MANUAL ATTITUDE CONTROL OF THE LUNAR MODULE

by

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Abstract

During critical phases of the Apollo mission, spacecraft attitude is manually controlled by the astronaut-pilot. In such instances, the pilot's ability to perceive the state of his vehicle and to apply alternatives to the nominal control is an asset.

The primary guidance, navigation, and control system (PGNCS) uses a digital control system, which is executed on a time-shared basis within the Lunar Guidance Computer. Control laws have scheduled gains, are nonlinear, and follow conditional paths within the computer.

PGNCS manual attitude control using a rate command/attitude hold mode employs parallel logical paths for fast, precise rate response and for attitude hold about one axis. Improved handling qualities afford reduced control jet usage and miss distance during the landing.

The LM's PGNCS holds promise for improvement of the spacecraft's handling qualities within the framework of fixed hardware and physical response. An acceptable manual control system, employing directional stability, coordinated turn capability, and attitude command, is outlined.

Introduction

The Lunar Module of the Apollo program presents a control problem unlike that of any other manned vehicle. The Lunar Module (LM) operates as a VTOL craft in an airless environment with one-sixth earth's gravitation. It is a deboost and launch vehicle capable of leaving, and returning to, lunar orbit. It is a spacecraft that must rendezvous and dock with another spacecraft. Under normal conditions, the vehicle's moments-of-inertia have a 12:1 ratio, but under the conditions, that range may be extended to 239:1. Attitude control is provided by a reaction control system, and, during automatic powered flight with the descent stage propulsion system, by a main engine whose gimbal system was designed to provide only bias acceleration trim. Primary control logic is entirely digital. Fuel available for attitude control is strictly budgeted. At critical times during the lunar mission, the Lunar Module is controlled directly by its crew.

Descending from lunar orbit, the LM follows a braking trajectory under explicit automatic guidance. The landing point can be retargeted manually during this phase but the pilot does not enter the control loop. Upon reaching the landing point with nullled horizontal velocity, the LM is aligned with the local vertical in a hover mode. It descends to the lunar surface with a 3-ft/s sink rate. The automatic system is incapable, however, of sensing and avoiding obstructions, such as craters or rocks, nor can it decide at the last moment that a nearby site is a more favorable landing point; it cannot cope with the unexpected. For the terminal phase of the lunar landing, the pilot must have the option of flying his craft to an alternate location.

Upon return to lunar orbit, the Lunar Module must rendezvous and dock with the Command and Service Module (CSM). The ascent trajectory follows explicit guidance, and the rendezvous can be either manual or automatic; however, there is provision only for manual control of docking. The astronauts of either the LM or the CSM must maneuver their craft in this final phase.

The Lunar Module performs attitude maneuvers during unpowered orbital flight. To achieve a precisely defined attitude, such as that required for initial thrust-vector positioning, an automatic maneuver usually is more efficient. For less precisely determined tasks, such as coarse alignment of the inertial measurement unit (IMU) or station-keeping, manual control is better. In addition, IMU gimbal-lock avoidance is not automatic; it must be performed manually.

Manual attitude control can be effected through three independent logical paths. The pair of hand controllers, one for the Spacecraft Commander and another for the Lunar Module Pilot, can issue attitude commands in any of six ways.

The Abort Guidance System (AGS)\(^{(2)}\) is a backup system that duplicates many features of the primary system. It provides a Direct Mode, a rotational acceleration command mode in which control thrusters are commanded "on" for as long as the hand controller is deflected. The AGS Pulse Mode delivers thruster impulses at a rate of 1.5 pulses per second and is an open-loop, quantized rotational rate, command mode. The AGS Rate Command/Attitude Hold Mode is a closed-loop mode using the backup analog stabilization system of the control electronics section.

The Direct Firing Mode commands the thrusters whenever the hand controller deflection exceeds the soft stop, closing the manual override switch at 11° deflection. This control is always available, independent of the guidance mode selection.

Two manual attitude control modes are implemented in the third logical path, the Primary Guidance, Navigation, and Control System (PGNCS). The Minimum Impulse Mode provides a single 14-ms thruster pulse each time the controller is deflected. This mode is useful when a small, steady rate is required, as in IMU alignment. The major mode, and the subject of this paper, is the PGNCS Rate Command/Attitude Hold Mode, which incorporates a number of features that enhance the rapidity and precision of control response.

