APOLLO SPACECRAFT CONTROL SYSTEMS

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ABSTRACT

The overall Apollo spacecraft configuration includes two separate manned spacecraft. They are the command module designed for earth launch and reentry and cislunar flight including lunar orbit, and the lunar excursion module designed for the excursion from lunar orbit to the moon's surface and return. Each spacecraft has its own independent guidance and control system. This paper describes the Apollo spacecraft control systems including engine control and rocket engine configurations for attitude control. The Apollo guidance systems are not discussed.

INTRODUCTION

The purpose of this paper is to describe the automatic control systems employed for maintaining attitude control over the Apollo spacecraft. The Apollo spacecraft is a modular design and is defined as that part of the Apollo space vehicle which sits atop the Saturn launch vehicle and which is separated from the launch vehicle after injection into a translunar trajectory, in the case of a lunar mission, or into an earth orbit, in the case of an earth-orbital mission. The Apollo space vehicle is defined as the total configuration at launch. Fig. 1 illustrates the Apollo space vehicle, except for most of the Saturn launch vehicle which has been deleted to show more detail of the spacecraft.

The launch escape assembly houses a system of solid-fuel rockets which is employed to separate the command module from the rest of the space vehicle if it is necessary to abort the mission during the atmospheric phase of the launch trajectory. The abort maneuver is passively stabilized, and no control system is employed. In normal missions, the launch escape assembly is jettisoned after the space vehicle has left the atmosphere.

The command module houses the three-man crew during the entire mission, except for the excursion trip from lunar orbit to the moon's surface and return which is accomplished with the lunar excursion module. The command module, which also provides protection to the crew against reentry heating and acceleration, has a system of hypergolic rocket engines for three-axis control during the final earth entry phase of the mission. It also houses the command-service module guidance and control system which includes the sensing devices, electronics, displays, and controls which constitute the automatic and manual control systems for the spacecraft.

The service module houses the service propulsion system and the major support elements for providing environmental control and electrical power for the spacecraft. The service propulsion system includes a gimballed engine which provides the major velocity corrections for changing the trajectory after separation from the launch vehicle, and a system of hypergolic rocket engines similar to those on the command module for providing three-axis attitude control and vernier translational control for the spacecraft.

The lunar excursion module (LEM) which houses a two-man crew separates from the command-service module (CSM) in lunar orbit for the excursion trip to the moon's surface and return. The LEM employs a descent engine, which is staged on the moon's surface, an ascent engine, and a system of hypergolic rocket engines similar to those on the CSM for three-axis attitude control and vernier translational control. The LEM has its own independent guidance and control system including sensors, electronics, displays, and controls.

The Saturn instrument unit is a part of the Saturn launch vehicle and contains the Saturn guidance and control system which controls the space vehicle during all the boost phases of the mission. The guidance system in the command module provides data to the crew for monitoring the performance of the Saturn guidance system. The command module system is also capable of providing the steering signals to the Saturn control system as a back-up to the Saturn guidance system. While coasting in earth parking orbit the crew in the command module can also provide attitude control commands to the Saturn control system. Neither the Saturn control system nor the monitoring and steering interfaces of the command module system with the Saturn system are discussed in this paper.

MISSION PROFILE

A summary of the several phases of the Apollo mission is shown in Fig. 2. The Apollo space vehicle is launched into earth orbit (1) under the control of the Saturn launch vehicle and its separate guidance and control system as described above. The space vehicle coasts for one or more orbits (2) until the correct position for launching into the translunar trajectory is reached. Upon completion of the translunar injection boost phase (3), which is accomplished in the same manner as the earth orbit injection, the CSM separates from the space vehicle, rotates through 180°, and docks with the LEM which is still attached to the last launch-vehicle stage. The CSM and LEM separate from the launch vehicle and continue the mission alone. The necessity for this procedure can be seen by comparing Fig. 1 which shows the relative position of CSM and LEM at the end of translunar injection, and Fig. 5 which shows their position is readiness for the first midcourse correction maneuver which is to be executed as soon as practical after injection. The CSM service propulsion engine provides the thrust for that maneuver.

A maximum of three midcourse maneuvers (4) is planned prior to reaching the vicinity of the moon where the spacecraft is inserted into a circular orbit around the moon (5). After an appropriate number of orbits, the LEM with a crew of two separates from the CSM and maneuvers into a transfer orbit (6) which will take it near the moon's surface. As the surface is neared the descent engines are started, and the final powered descent and landing (7) is made on the surface of the moon. At the prescribed time the LEM, using the ascent engine, is launched from the moon's surface (8) into a lunar orbit along an intercept trajectory with the CSM. One or more additional maneuvers are performed (9) to bring the LEM into position with the CSM so that docking can be accomplished.

When the crew of three men has once again been assembled in the CSM, it is separated from the LEM and at the appropriate time is injected into a transearth trajectory (10) leaving the LEM in lunar orbit. The necessary midcourse correction maneuvers are made (11) as on the out-bound leg and, finally, the command module is separated from the service module and oriented for entry into the earth's atmosphere (12). During the atmospheric entry phase the command module is stabilized in two axes and maneuvered about the roll axis in order to direct the aerodynamic lift vector of the module in such a way as to achieve the desired landing site on the earth's surface. When the velocity has been reduced to a low value and the module is in essentially vertical fall, a parachute system is deployed to achieve a landing.

OVERALL BLOCK DIAGRAMS

The overall guidance and control block diagram for the CSM is shown in Fig. 3 and that for the LEM is shown in Fig. 4. The early development flights in earth orbit will be accomplished with the CSM Block I configuration shown in Fig. 3a. All subsequent flights of the CSM including lunar missions will fly the Block II configuration shown in Fig. 3b. The similarity between the system concepts of the LEM and CSM is illustrated in Figs. 3b and 4. On the left side of the diagrams are depicted the controls and displays which comprise the interface between the crew and the automatic guidance and control systems. The displays for the CSM and LEM are designed to provide spacecraft attitude and rate information, velocity information, and other data tailored to the particular requirements of each spacecraft. Each spacecraft has a hand-controller for three-axis spacecraft attitude control by command inputs from the crew and a hand-controller for three-axis translational control of the spacecraft. There are several modes of control available to the crew through these hand-controllers including attitude-hold, rate-command, and open-loop acceleration control. No more detailed discussions of the displays and controls will be given in this paper.

On the right side of the block diagram of both CSM and LEM are depicted the engine controls and attitude-control engines which are the primary control elements for accomplishing two general classes of spacecraft maneuvers. These are orientation maneuvers in coasting flight and steering maneuvers in powered flight. In addition, there is a special class of maneuvering flight in the atmosphere in which orientation of the lift vector accomplishes the equivalent of steering the command module to control the reentry trajectory. The engine configurations are the same for CSM Block I and II, but the LEM configuration is somewhat different since the mission is different from that of the CSM. These will be discussed in more detail later in this paper.

The center portion of the block diagrams for CSM and LEM includes the sensors, electronics, and computation necessary to close the overall guidance and control loops. In the CSM Block II and the LEM there are two major systems, a primary guidance and control system and a stabilization and control system which is employed as a secondary channel of control available to the crew. With the back-up attitude reference the stabilization and control system is sufficient to allow the crew, with assistance from ground control systems, to bring the CSM safely back to earth in the event of primary guidance and control system failure. An abort guidance system is required to provide steering signals to the stabilization and control system for the LEM to enable the crew to abort the descent to the moon and steer back to the CSM in case of failure of the primary guidance and control system.

The primary difference between CSM Block I and Block II is that in Block I the two major systems are operated in series and in Block II they are operated in parallel. In the Block I configuration shown in Fig. 3a, the stabilization and control system (SCS) performs the primary control function, accepting steering error commands from the primary guidance system or from the crew controllers and sending signals to the gimbal-drive electronics of the service-propulsion engine and to the solenoid-control valves of the reaction-control system. In the Block II configuration shown in Fig. 3b, the primary guidance system is expanded by increasing computer capability to include the stabilization and control function. The guidance computer accepts inputs from the crew controllers and sends signals directly to the gimbal electronics for the service-propulsion engine and to the driver-amplifiers for the reaction-control solenoid valves. The SCS becomes a parallel back-up system available to the crew. The link between the primary guidance computer and the SCS retains the option for series operation of the two major systems. The remainder of the paper is concerned with the stabilization and control systems of the CSM and the LEM and with the engine control and attitude-control engine configurations. The primary guidance and control system is not discussed.

CONTROL CONFIGURATIONS

In this section the right-hand portions of the overall block diagrams of Fig. 3 and Fig. 4 are discussed. These are the primary control elements for accomplishing spacecraft maneuvers. They are employed with both the SCS and the primary guidance and control system. Two classes of engines are discussed: the main rocket engines for developing the thrust necessary for accomplishing major maneuvers for changing the spacecraft trajectory, and the small reaction-control engines for developing the control torques necessary for controlling the attitude of the spacecraft. The command module has 12 reaction-control engines. The service module has 1 large rocket engine and 16 reaction-control engines. The LEM has 2 large rocket engines, 1 for descent and 1 for ascent, and 16 reaction-control engines. The reaction-control engines for the LEM and service module are also employed to obtain vernier translational control.

