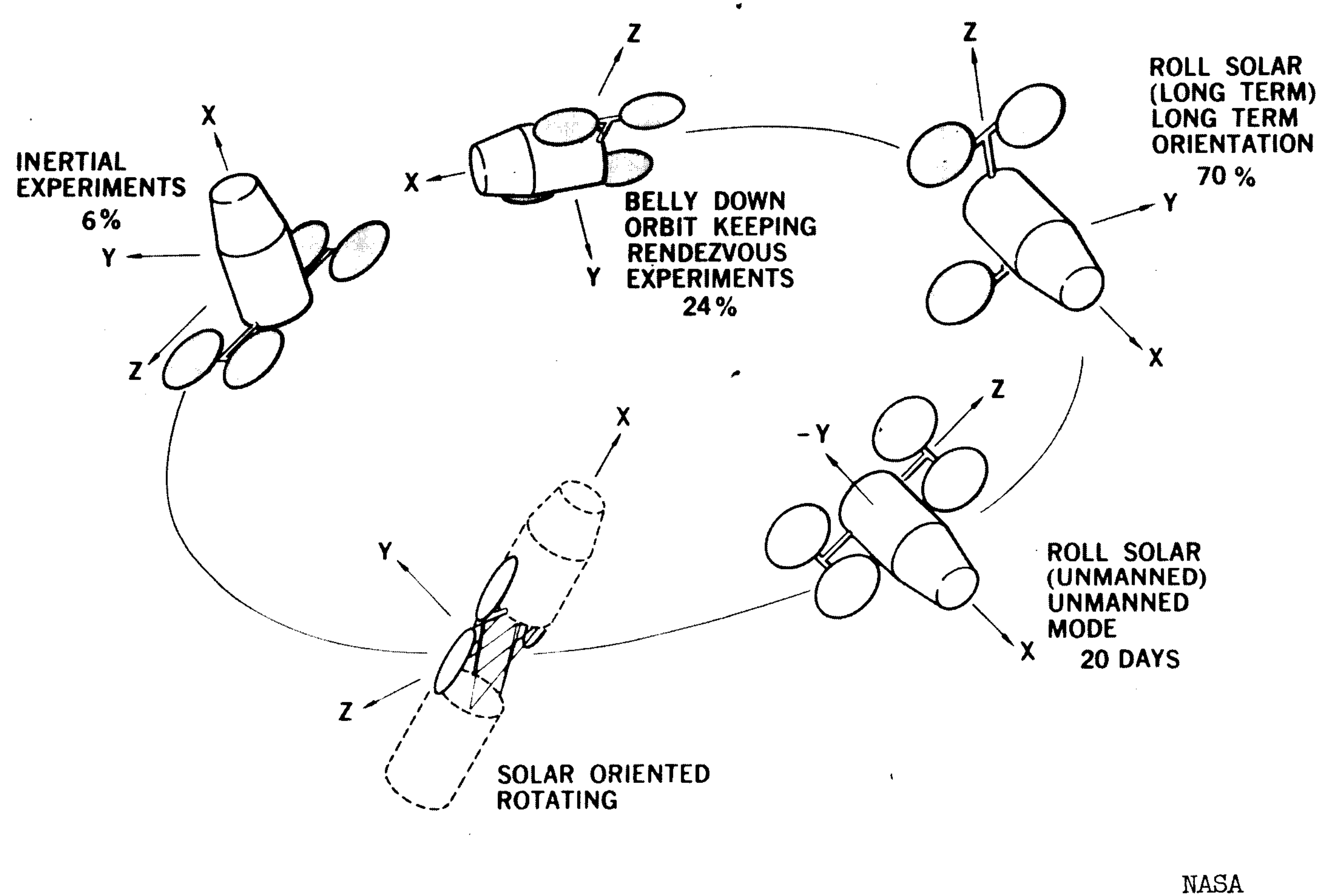

Figure 3.- Orientation profile for MORL.