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General
The Lunar Module, shown in Fig. 1 to 3, assumes three control configurations during the lunar mission. The LM—Alone Descent configuration, Fig. 1, with a fully-loaded mass of 15,000 kg and roll, pitch, and yaw inertias of 34,000, 33,900, and 31,200 kg·m², loses over half its mass during the descent. Its inertias drop to 20,300, 16,800, and 16,200 kg·m² when the descent stage propellant is fully used. The LM—Alone Ascent configuration mass is 4900 kg; its empty mass is 2600 kg. Initial inertias of 8250, 4700, and 9100 kg·m² drop to 2800, 3900, and 4400 kg·m² at propellant depletion. The CSM-Docked configuration, with the Lunar Module unstaged and all tanks fully loaded, has a net mass of 42,800 kg. Yaw inertia has climbed to 56,000 kg·m², while roll and pitch inertias have mushroomed to 676,000 and 671,000 kg·m². Principal axes of the spacecraft are close to the X, Y, Z body axes in all configurations.

Figure 1 The Descent Configuration of the LM

Figure 2 The Ascent Configuration of the LM

Figure 3 The CSM-docked Configuration of the LM

The Reaction Control System (RCS) is composed of two 8-thruster systems, whose thrust vector orientations are shown in Fig. 4. Each rocket produces a nominal 445-newton (100-lb) thrust, although the down-firing jets, #2, 6, 10, and 14, produce secondary thrusts and torques due to

Figure 4 The 16 Jets of the RCS and their Thrust Directions
exhaust impingement on the descent stage. Yaw jets each provide torques of 695 Nm², while the roll and pitch jets produce primary torques of 746 Nm². Total RCS propellant mass is 267 kg. Propellant is used at the rate of 0.16 kg/s/jet.

Figure 5 indicates the orientation of the control axes with respect to the spacecraft. The X,Y,Z body-axis system is coincident with the P,Q,R rotational rate system. X is parallel to the thrust axis and is vertical with respect to the crew; the Y-axis is to the astronauts’ right, and the Z-axis points forward. The terms "yaw, pitch, and roll" are pilot-oriented. A P-rotation is yaw; Q and R represent pitch and roll. The RCS thrusters are oriented 45° from the Q,R-axes. To facilitate jet selection and command, the P,U,V system is defined with the U and V axes passing through the thruster assemblies. Yaw control is executed about the P-axis only. Roll and pitch control is implemented in the U,V frame.

The RCS thrusters are inefficient for short-duration firings; propellant is not fully consumed and may collect in the lines and combustion chambers. To prevent this, a minimum impulse of 14-μs is imposed within the PGNCS Lunar Guidance Computer. This produces a finite resolution in rate change which varies with configuration. There is a small uncertainty in the thrust profile of the RCS jets.

The Inertial Measurement Unit provides (1) spacecraft attitude with respect to a specified alignment, and (2) translational accelerations within the same frame. The IMU has a 3-gimbal platform and is therefore susceptible to gimbal lock; however, careful alignment prior to all thrusting maneuvers minimizes the possibility of gimbal lock during powered flight. The outer gimbal axis is aligned with the vehicle X-axis. For such maneuvers, the inner gimbal axis is normal to the plane of the planned maneuver. The middle gimbal angle is initially zero, placing the inner gimbal axis perpendicular to the other two. To preclude gimbal lock, the middle gimbal angle must remain outside a 25° band about ±90°. For the lunar landing, IMU gimbal orientation is such that all gimbal angles are zero when the spacecraft is aligned to the local vertical in the plane of the descent trajectory at the nominal landing site. At this point, yaw produces rotation about the outer gimbal axis, while roll and pitch produce rotations about the middle and inner gimbal axes.

IMU gimbal angles undergo analog-to-digital conversion in Coupling Data Units (CDU). Spacecraft attitude angles are thus obtained in a digital form, and rotational rates and bias accelerations are derived from these data.

The panel displays relevant to attitude control are the Display and Keyboard and the Flight Director Attitude Indicator. The Display and Keyboard (DSKY) is the primary interface between the astronauts and the Lunar Guidance Computer. Control and numerical keys on the DSKY allow the crew to initiate and terminate guidance programs, to call up variables for the numerical display, to instruct the computer at critical branches, and to enter numerical data. The 3-register display shows the crew a variety of information vectors, or "hounds".