There are some general statements that can be made about the engines before going into particular configurations. All are hypergolic rocket engines designed for multiple starts. They employ hydrazine and nitrogen tetroxide or variations thereof as fuel and oxidizer. All of the reaction-control engines are very similar in thrust level and other design features. Those on the command module require special attention with regard to cooling. The reaction-control engines are solenoid-controlled to provide off-on thrust control. The total of the hypergolic chemical reaction time and the electro-mechanical response time of the solenoid valves and driver is very short; therefore, very short control pulses can be obtained. For this reason very good limit-cycle performance can be achieved in the control loops.

In the remainder of this section the control configurations will be discussed for the command-service module combination both with and without the LEM attached, the command module alone, and the LEM alone.

Command-Service Module Configuration - There are two CSM control configurations, the CSM with LEM attached (Fig. 5) and the CSM alone (Fig. 6). As described above, the service module employs 1 large rocket engine for performing the major thrusting maneuvers and 16 small attitude-control engines which make up the reaction control system. The reaction control system is employed for three-axis attitude control, three-axis translational control for docking, ullage for the service propulsion system, and vernier control for midcourse corrections and separation of various stages. As illustrated in Fig. 5 the reaction control system includes four hypergolic rocket engines in a quad arrangement located at four stations around the sides of the service module. Fig. 5a illustrates how the engines are employed for three-axis attitude control in coasting flight. The engines are normally fired in pairs to produce control couples in pitch, yaw, and roll. There is a redundant pair of roll engines. A partially redundant control capability exists for the pitch and yaw axes since the engines can be employed singly with only minor degradation in performance.

Fig. 5b illustrates the operation of the service propulsion engine for performing the major thrusting maneuvers such as lunar orbit insertion, transearth injection, and cislunar midcourse corrections. This engine operates at constant thrust level and is designed for multiple starts. The engine assembly is gimbal-mounted and controlled by electro-mechanical servo actuators to achieve pitch and yaw control while thrusting. The gimbal drive servo consists of a constant speed motor driving a gear train and two magnetic-particle clutches for driving the gimbals in the positive and negative directions. The servo loop incorporates both position and velocity feedback for gimbal position control. There are two complete servo loops for each axis to provide parallel redundancy. Roll control while thrusting is obtained from the service module reaction control system as illustrated in Fig. 5b. Two roll engines are shown operating, but all four roll engines may be operated at the option of the crew. Special provisions will also allow the use of only one roll engine when desired. The need for this occurs when taking navigation sightings under conditions of low inertia. In pitch and yaw a special sequence is followed when a thrust maneuver is initiated. The pitch and yaw reaction control engines are disabled 1 second after ignition of the service propulsion engine to prevent transients during thrust buildup and to conserve fuel. The gimbal servo-actuators are turned off 1 second after engine cutoff to prevent transients during thrust decay.

Fig. 6 illustrates the operation of the reaction control system to achieve three-axis translational control. The engines are operated in pairs in order not to induce disturbing moments. For translation along the longitudinal axis, either two or four engines can be employed at the option of the crew. There is no redundancy afforded for lateral translation except by rolling through 90°.

Command Module Configuration - Fig. 7 illustrates the configuration of reaction control engines required to provide three-axis attitude stabilization and control for the command module. Two completely independent systems are provided for parallel redundancy. The center of gravity of the command module is off-set from the axis of symmetry to cause the reentry body to assume an aerodynamic trim angle with the relative wind. The resulting lift is employed to control the reentry trajectory so that the desired landing site can be reached. This is achieved by controlling the roll angle of the spacecraft during reentry. When the lift is directed downward, the trajectory steepens; when it is directed upward, the trajectory becomes shallow, and right and left roll angle causes the trajectory to curve in that direction.

Because the command module is at a constant angle of attack with respect to the relative wind, one side of the module experiences much more heating and is unsuitable for locating control engines. As shown in Fig. 7 they are all located in the upper half of the conical section of the module. No attempt is made to provide control couples. It is very difficult to position the rocket engines without introducing excessive inter-axis coupling.

LEM Descent Configuration - The LEM descent configuration illustrated in Fig. 8 employs a single hypergolic engine for achieving the necessary thrust for the descent and landing maneuver. The engine is throttle-controlled over a wide range of thrust to allow the capability for hovering above the surface of the moon. Although this engine is gimbal-mounted, as in the case of the service module, the gimbal actuators are very different. The LEM descent-engine gimbal actuators are employed only as a relatively slow-acting trim loop. The main control loop is closed, utilizing the small rocket engines of the LEM reaction control system. The gimbal actuators are screwjacks driven by a reversible constant-speed motor which is operated in an off-on mode.

The LEM reaction control system (Fig. 8) is made up of four sets of engines fixed to the spacecraft with four engines at each location. The engines are located on axes rotated 45° in roll from the spacecraft axes. They are operated as control couples for three-axis attitude control. As can be seen in Fig. 8 two pairs of control couples are available for each axis. At the option of the crew, both pairs may be selected to provide double control authority. The method of providing translational control while in the hovering condition is to tilt the spacecraft by means of the attitude control system. This produces a lateral component of acceleration from the descent engine thrust in the desired direction which is stopped by returning to vertical and reversed by tilting in the opposite direction.

LEM Ascent Configuration - The LEM ascent configuration illustrated in Fig. 9 employs a single rocket engine of constant thrust for achieving the launch ascent. The engine is fixed, and attitude control is obtained by the reaction control system as described for the descent configuration. The control power is sufficient without the necessity for the main engine trim feature. In the ascent configuration, attitude control is obtained as in the descent configuration except that all of the engines pointing upward are disabled. This allows all the downward-firing engines to augment the ascent thrust. The fuel saving for ascent propulsion more than offsets the extra fuel burned as a result of cross-coupling which this introduces. In case of failure of an engine, normal operation is resumed. Fig. 9 illustrates how the same reaction control system is employed for three-axis translational control to achieve final rendezvous and docking with the command module. The operation is essentially the same as that employed for the CSM.

SCS FUNCTIONAL DESCRIPTION

In this section the SCS systems of the CSM and LEM are discussed. The general requirements for both systems are the same. Attitude control is required under conditions of large disturbance torques (during thrusting maneuvers); attitude control is required under conditions of very small disturbance torques (during coasting flight); provisions are required for accurate control (narrow dead band) to meet certain maneuver requirements (for example, LEM attitude control while main engine is thrusting); provisions are required for coarse control (wide dead band) to provide stabilization economically for long periods of time; provisions are required to achieve the ultimate capability of the reaction control engines to deliver a small impulse in order to assure that limit-cycle periods during long duration coasting flights are economical; and provisions are required for control to be exercised by the crew under various conditions of automatic assistance by stabilization loops. However, the configurations of the spacecraft, the engine configurations and the missions are different, and the SCS mechanizations to meet these requirements are different for each spacecraft.

Before describing the individual systems some remarks are in order concerning the design of space stabilization systems employing reaction control engines which operate in an off-on mode. The characterizing feature of such a system is that a large dynamic range is required. Control for maneuvering and control against relatively large disturbance torques require a high gain or effective control power. To provide economical long-term limit-cycle stabilization in the presence of extremely small disturbances requires small vernier control capability. It is desirable, therefore, to employ a control logic which provides off-on control in the classical sense when large control gain is required and which meters out small control impulses to achieve low-rate limit cycles in the presence of small errors. As stated previously the Apollo reaction control engines have a very short response time permitting low impulse operation. Therefore attention to the control logic has large potential benefit to the system operation. Two different principles are employed in the CSM and LEM to achieve essentially the same result. Each transforms the input signal to a series of width and frequency-modulated pulses which drive the solenoid control circuitry. In the CSM the technique is called pseudo-rate logic; in the LEM it is called pulse-ratio modulation. These two techniques will be described in more detail in the paragraphs to follow.

CSM - The SCS functional diagram for the CSM is illustrated in Fig. 10. The control loops for the reaction control engines and for the service propulsion gimbal drive actuators are functionally independent. The latter is called the thrust-vector control loop since it is employed for all major thrusting maneuvers. The primary mode for thrust vector control, as illustrated in the lower half of Fig. 10, has the loop closed to hold a constant attitude in space. A manual gimbal trim capability is provided to aline the engine thrust axis with the estimated position of the spacecraft center-of-gravity prior to initiating thrust. Rate gyro feedback is employed, and filtering and gain adjustment are provided to accommodate the large differences in inertia and bending frequencies between the configuration with LEM attached and CSM alone. Gimbal position is integrated and summed with the attitude error in order to reduce the error in pointing the thrust vector which results from lateral shifts of the center-of-gravity. This technique is employed in the interest of simplicity since it is a back-up mode. The primary guidance and control steering loop is not subject to this error. The gimbal-drive actuator servo loop was described in a precious section. By inputs from the attitude controller the crew can control this loop employing visual reference either by direct control of the gimbal-drive servo loop or with assistance by closing the rate gyro feedback loop.