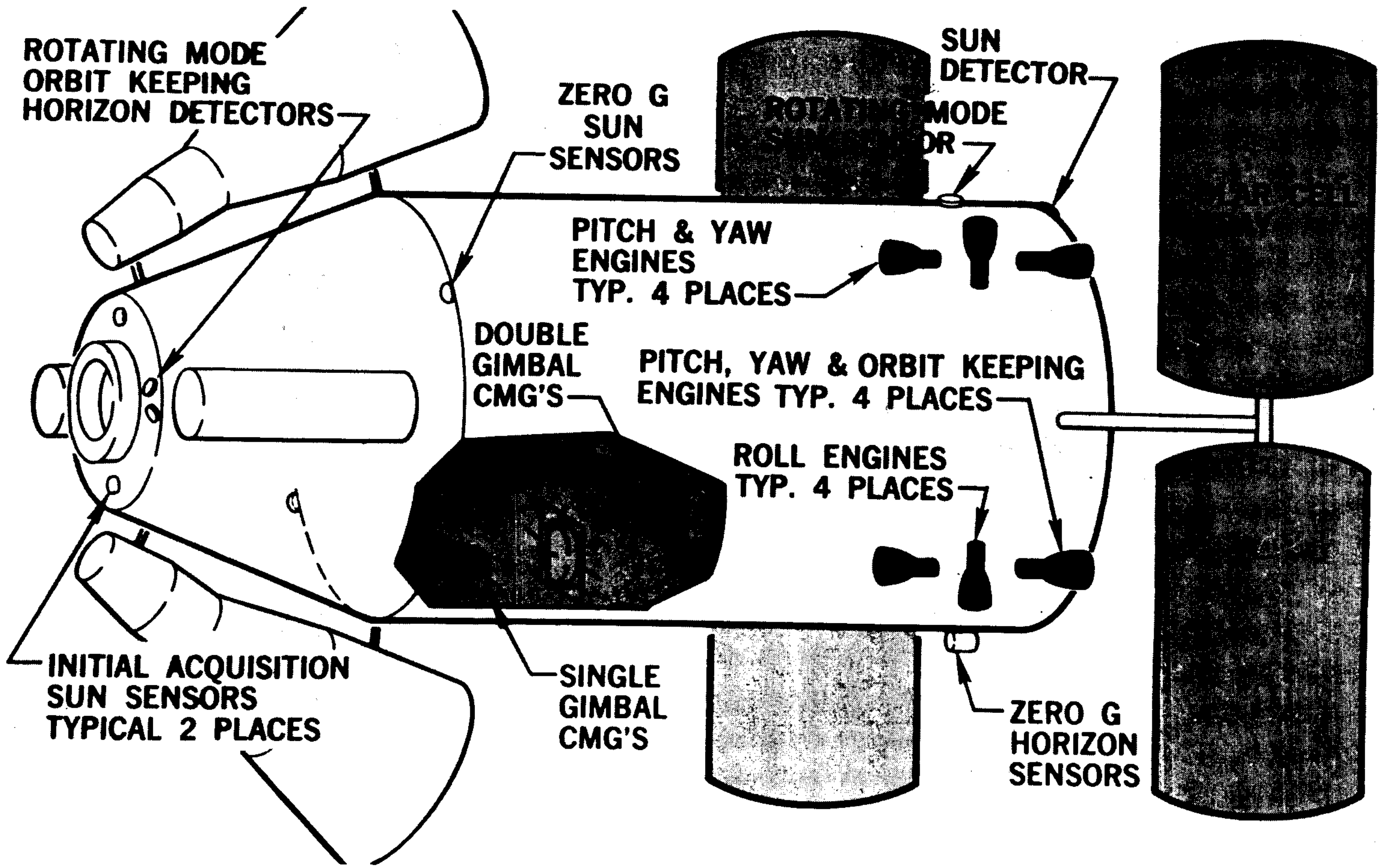

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Figure 4.- Sensor and actuator location.