The Flight Director Attitude Indicator (FDI) uses a 3-gimbal, servo-driven sphere to display total attitude. Body angle rates and attitude errors are displayed on needles around the face of the sphere.

Characteristics of the Attitude Controller Assembly (ACA) are illustrated in Fig. 6. This 3-axis hand controller has an 800-Hz output proportional to deflection, beginning 20° from the center position. The voltage output is digitized to 42 counts at the 10° soft stop deflection; the soft stop is considered "full-scale", although voltage and counts increase until the hard stop is reached at 130°. The detent switch closes at 1.25°, plus or minus 0.75°. Depending upon the particular ACA, it is possible to close this switch, informing the guidance computer of a deflection, without issuing a command voltage; control can switch from automatic to manual logic with zero commanded rate in this case.

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Figure 6 Attitude Controller Assembly Characteristics

The Lunar Guidance Computer (LGC), the central processor of the Primary Guidance, Navigation, and Control System, contains 36,864 words of fixed memory and 2048 words of erasable memory. Each word consists of 15 data bits plus a parity bit. All computations use fixed-point arithmetic; mean cycle time is 12 $\mu$s. The computer processes a number of jobs and tasks on a priority-interrupt, time-sharing basis. Programs are executed in synchronous, asynchronous, or time-available modes depending upon the urgency of the computation. For example, state-vector updates and autopilot functions occur at regularly-spaced intervals. Inputs can be accepted as they occur and RCS firings can be commanded as required. Routines that are not time-critical have lowest priority and are computed between interrupts.

Attitude control, jet select logic for translations using the RCS thrusters, and attitude estimates are computed in that portion of the LGC program called the Digital Autopilot (DAP). Manual attitude commands are also processed in this coding. The Digital Autopilot (DAP) occupies 11 percent of the LGC memory.

Estimates of bias acceleration, rate, and attitude are calculated in a recursive system of equations similar to a Kalman filter; however, filter gains are not the Kalman optimal estimates. The state is extrapolated using past estimates plus the computed contributions due to descent engine rotation and RCS thruster firings. The extrapolation is corrected by a nonlinear function of the difference between the extrapolated attitude and the CDU measurement of IMU gimbal angles. No correction is made if the difference lies within a threshold or "trap". If the trap is exceeded, the difference is attenuated by a gain which is a function of the number of recursions since the last correction. The trap excludes small oscillations due to structural bending and CDU error. The gain provides first-order attenuation.

Attitude control using RCS thrusters is implemented with phase plane logic about 3 independent axes. The switch curves, which are parabolic for the LM-Alone case and linear for the backup CSM-Docked case, determine command times and firing duration for the thrusters. Attitude is controlled within a deadband; thus there is a coast zone between switch curves. Attitude normally limit cycles at a low rate in undisturbed flight. The LM-Alone switch curves are shaped as a function of the mass estimate. In powered flight, they are positioned by the bias acceleration estimate value. Limit cycling with one-sided RCS firings is particularly important in the Ascent configuration, for the ascent engine is not gimbaled, and a moment offset will persist.

The Digital Autopilot is executed 10 times per second. Computation time varies between 6 and 25 $\mu$s depending upon the mode of operation and the number of interrupts which occur during the execution. The DAP sequence is initiated by a counter and an interrupt. Only FDI attitude error display and desired attitude update are performed under interrupt status; the remaining DAP computations, including state estimation and control, are not.

The crew can select "AUTO", "ATT HOLD", or "OFF" via the DAP Mode Selector Switch. In the last instance, only the interrupt-status computations are executed. "AUTO" must be selected for automatic maneuvers. During descent engine burns, control is effected by Reaction Control System, and the main engine Trim Gimbal System on alternate DAP cycles. The crew can manually command the X-axis ("X-Axis Override") while "AUTO" is selected, except during the last portion of the lunar landing braking phase (program P63) and during the approach phase (program P64). In P64, the ACA is used to retarget the landing site, pitch and roll deflections corresponding to discrete angle changes in the flight path; however, automatic guidance is maintained. ACA control about all axes is possible only in "ATT HOLD". In this mode, moment offsets are nulled by descent stage main engine gimbalning, and manual control using the RCS thrusters occurs at a 10-per-second sampling rate.

The crew can perform a "DAP Data Load" with the DSKY. A number of quantities, including hand controller scaling (Normal or Fine) and attitude deadband (Narrow or Wide), can be specified.