The reaction-control engine loop is illustrated in the upper half of Fig. 10. Attitude error and rate gyro feedback are provided in the same manner as in the thrust-vector control loop. The attitude error is limited in order to limit the maximum maneuver rate in the interest of fuel economy. The output of the attitude controller is limited for the same reason when the crew exercises manual control. The attitude dead band is selectable at either $\pm 5^\circ$ or $\pm 1/2^\circ$. The switching amplifier and pseudo-rate logic provide an off-on pulse to the engine-select logic in response to the analog error signal input. The principle of operation of pseudo-rate logic is illustrated in Fig. 11. This technique, sometimes called derived-rate increment stabilization(1), has been employed in other space stabilization applications. The on-off output of the switching amplifier controls the thrust of the reaction control engines and, therefore, in an idealized system, is proportional to vehicle angular acceleration. When this signal is feed back through the lag network, the feedback in a short period sense is proportional to angular rate, hence the name pseudo or derived rate. The gain and time constant of the lag network are selected to provide the desired signal for an average spacecraft inertia. When the switching amplifier is closed, the feedback signal builds up until, through the hysteresis loop of the dead band, it is opened again, thereby shaping the pulse to the solenoid control valve. The hysteresis loop is set to obtain the desired thrust impulse for limit cycling. During reentry and during manual maneuvers the pseudo-rate feedback is switched out to prevent an overdamped response.

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(1) Superior numbers refer to similarly numbered references at the end of this paper.

The control pulse enters the engine select logic which also accepts signals from the translation controller. The function of the logic is primarily to provide isolation of the jet driver circuits to prevent undesirable electrical interaction. The solenoid drivers apply a fixed voltage to the engine control solenoid valves. The circuit is designed to suppress inductive spikes at turn-off. The solenoid control valves of both command module and service module reaction control system have a primary and a secondary coil. The primary coil provides the normal driving force. The secondary coils are connected directly to the translation and attitude controllers and are powered from the battery bus.

LEM - The SCS functional diagram for the LEM is illustrated in Fig. 12. The loop is closed in a conventional manner about attitude error and rate gyro feedback. The attitude error is limited for the same reason as stated for the CSM. The loop error is introduced to a separate assembly mounted on the descent stage. This is the descent-engine gimbal trim function which is left with that stage when the LEM is launched from the moon. The trim function was described in an earlier section. As in the case of the CSM, the LEM SCS provides a narrow dead band and a wide dead band. They are ±0.3° and ±5°, respectively.

The combinational logic for the LEM provides, in addition to the isolation function of the CSM engine logic, the necessary logic circuitry to select the proper combination of engines to be fired to achieve the desired torque. This is required because of the 45° engine configuration described earlier. Each engine is capable of producing torques about two axes. The combinational logic selects the desired engines to perform either rotation or translation about any axis without firing opposing engines. From the combinational logic the signal goes to the pulse-ratio modulator which produces the off-on control signals which drive the solenoid control valves. The solenoid drivers and control valves work in the same fashion as described for the CSM except that the translation controller is not connected to the secondary coils of the solenoid valves. This emergency translation feature is provided in the positive longitudinal direction only and is controlled from a panel switch.

The pulse-ratio modulator (PRM) is so named because the input signal controls the duty ratio of the pulse train(2). The resulting performance can be similar to that obtained from proportional control. Fig. 13 illustrates the switching characteristics of the PRM in comparison with off-on control. PRM introduces an interim range of values of attitude error between that required to exceed the dead band and that required for full "on" control. The linear PRM characteristic gives a proportional relationship between duty ratio and attitude error. The PRM for the LEM SCS has a non-linear characteristic. PRM performance for LEM is illustrated in Fig. 14. The duty ratio varies nonlinearly with attitude error making the transition from small infrequent pulses to full off-on over a small range of errors. The minimum pulse width is approximately 10 milliseconds. The maximum pulse frequency is less than 6 pulses per second in the interest of reducing the number of cycles for the solenoid valves.

CONCLUSIONS

This paper has described in some detail the engine controls and attitude-control engines which are the primary control elements for accomplishing the maneuvers required of the Apollo spacecraft. The stabilization and control loops for the command-service module and the lunar excursion module have also been described. These loops comprise the back-up method of providing control to the crew for returning safely to earth in the event of failure of the primary guidance and control system.

NOMENCLATURE

CCW	counterclockwise
CSM	command and service module combination
CW	clockwise
LEM	lunar excursion module
K	gain
PRM	pulse-ratio modulation
SCS	stabilization and control system
T	time constant

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(2) Schaefer, R. A., A New Pulse Modulator for Accurate D.C. Amplification with Linear or Nonlinear Devices, IRE Transactions on Instrumentation, Volume I-11, No. 2, Sept. 1962, pp. 34-47.

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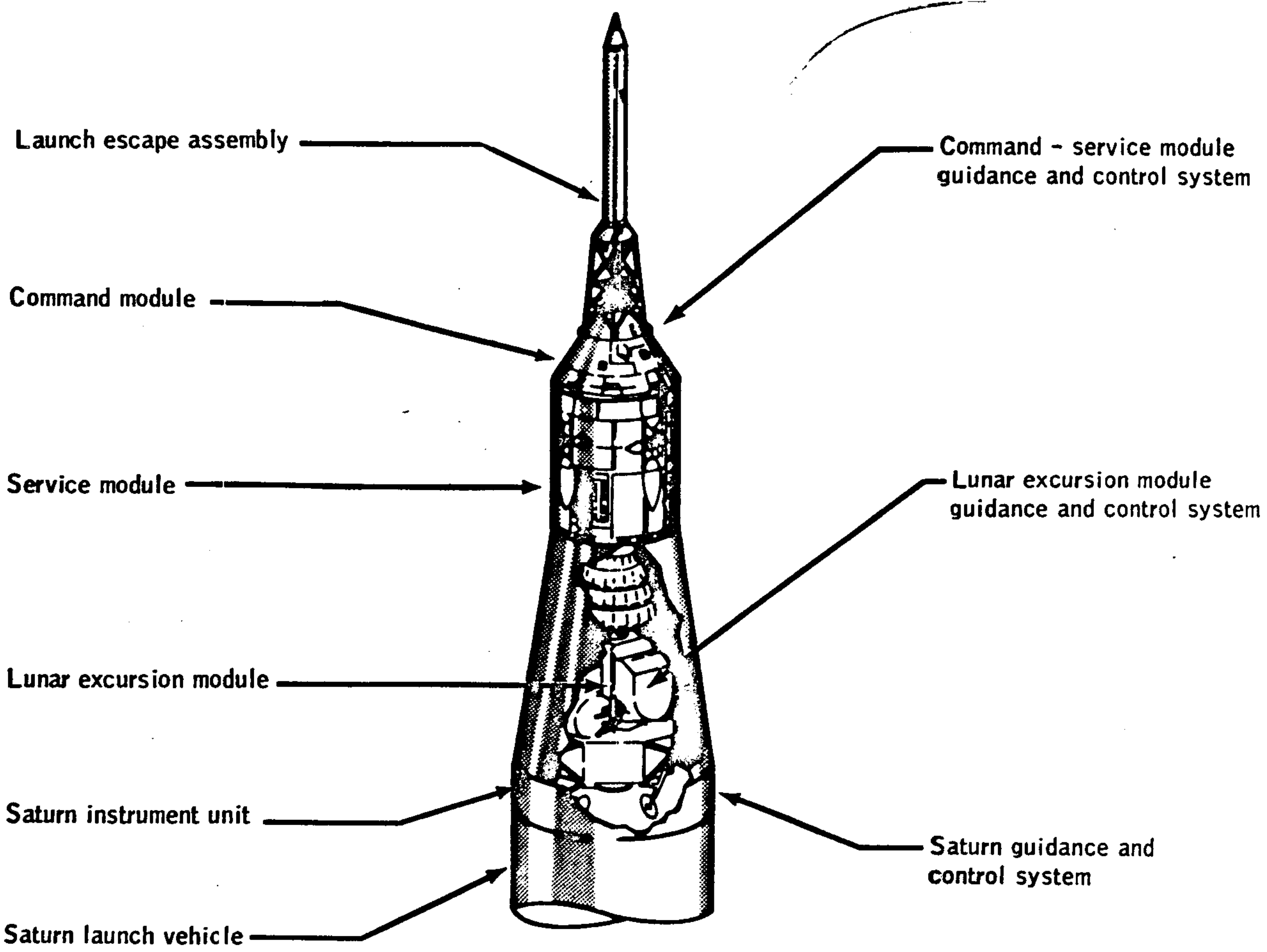