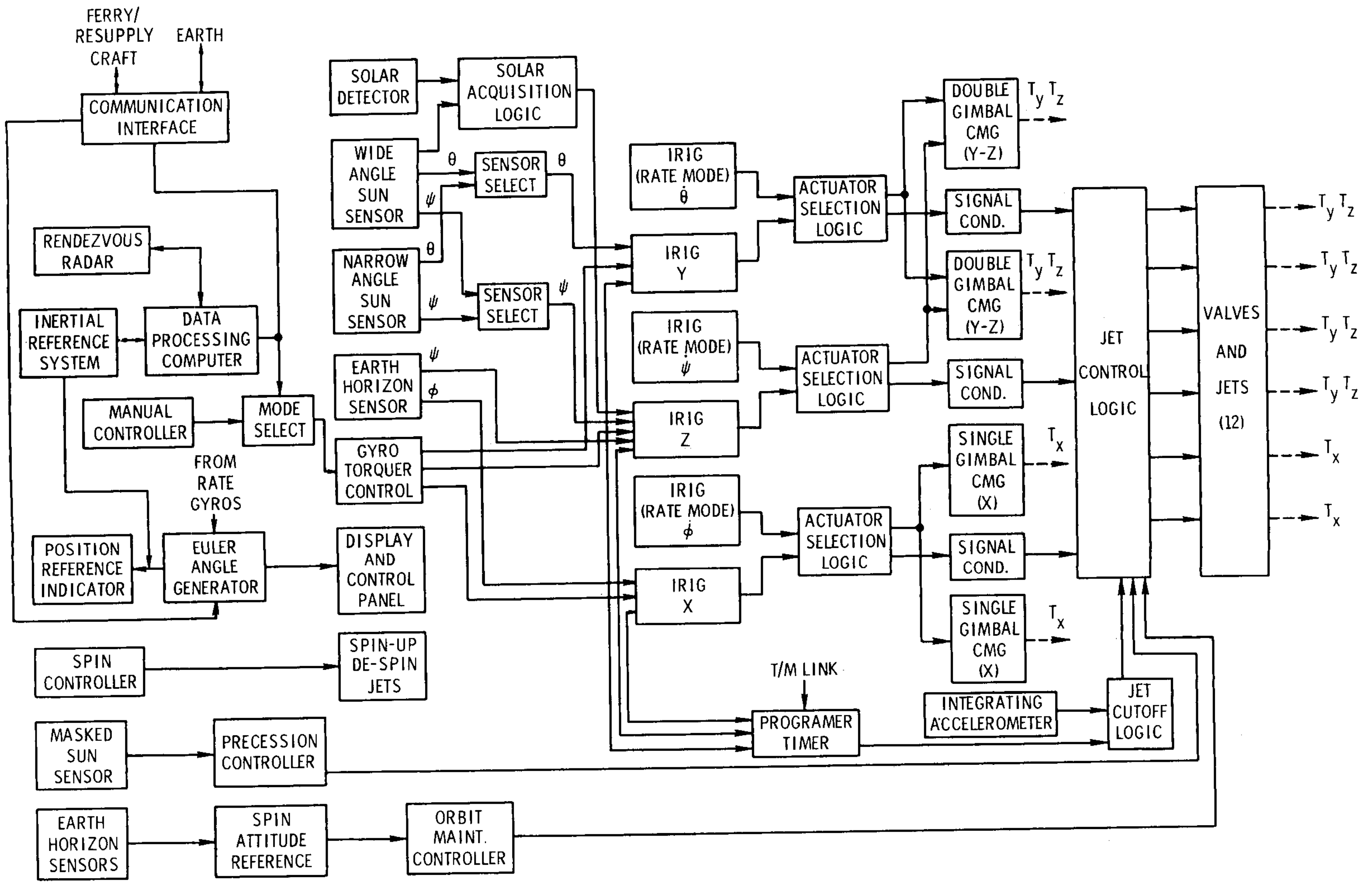

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Figure 5.- Schematic of integrated control system.

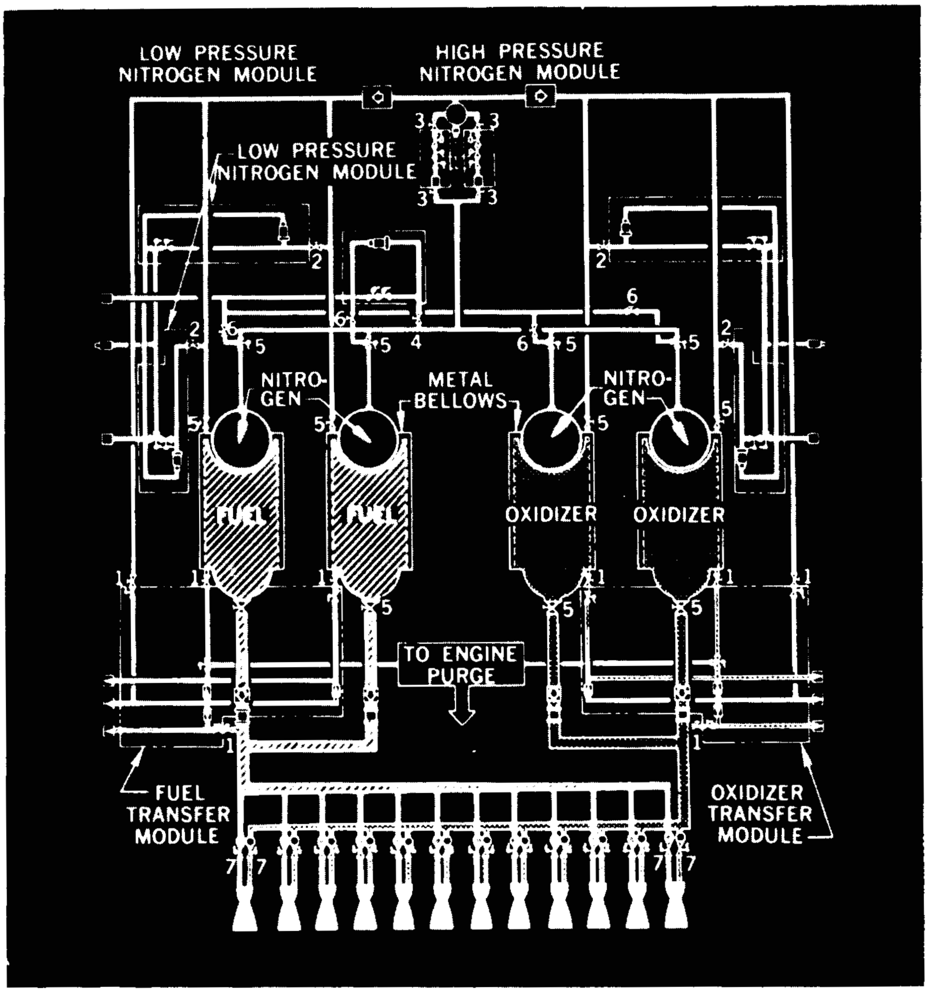

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Figure 6.- Schematic of reaction control system.