SUNDANCE: Manual Rate Command

The LGC program for Apollo 8, given the project name SUNDANCE at the Instrumentation Laboratory, contains manual rate command logic which is a digital realization of early reaction control rate command systems, such as those used in design studies, on the Lunar Landing Research Vehicle (LLRV), and with the Lunar Landing Research Facility (LLRF). This logic(5) provides rate command within a rate error deadband when the ACA is out-of-detent. Automatic attitude hold is maintained with the controller in-detent.

Forty-two counts of the ACA output are scaled to a maximum commanded rate (MCR) of 200/s in "Normal" and 40/s in "Fine". The normal scaling would be used for the lunar landing, in which high maneuver rates might be a necessity. Fine scaling would be used for all other operations, where a premium is placed on precision and fuel-saving low rates. Granularity of the scalings is 0.476 and 0.0895/s/count.
ACR scaling, inadvertent hand motion, minimum impulse, state estimation, and high-frequency limit cycling place constraints on the rate deadband. Granularity and controller sensitivity produce a "staircased" version of inadvertent hand motions. The deadband should trap the majority of these spurious motions to prevent unnecessary RCS firings. The deadband must be large enough to prevent minimum impulse chattering in the lowest-inertia configuration (empty ascent). The rate change due to a minimum impulse becomes larger as moment-of-inertia decreases; it must not be possible for a minimum impulse to move the rate error from one firing zone to the opposite. Errors from many sources, e.g., estimator errors, jet on-time variance, and aerodynamic, gravity gradient, and solar torques can increase limit cycle frequency. Widening the deadband is one means of reducing this frequency.

Figure 7 illustrates the error phase plane for a single manual control axis, with estimated rate error plotted against estimated attitude error. The thrust vector switch curves have a ±1.40°/s deadband in normal scaling and ±0.40°/s deadband in fine scaling. Because this logic is applied in the P,U,V frame, the yaw deadband has these numerical values, but pitch and roll deadbands are geometrically raised to ±1.86 and ±0.57°/s.

![Rate Error vs Attitude Error Diagram]

Transportation lag of the manual control system is large, ranging from 130 to 250 ms. The ac voltage output of the ACR feeds an analog-to-digital converter, which must be zeroed and enabled each time a reading is desired. The ACR counters are not read until the detent switch is closed. Once this happens, there is a 0- to 100-ms delay until the next DAP sampling instant. Although the controller is deflected and is indicating a voltage, the counters must be zeroed and enabled, and the rate commands are zeroed for the present DAP cycle. On the next cycle, the counters contain valid (but 100-ms old) data. There is an additional 30- to 50-ms computational and thrust buildup delay.

**LUMINARY Manual Rate Command**

**Design Philosophy**

The SUNDANCE program provides acceptable manual control for the LM-Alone and has successfully undergone extensive testing in all modes of operation and in simulation and orbital flight. It is apparent from these tests, however, that improvements in the manual rate command are desirable. An upgraded rate command has been implemented in LUMINARY, the LGC program to be used for the first lunar landing. The program was first used on the Apollo 10 flight.

The LUMINARY manual rate command mode has been designed to meet the following objectives:

1. to reduce drift about uncommanded axes,
2. to provide more precise rate control,
3. to improve handling qualities,
4. to assure positive return to automatic modes from manual control,
5. to make manual rate command available in CSM-Docked configuration, and
6. to reduce on-time of the +X-firing thrusters during the lunar landing.

Although rate command w/deadband is an acceptable mode from a handling qualities viewpoint, it is open-loop for small, secular errors. Because the switch curves of Fig. 7 are independent of attitude error, it is possible for the spacecraft to have an uncorrected drift rate that is incrementally smaller than the deadband.

Two factors complicate the drift problem. If the hand controller is out-of-detent about any axis, all three axes use the manual logic. Consequently, the spacecraft can drift about uncommanded axes (up to nearly 20°/s with normal scaling). Also, an unmodelled (bias) acceleration can cause the phase point to chatter along the switch curve. Sampling and state estimation delays compound this drift.

To limit drift inexorably, attitude errors must be incorporated in the control computations.