Figure 1 Apollo space vehicle

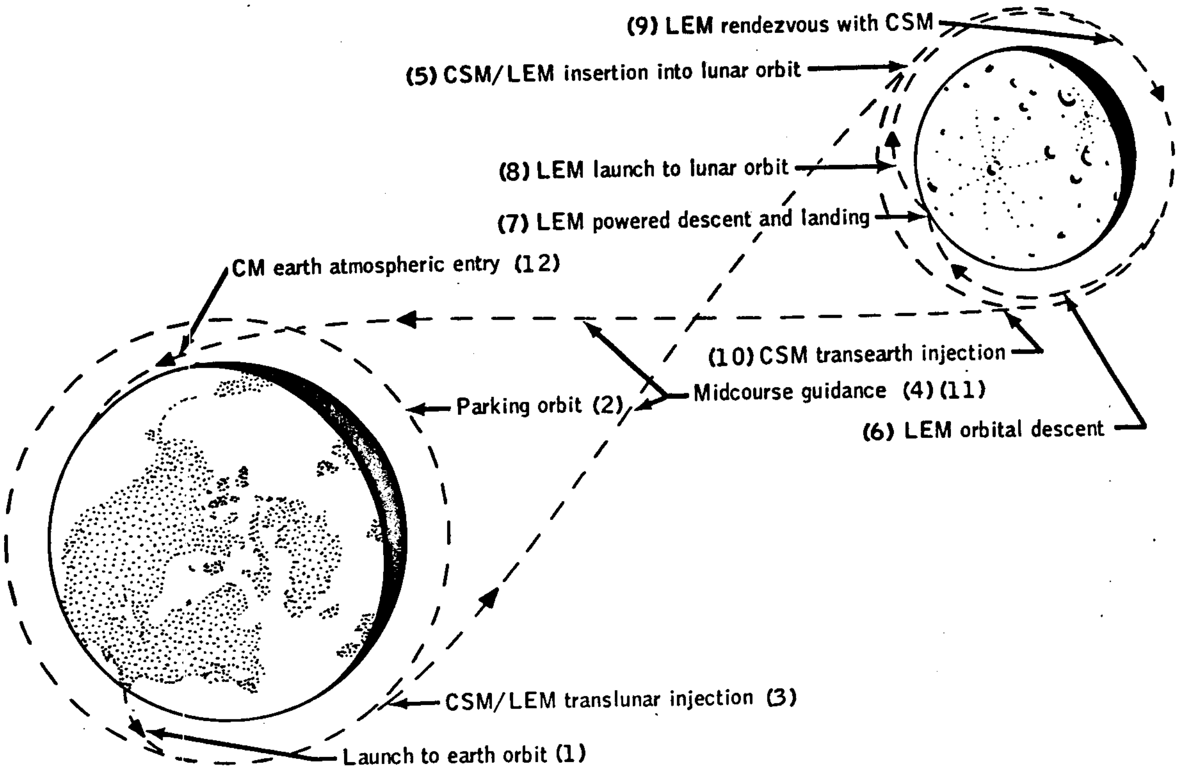

Figure 2 Mission phase summary

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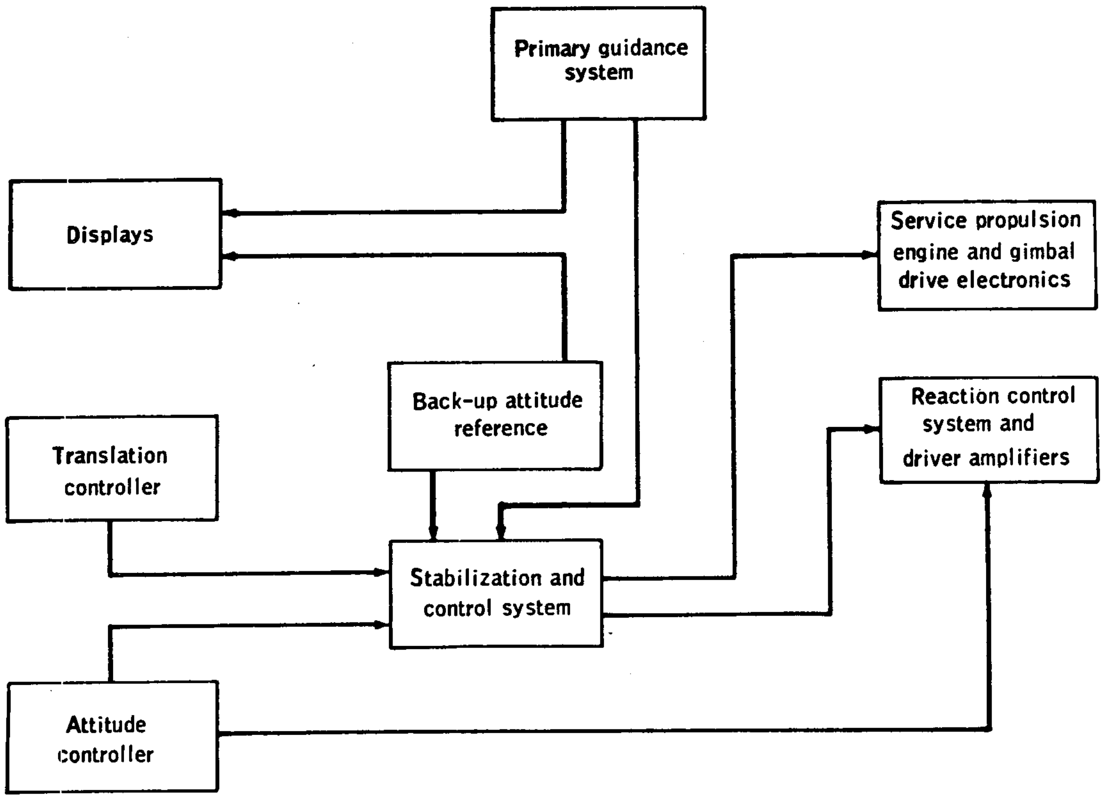

Figure 3. - CSM overall guidance and control block diagram

Part a. Block I configuration

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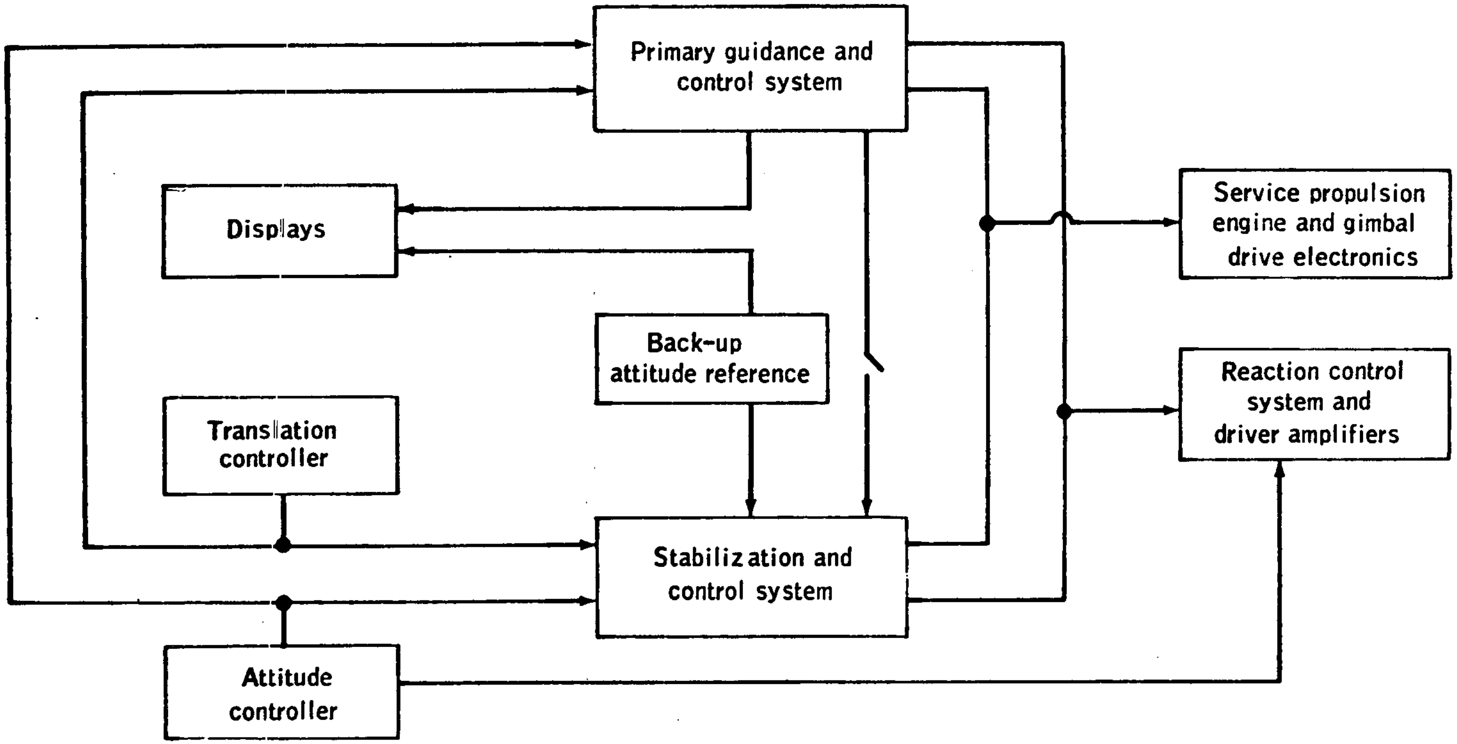