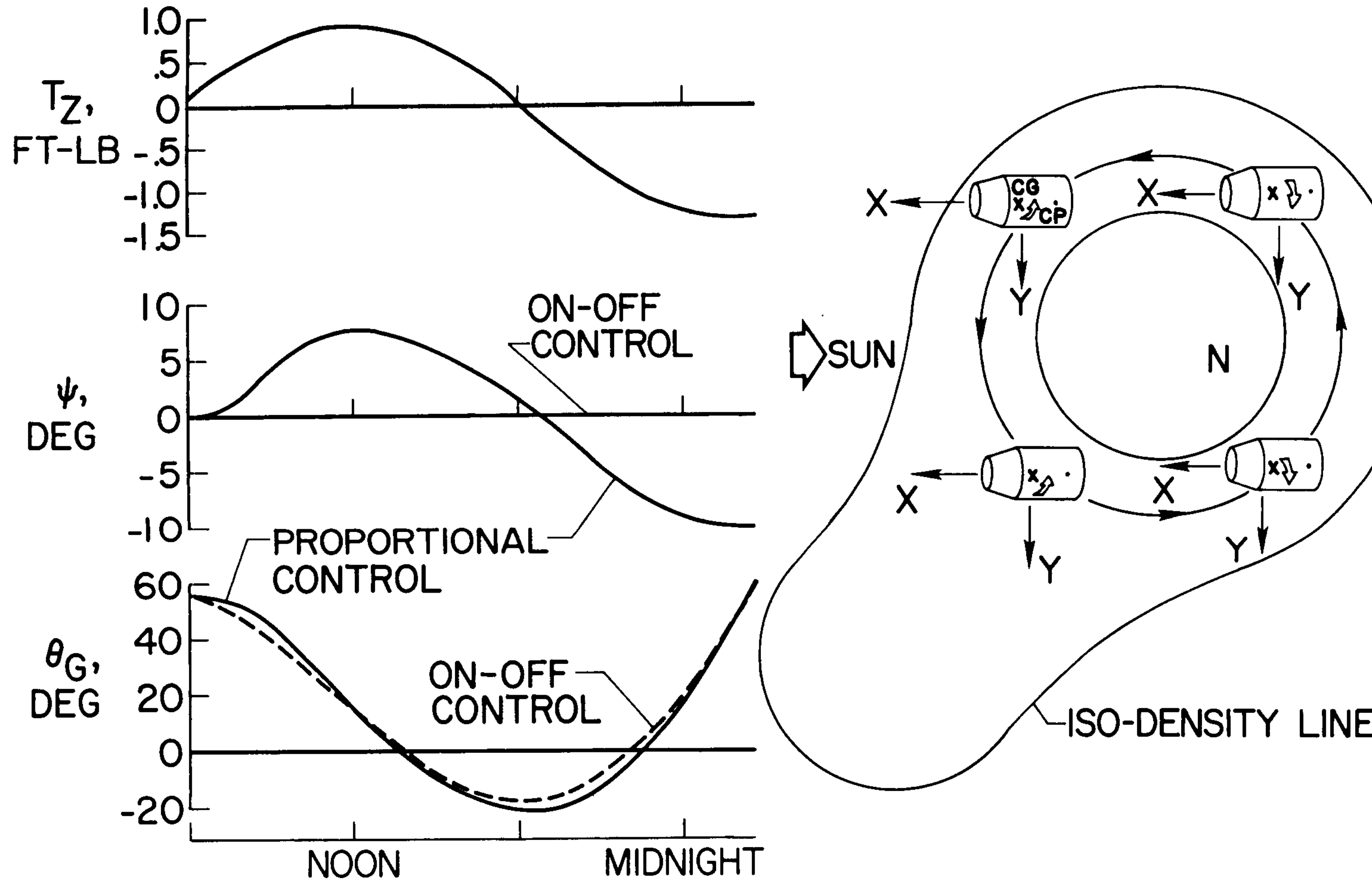

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Figure 7.- Laboratory control with aerodynamic and gravity gradient disturbances.