The rate deadband determines the resolution of rate control. Targeting jet on-time for zero rate error and using inertia and bias acceleration estimates often result in rate step response with errors initially smaller than the deadband, but such precision cannot be guaranteed. Once the rate error is within the deadband at a sampling instant, firing ceases. A heavy configuration requiring more than 0.1-s firing for a rate change equal to the deadband will never have rate error nulled entirely, and firing may stop just within the deadband for lighter vehicles (depending on initial rate error). Furthermore,
uncertainty in command response extends to twice the deadband width, measured from zero. If the rate error is incrementally smaller than the negative limit and a positive change is requested, the rate error must traverse the entire dead zone before a firing occurs.

To obtain precise rate control, integral compensation is required.

Rate uncertainty is reflected in the manually commanded rates obtained during 15 lunar landing simulations. The landings, simulated on NASA's Lunar Module Mission Simulator (LMS), were controlled by astronaut and engineering pilots. An early version of the LUMINARY program, containing the SUNDANCE manual control was used as the LGC program. As shown in Fig. 8, which presents a typical record of rotational motion, vehicle rates during the landing are best characterized as impulses. This indicates, incidentally, that integrals of angular rate, e.g., angular attitude and horizontal translation, are the quantities of highest concern to the pilot.

Frequency distributions of the maximum pitch and roll rates obtained in the 15 landings are presented in Fig. 9. It is immediately evident that rates within the Normal deadband are excluded. The high peaks for minus roll and plus pitch are indicative of piloting technique and the trajectory shaping required by the landing task. The pilot does not need high rates often, and no commands greater than $10^9$ are issued in any of the tests (although the MCR is $20^9/s$). Three to $4^9/s$ rates occur most frequently in all quadrants, and the smallest available rates, $2$ to $3^9/s$, are not used often. In summary: a) very small rates are excluded by the rate deadband; b) there is a hesitance to use rates just outside the deadband; c) with the exception of the "excluded middle", there appears to be a desire to use the smallest rates that can be obtained with certainty.

Tightening the rate loop alone is insufficient to improve the pilot's estimation of handling qualities in the landing task: one astronaut's reaction to the change was that it was still impossible to achieve small attitude change in landing simulations. The difficulty lay in the deflection required to obtain ACA output and in the controller sensitivity. In "shirtsleeves" simulator tests, the pilot can feel and hear the detent switch click, yet, depending upon the particular unit, the ACA must be deflected up to 1.80 minutes before the change to voltage buildup. Having reached the voltage ramp at 20° deflection, the commanded rate increases 2.50/s for each degree of controller deflection, in steps of nearly 0.50/s. Using small, smooth hand motions, small attitude changes are indeed difficult to command, because the pilot cannot predict when the voltage buildup will begin.

The ACA characteristic is fixed, but controller sensitivity is easily changed in the guidance computer program.

Once the hand controller has been returned to detent, control should be passed from manual to automatic, and automatic attitude hold engaged with a minimum transient. The latter requirement is met if rates are damped before the switch; if the rate error were large, the automatic phase plane logic could command oscillatory response in seeking to null the attitude error in minimum time, using RCS propellant unnecessarily. Small rate error is imperative for mode change, voltage buildup to automatic control should be assured whenever the Attitude Controller Assembly is returned to detent, even if any or all components of angular rate fail to damp within a short time. Once damping about an axis has reduced the rate error to a small value, that axis should be considered to have passed the damping test. Chafering about more than one axis can delay, and possibly prevent, return to attitude hold. In the SUNDANCE logic, the requirement for the return, after the ACA is returned to detent, is that all rate errors be less than the rate deadband simultaneously. Phase points chafering out-of-phase will fail this test. If this occurs as a result of an unanticipated jet failure or mass uncertainty, the only ways to return to attitude hold are to inform the LGC of the failure or to momentarily switch the DAP off.

Rates about all axes should be damped before manual-automatic mode switching; however, the return should be made after a short time, in any case.

CSM-Docked rate command is not a requirement of the SUNDANCE program. Although there is no planned use of manual rate command in this backup system, only minor changes need be made for this mode to be usable. These changes have been made in the LUMINARY program.
LMS tests of an early version of the LUMINARY program uncovered an excessive total on-time of the RCS thrusters during manual landing simulations. The additional RCS propellant usage was discomforting, but the primary concern was the cumulative heating of the descent stage which would be caused by exhaust impingement of the down-firing (+X) RCS thrusters. Inhibiting the +X jets for small rate errors was proposed as a solution; however, the deterioration in handling qualities was unacceptable. In LMS simulations, pilots were forced to use larger rates more often, bringing the +X jets back into use. As a result, on-time savings were unpredictable. This was one indication that handling qualities were at the base of the problem. Prior research indirectly indicated that improved handling qualities, through reduced controller sensitivity, might alleviate the problem. This proved to be the correct solution, as will be shown in a later section.