Figure 3. - CSM overall guidance and control block diagram

Part b. Block II configuration

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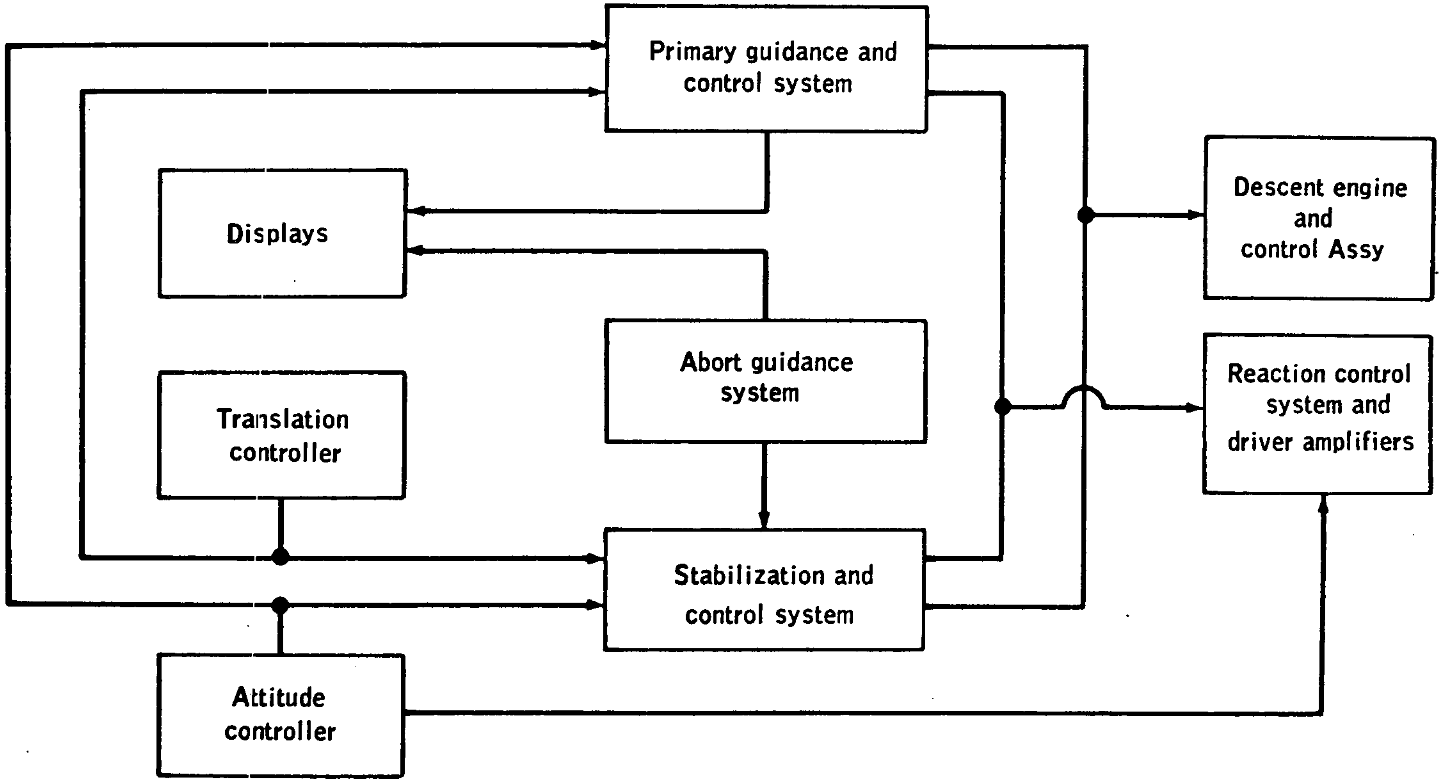

Figure 4. - LEM overall guidance and control block diagram

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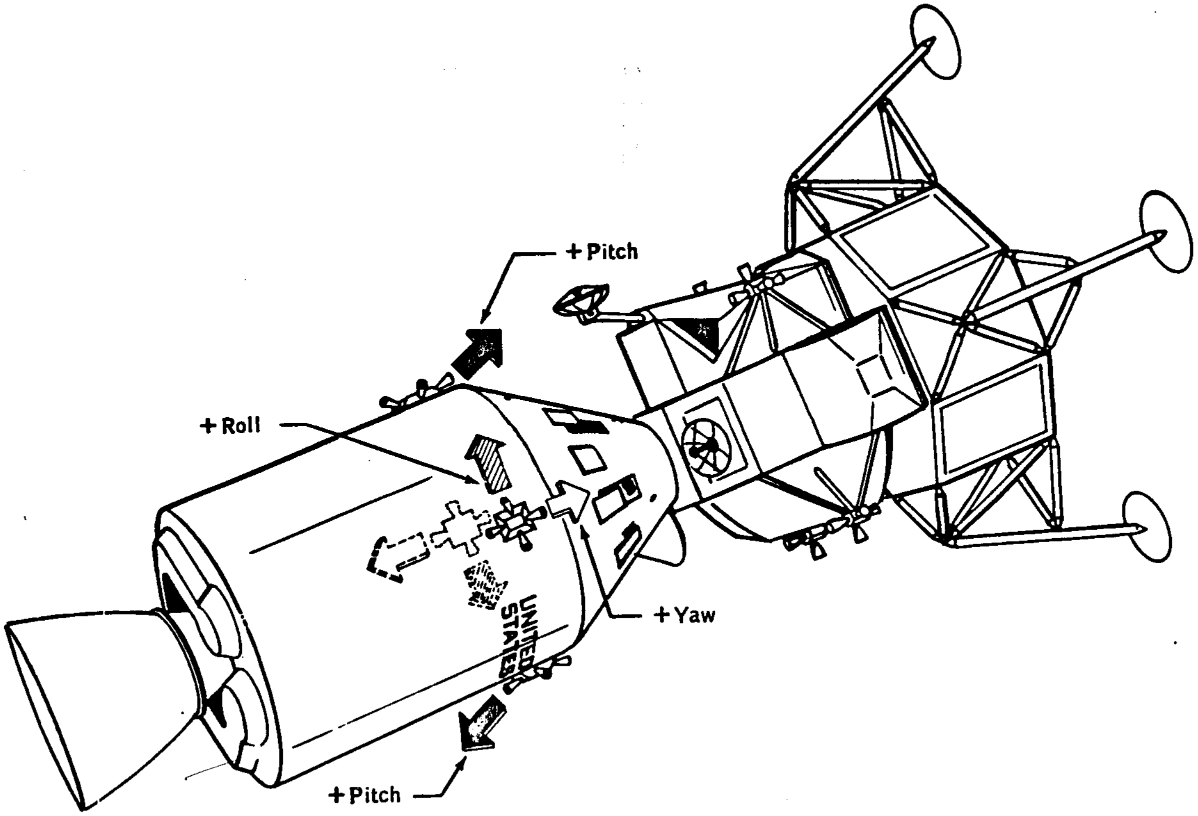

Figure 5 Attitude control of command-service module (with and without LEM)

Part a Coasting flight

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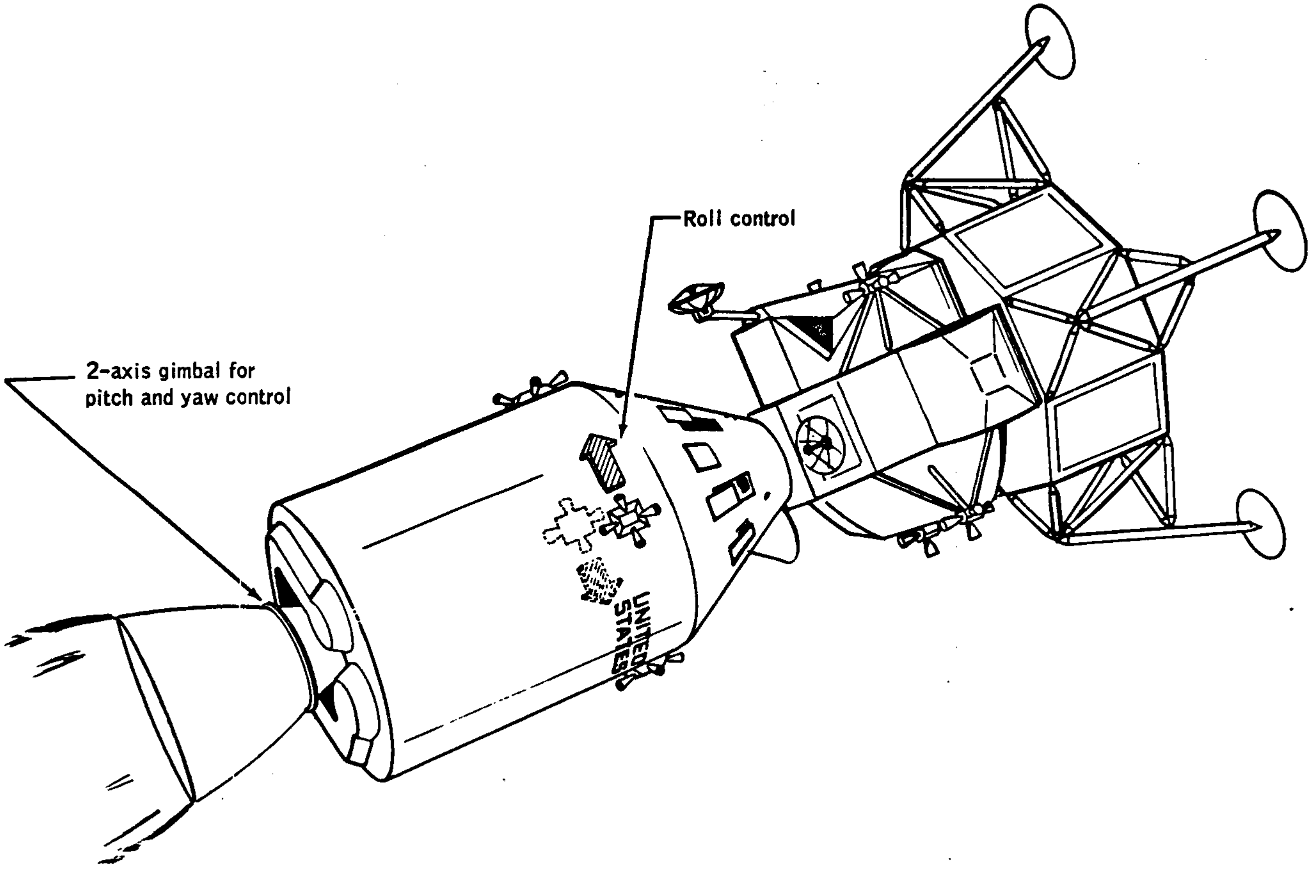