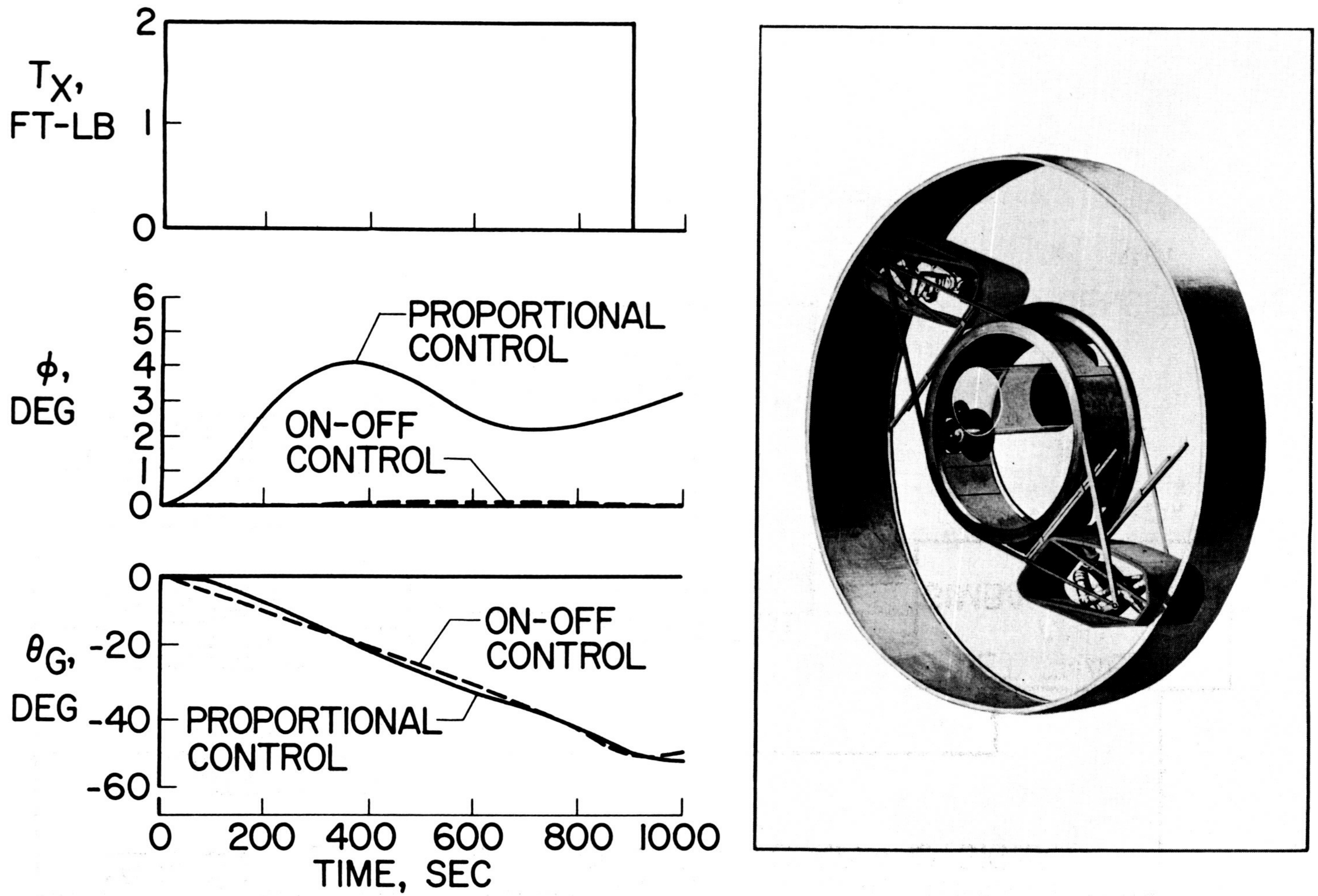

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Figure 8.- Laboratory control with centrifuge operation.

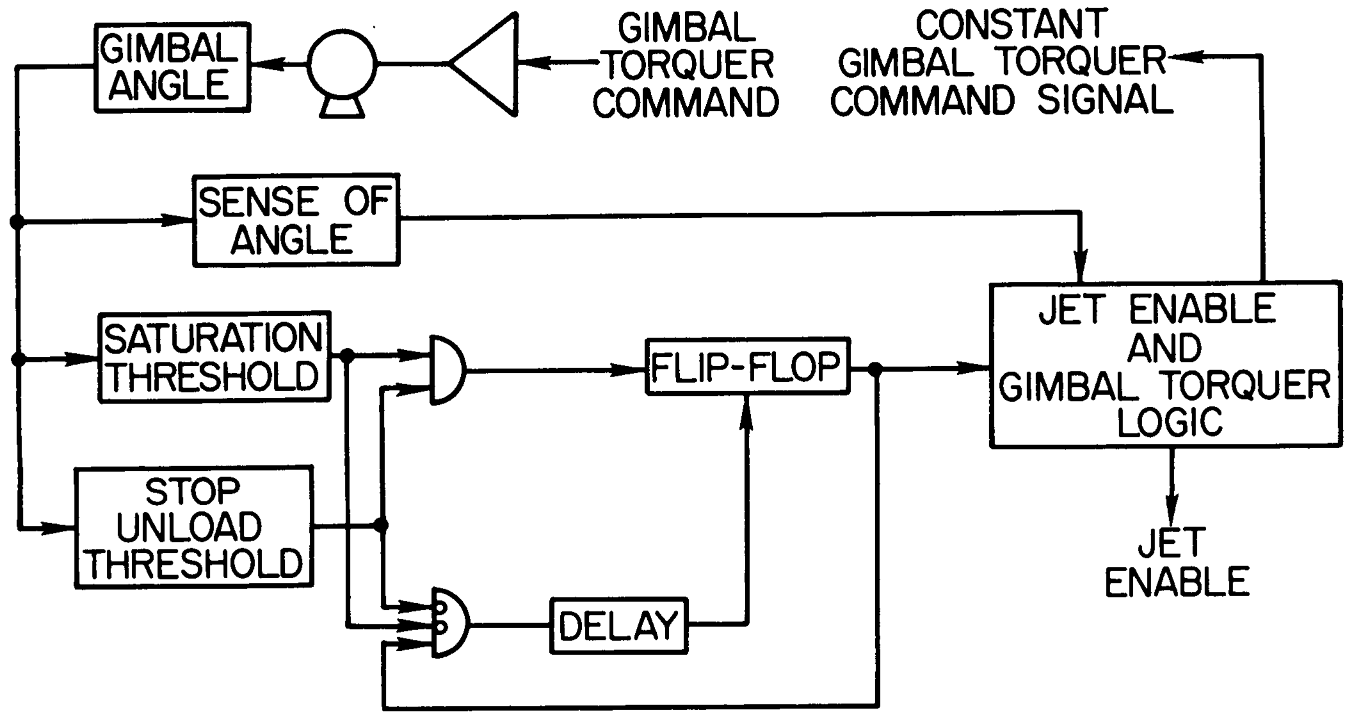

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Figure 9.- Schematic of differential desaturation system.