To minimize RCS on-time in manual control, handling qualities should be optimized.

In addition to the above objectives of the redesign, the manual rate command mode must operate satisfactorily in the presence of detected and undetected jet failures (on and off), with mass estimate errors in the LOC, and in the presence of unmodelled accelerations.

Manual Rate Command Logic

Two modes of control are employed in manual rate command: the Direct Rate and the Pseudo-Auto modes. Neither mode alone meets the requirements of the previous section; however, by alternating between the 2 policies, fast, precise response is obtained. The first mode can be likened to rate command w/ deadband, although there are important differences. The second mode allows manual commands to be processed by the autopilot phase plane logic.

The block diagram of Fig. 10 traces the major paths of this digital control system for all three axes. The hand controller deflection is scaled to a rate command, which is differenced with the estimated vehicle rate to form a rate error. The command is integrated and is subtracted from an integrated sum of IMU gimbal angle increments transformed to body axes, providing an attitude error. Attitude and rate errors are referenced to body axes; therefore, although the transformation matrix for gimbal angle increments is updated every 240 ms, the attitude errors are meaningful only when they are relatively small. One of the features of the dual mode operation is that these errors rarely become large.

The commanded rate, \( \omega_c \), is supplied to the control logic to perform a switching function. If the change in commanded rate between successive DAP cycles exceeds a breakout level, the Direct Rate mode is used to null rate error, computing a firing time for the RCS thrusters as,

\[
T_{\text{jet}} = -\frac{E_\omega}{a}
\]

where,

- \( E_\omega \) = Actual rate minus commanded rate,
- \( a \) = Net available rotational acceleration, including estimated bias acceleration.

The sign of \( T_{\text{jet}} \) determines the sense of the commanded rotation. If the firing time exceeds 150 ms, the jets are commanded on, and a new firing time is computed on the next DAP cycle. If the firing time is less than 150 ms (but not zero), the jets are commanded on for the correct time, but the computation is skipped on the next cycle. This procedure takes place: a) every time the breakout level is exceeded, b) until \( E_\omega \) falls within the target deadband, or c) until a time limit is exceeded. The Direct Rate computation ignores the attitude error, computing firing times as the SUNDANCE program does.

The Direct Rate mode has 2 important attributes. Subject to the transportation lag, which is unchanged from SUNDANCE, the mode provides immediate response to urgent commands, while ignoring slow controller inputs. The commanded rate need not be large, but if it is requested quickly, the Direct Rate mode is used. By comparison, small commands originating in the coast zone of the automatic control logic must integrate to the boundary before a firing occurs. The second point is that large rates can

Figure 10 Manual Rate Control Logic

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be commanded without significant rate overshoot. With constant acceleration, phase plane trajectories are parabolas; however, the phase plane logic of the automatic system, shown in Fig. 11, is always entered (from Direct Rate) below the target deadband, with attitude error initialized to zero, i.e., in the coast zone.

![Diagram of phase plane logic](image)

**Figure 11 Phase Plane Control Laws**

By itself, the Direct Rate mode is inadequate for control. Small commanded rate changes are passed by. Once the time limit is exceeded, the mode is switched off. Furthermore, the resolution limit is the target deadband, so the mode is no more precise than rate command with deadband.

The Pseudo-Auto mode limits drift about uncommanded axes and makes precision rate control possible. Attitude cannot drift beyond the attitude deadband, and small rate errors are integrated to the coast zone boundary, where a corrective RCS firing is commanded. As illustrated in Fig. 11, the phase plane logic takes different forms for the LM-Alone and CSM-Docked configurations. The LM-Alone logic uses parabolic switching curves which are shifted to optimize limit cycles in powered or coasting-flight. Because of the LGC's scaling limitations, this logic cannot be applied to the CSM-Docked backup control mode, and a simplified logic is used in this latter case. The Pseudo-Auto mode interfaces with whichever switch curves are appropriate.

If the rate command is applied slowly, the Pseudo-Auto mode is entered immediately. If the Direct Rate mode is used initially, Pseudo-Auto control begins when the rate error is less than the target deadband or when the time limit is exceeded. If the mode is entered with jets on, the firing is continued to zero rate error, even though the phase point is in the coast zone.