Figure 5 Attitude control of command-service module (with and without LEM)

Part b Service propulsion engine thrusting

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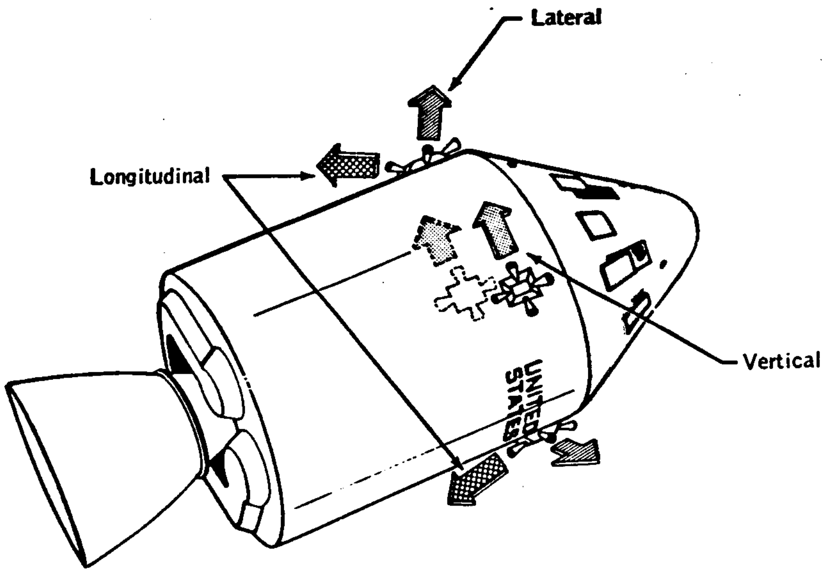

Figure 6 - Translational control of command-service module
(with and without LEM)

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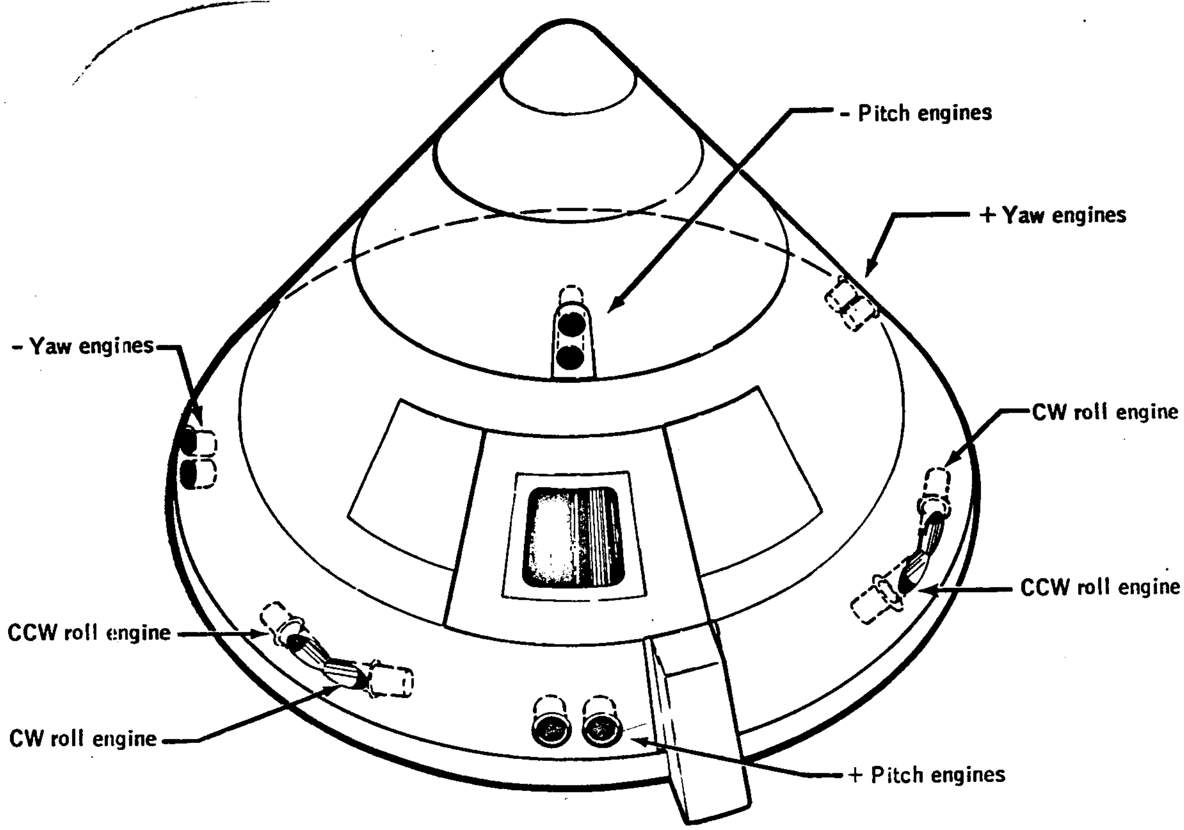

Figure 7   Command module attitude control

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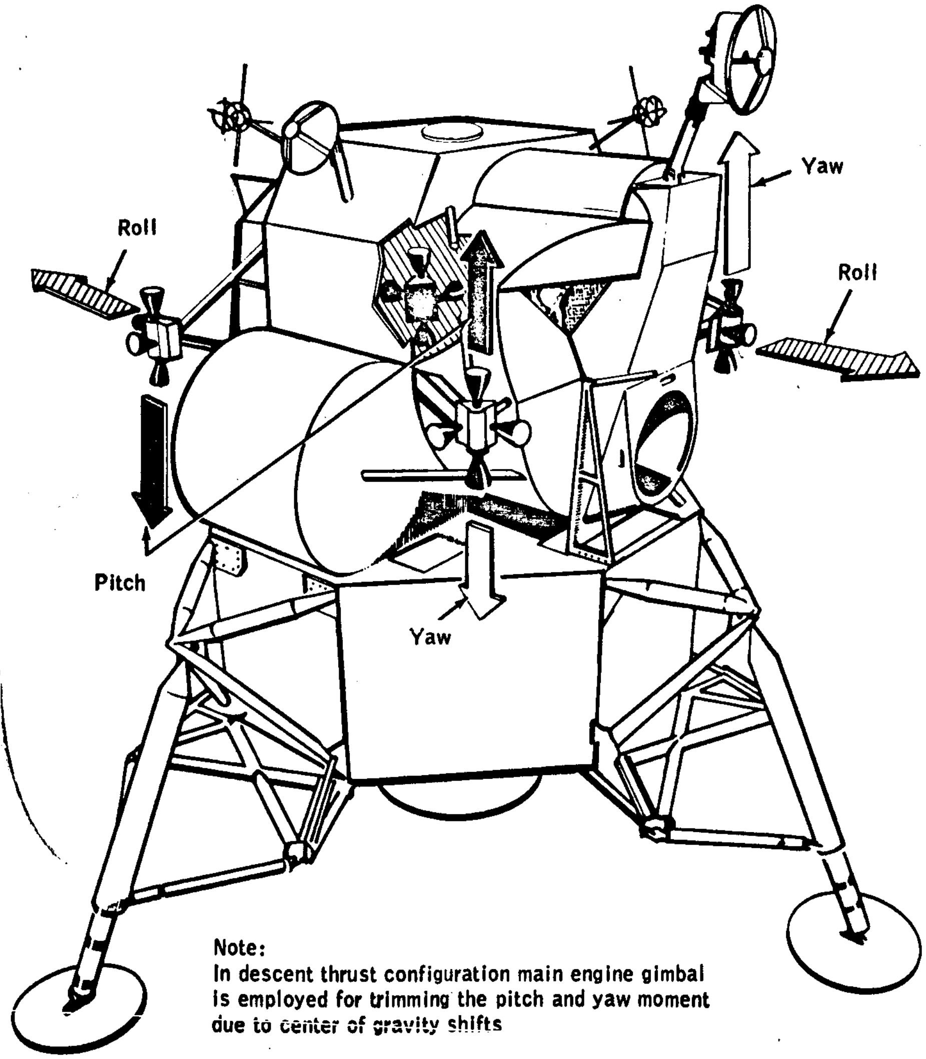