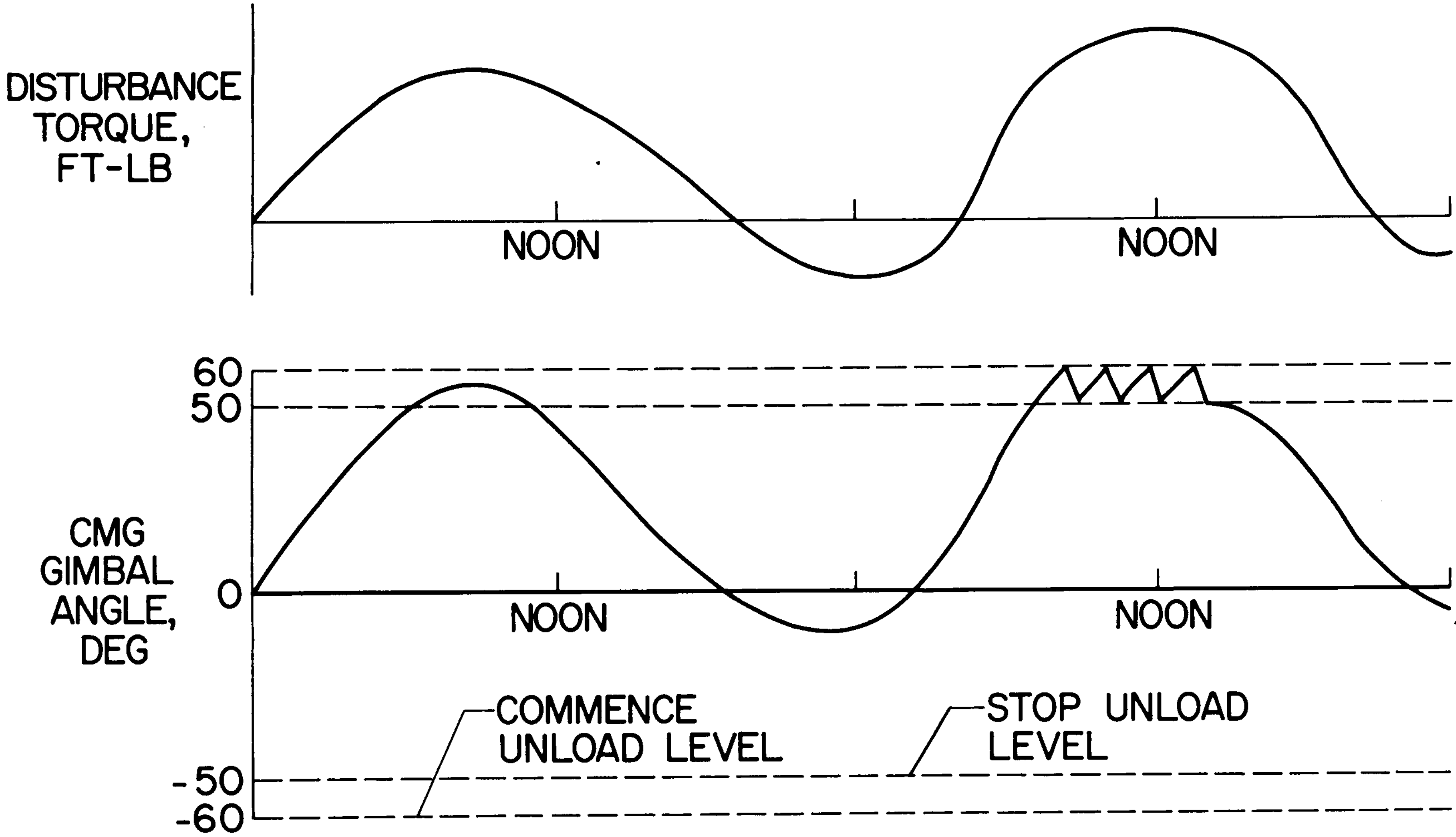

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Figure 10.- Sketch of gimbal angle response during differential desaturation.