In coasting flight and in the powered-Descent configuration, this mode holds the commanded rate within the resolution of the rate change due to a minimum impulse; the actual rate limit cycles about the desired rate.

Direct Rate/Pseudo-Auto switching is carried out independently in the $P$-axis and $Q$, $R$-axes. Thus it is possible to hold $Q$, $R$ commands are issued in pitch and roll; the opposite is also possible. Logical flow of the manual control is charted in Fig. 12a and b. The coding is separate to facilitate $P$-axis manual control for X-axis Override. The logic is quite similar in the 2 frames, except that additional branches are required for the multi-axis, $Q$, $R$ control. Executive control of the rate command mode, including initialization, reading, zeroing, and enabling of ACA counters, and the decision to continue rate damping or to return to automatic control, occurs in the $P$-axis coding.

The breakout level and target deadband are currently set to the same value: 0.69/s for the LM-Alone and 0.30/s for CSM-Docked control. The time limit is 4 seconds.

### Hand Controller Scaling

The sensitivity of commanded rate to hand controller deflection is the most important manual control parameter once "control power" (rotational control acceleration) is fixed. In view of the different sensitivities that provides stable human pilot-loop closures often can be defined but, as a consequence of the pilot's adaptive ability, optimization of the sensitivity within that range is a subjective process. The choice of scaling can be affected strongly by control power, vehicle and control system dynamics, external disturbances, the control task, and the individual pilot's ability to perceive and react.

Early research on manual lunar landing explored the relationship between controller scaling and control power in fixed- and moving-base simulators[16-18]. Cooper Ratings, numbers assigned to subjective evaluations of handling qualities, are the primary figures of merit in these tests, although one fixed-base test[16] estimated RCS propellant consumption of the LLRV as a function of controller sensitivity and rate deadband. Evaluations based on landing point accuracy are notably absent; apparently, there was little difficulty in landing at a particular site.

In Fig. 13, Hewes summarizes control sensitivity/control power results obtained for pitch control with the LLRV and the LLRF[19]. The numbers appearing on the chart are Cooper Ratings, and the contour represents a tentative boundary for satisfactory handling qualities, based on Cooper Ratings of 3.5 or less. Here maximum commanded rate is used as a sensitivity measure. When control
Figure 12a Manual Rate Control Logic for the P Axis

Figure 12b Manual Rate Control Logic for the Q, R Axes

Figure 13 Contour of Acceptable Handling Qualities

power and the MCR are equal, i.e., when the MCR can be reached in 1 second, the ratings are good. Hewes suggests 12.5°/s MCR and 12.5°/s² control power as an optimum point. In this and other sources, improved handling qualities with reduced deadband are noted but dismissed because of the high frequency limit cycling which results. The LUMINARY manual control logic response to commands is analogous to vanishingly small deadband, yet its slow limit cycling is similar to the wide rate deadband characteristic.

Jarvis(8) presents flight test and fixed-base RCS propellant consumption as a function of controller sensitivity and rate deadband, for pitch and roll control powers of 10 and 140°/s². Figure 14 illustrates the results. The variation of average fuel consumption with rate deadband is not relevant to the LUMINARY manual control system, but variations with controller sensitivity are. Reduced controller sensitivity has a striking effect on the RCS propellant used; there is a monotonic reduction with decreasing sensitivity.

With descent engine propellant fully used, the 4-jet control powers of the Lunar Module are 11, 9, and 100°/s² in pitch, roll, and yaw; during the terminal phase of landing, control powers are 10 to 20% less. The Hewes data suggest that a 20°/s
MCR is a factor of 2 higher than the optima for these control powers. Jarvis's fuel-usage data also point in the direction of reduced sensitivity.

These trends are confirmed in LMS simulations using the LUMINARY manual rate command logic. Although Cooper Ratings were not recorded in all the tests, a reduction of MCR from 20 to 140/§ improved one experienced pilot's rating by 1; the consensus of several pilots was that handling qualities were improved. The emphasis in these tests was placed on accuracy in flying to a designated site and on reducing +X-jet on-time; however, handling qualities ratings continued to improve as the MCR was reduced to a final value of 80/§. The effect on +X-jet on-time is shown in Fig. 15. Flight to three landing sites with six MCR's was evaluated by two pilots. The average for the two hardest tasks shows a marked decrease in jet on-time with decreasing MCR. Maneuvering for the 1500-ft downrange increase is simpler, requiring less RCS propellant. The scatter in these points emphasizes the subjective nature of choosing MCR, although the favorable effect of reduced MCR is apparent. Reduced MCR also improved landing point accuracy in this series. These tests provide convincing evidence of the tangible benefits of improved handling qualities.