Note:
In descent thrust configuration main engine gimbal is employed for trimming the pitch and yaw moment due to center of gravity shifts

Figure 8 Attitude control of LEM (descent configuration)

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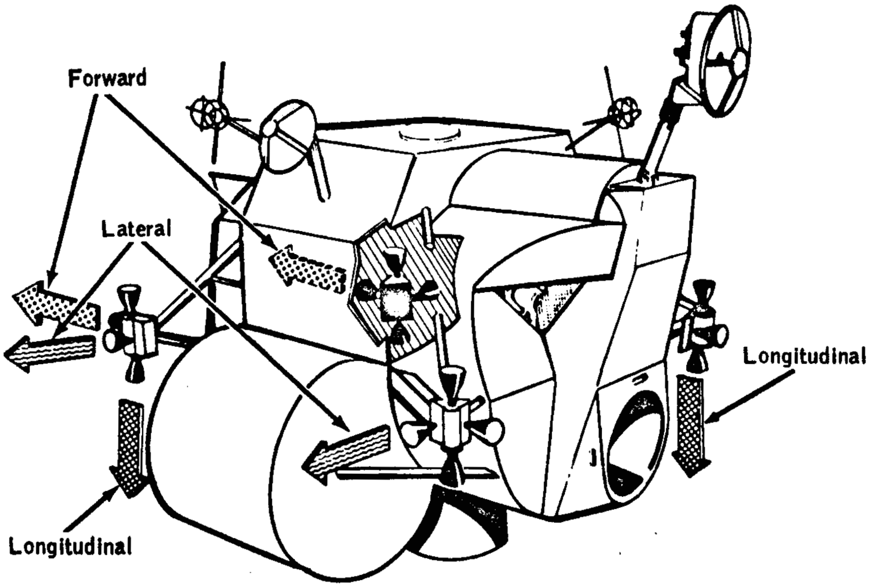

Figure 9 Translation control of LEM
(ascent and docking configuration)

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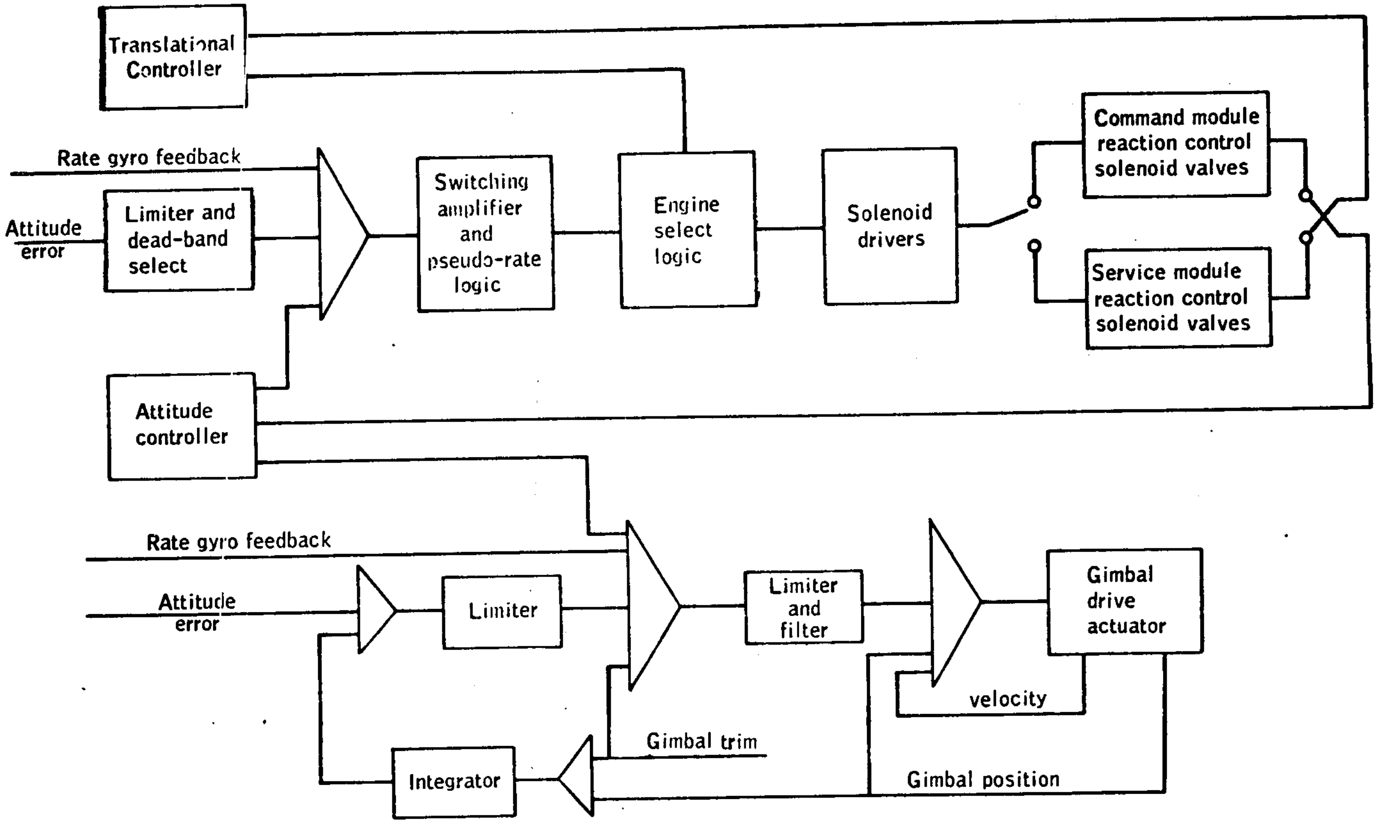

Figure 10. - CSM SCS functional diagram

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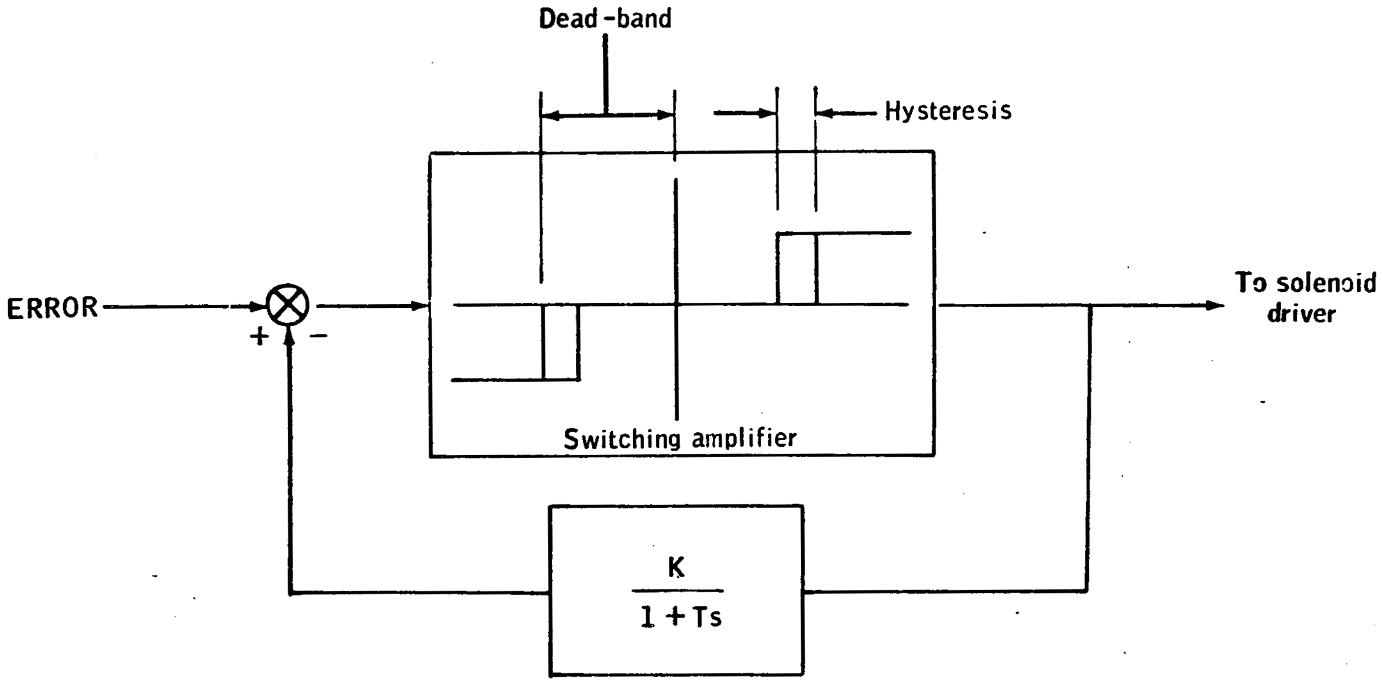