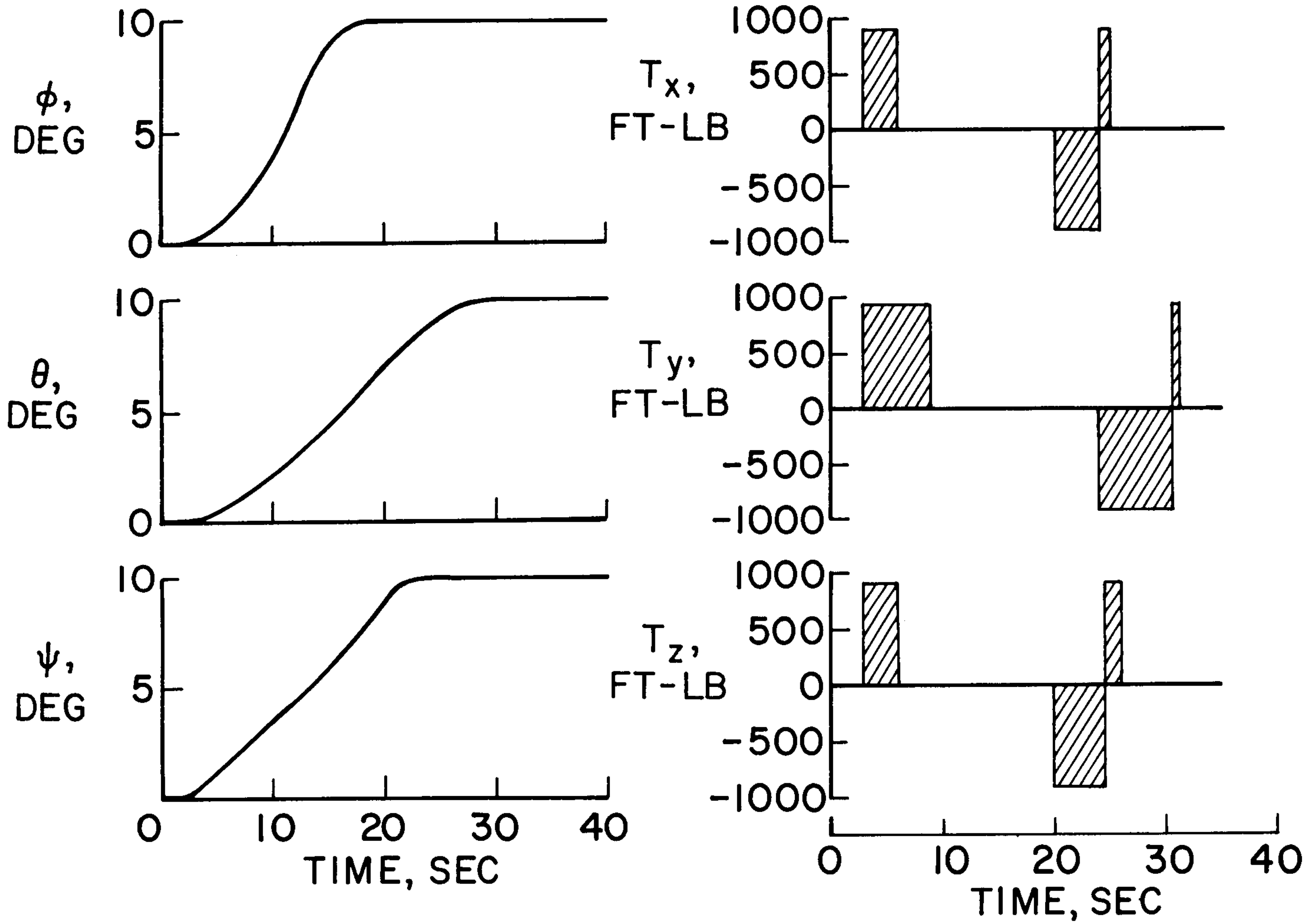

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Figure 11.- Three-axis laboratory maneuver with reaction control system.

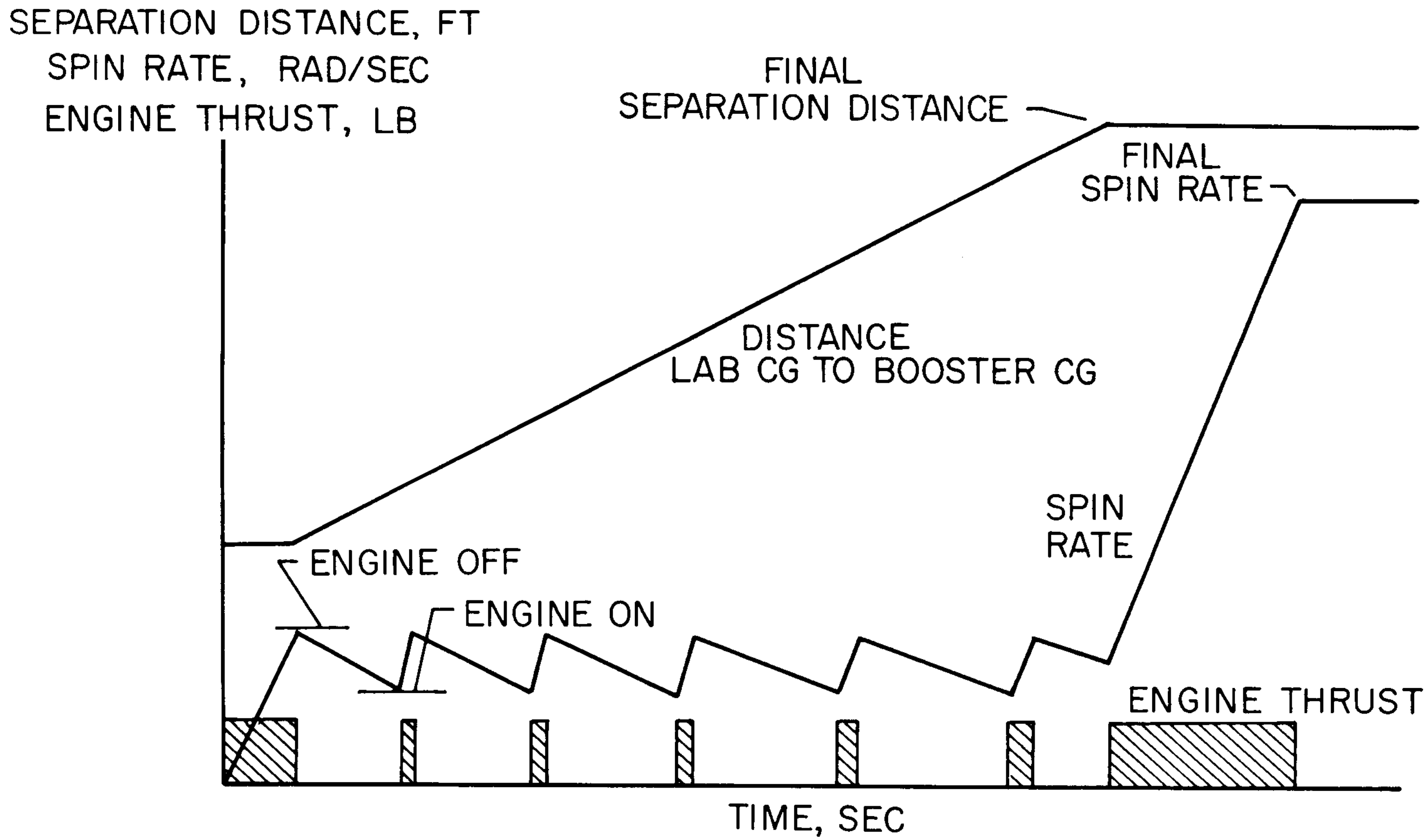

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Figure 12.- Schematic of spin-up operation.

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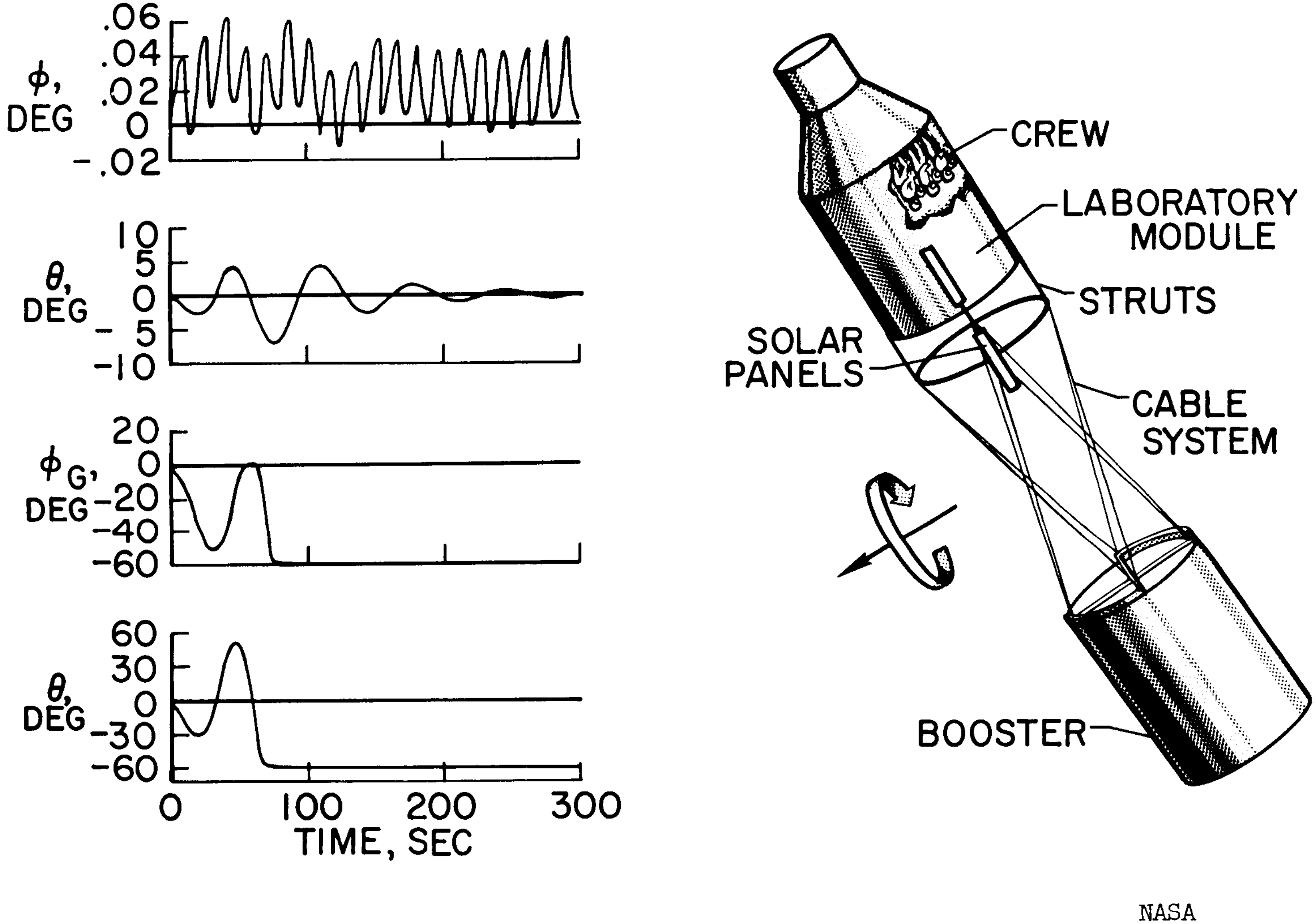

Figure 13.- Laboratory control for an instantaneous view motion.