Figure 11 - Switching amplifier and pseudo-rate logic

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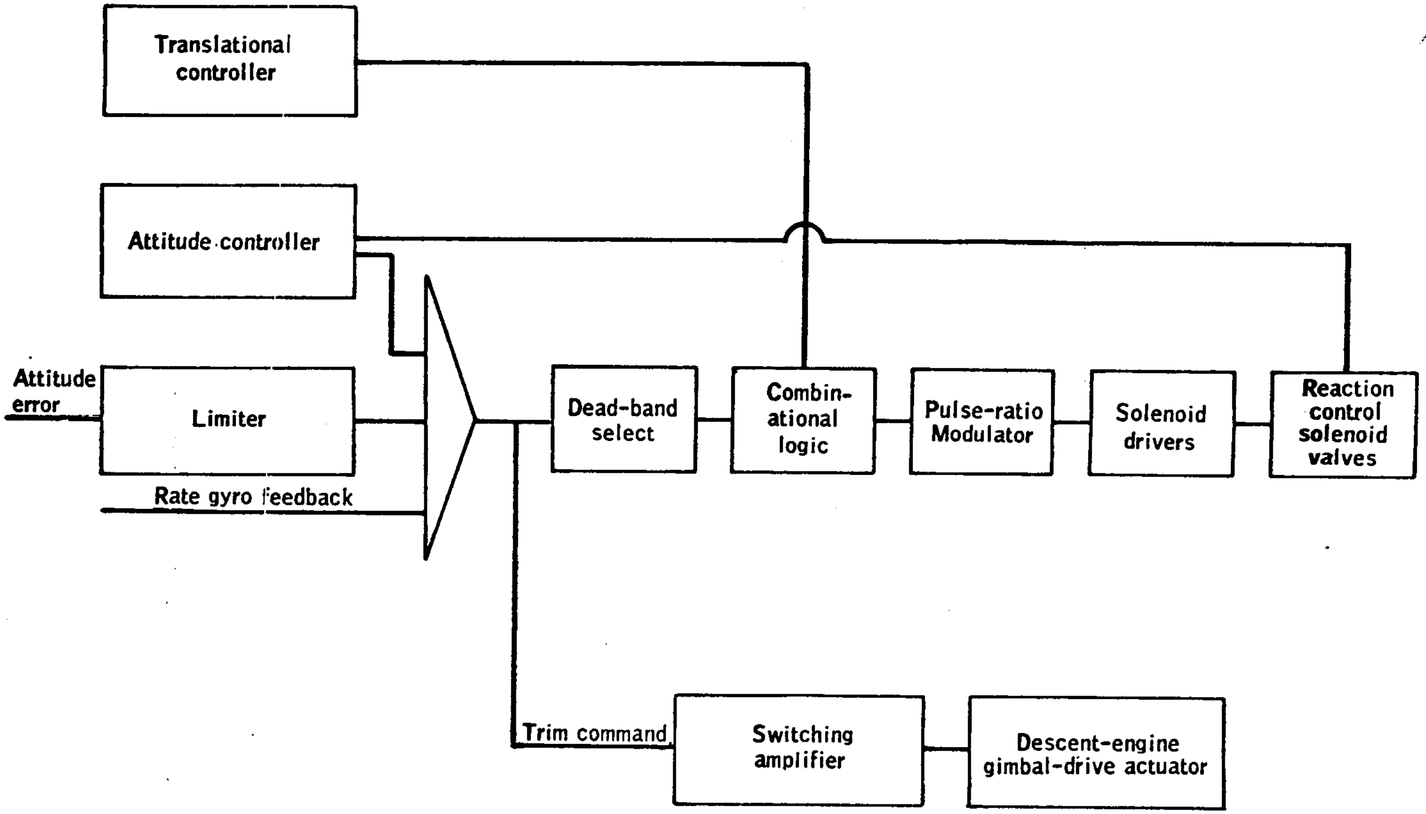

Figure 12 - LEM SCS functional diagram

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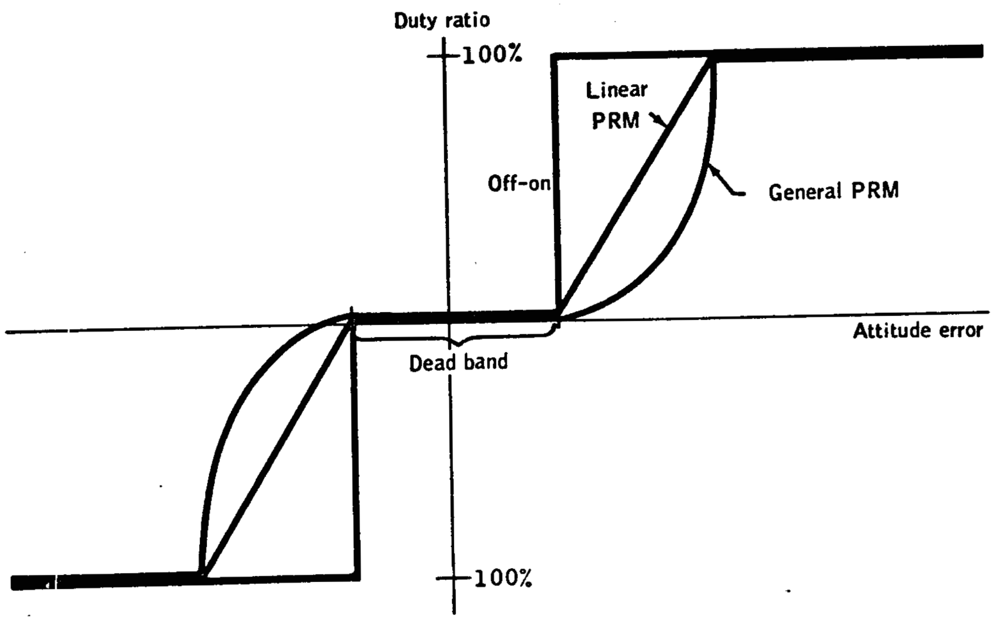

Figure 13. - Switching characteristics of pulse-ratio modulator

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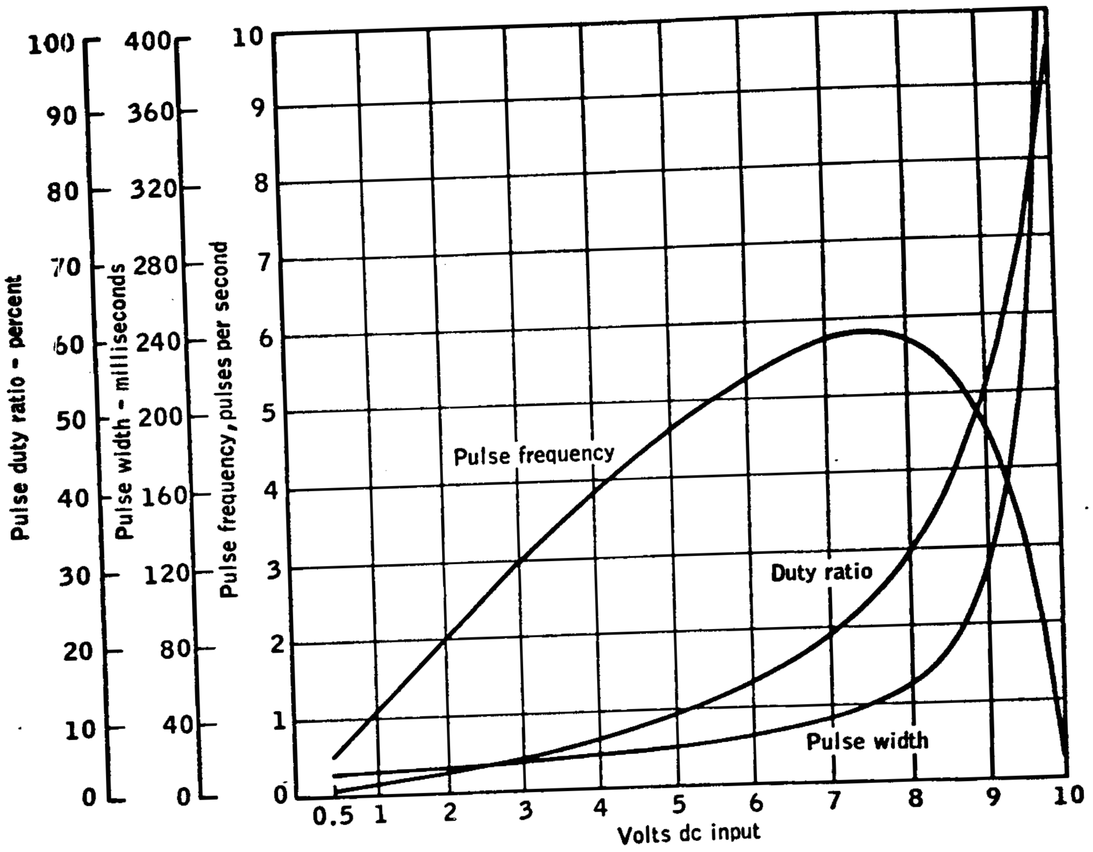

Figure 14. - Performance of pulse ratio modulator