In spite of the improvements resulting from reduced controller sensitivity, there remained one conflict: reduced sensitivity made small rates and small angle changes easier to obtain, but there was concern that the maximum commanded rate was insufficient for emergency conditions. A 200/§ MCR was deemed mandatory by the astronauts. The solution that has been adopted is nonlinear scaling of the ACA output.

Measuring ACA deflection, $\delta$, from the centered position, the linear normal scaling law of the SUNDANCE program is

$$\omega_c = \begin{cases} \frac{MCR}{8} \text{sgn}(\delta) \left[ |\delta| - 2 \right] & , |\delta| > 2 \\ 0 & , |\delta| \leq 2 \end{cases} \quad (2)$$

The maximum commanded rate is realized when $|\delta|$ is 100°.

Further LMS testing indicated that linear-quadratic scaling provided the low sensitivity required for small ACA deflections, as well as high MCR. The hand controller scaling that resulted from this testing is implemented in the LUMINARY program. The scaling law is,

$$\omega_c = \frac{MCR}{40} \text{sgn}(\delta) \left[ |\delta| - 2 + \frac{(|\delta| - 2)^2}{2} \right] , \quad (3)$$

with MCR equal to 200/§ in normal scaling.

Note that the linear portion alone would yield a 40/§ MCR, one-fifth of the former value. This characteristic is compared with several linear scalings in Fig. 16. It is interesting that the 100/§ linear law, which is near-optimum according to the Hewes data, intersects the new law at 40/§, which is in the most-frequently-used range of Fig. 9.
Equation 3 is not an exact relation, for the ACA output is quantized, and \( \omega_c \) is "staircased". Calling \( \delta_c \) the number of counts (an integer), the commanded rate is

\[
\omega_c = MCR \cdot \{0.0045335 \cdot (|\delta_c| + 10.5)\} \tag{4}
\]

and the increase in \( \omega_c \) per count is approximately,

\[
|\Delta \omega_c| = MCR \cdot \{0.0045335 (2|\delta_c| + 10.5)\} \tag{5}
\]

Little has been said about scaling for the docking task. Inertias of the nearly-empty Ascent configuration are quite low; control power and minimum impulse are 4 to 7 times larger than those of the landing configuration. In the only published account of LM-Active docking simulation, successful docking was achieved with 200/s MCR, although the possibilities for over-control were great\( ^{14} \). This indicates that attitude control is used to set up a proper attitude relative to the passive target. Once this is achieved, translational control is the primary concern, and the attitude control receives little exercise. It is important, however, that precision attitude control be provided, for several of the simulated docking attempts aborted due to over-corrections just prior to contact. The LUMINARY manual rate command retains the 40/s MCR in fine scaling, and Eq. (4) is used to give low sensitivity at small deflection.

Rates are limited to 20/s or less for backup CSM-Docked automatic control. Accordingly, the Nominal and Fine MCRs for manual control of this configuration are reduced to 20/s and 0.45/s, respectively.

The relationship of ACA scaling to Direct Rate breakpoint level is designed to emphasize the most useful traits of the new rate command system. In the normal LM-Alone scaling used for the landing, the ratio of controller sensitivity-to-breakout level is high; small deflection changes are considered urgent and, as the mean deflection increases, the change becomes more urgent. Equation 5 indicates that every count triggers the Direct Rate mode when \( \delta_c \) is 28 or more, i.e., when the commanded rate is greater than 0.779/s. The breakout level, 0.60/s, is unchanged for fine scaling, in order to encourage control to remain with the Pseudo-Auto mode. However, the Direct Rate mode is used, the Pseudo-Auto attitude reference is reinitialized. So long as Direct Rate is not used, absolute attitude reference is maintained; therefore, a small pitch command can be issued without disturbing roll reference. This is a useful attribute in the docking task, for the pilot usually sets up each axis individually, attaining the proper orientation in a sequential process\( ^{14} \).

Multi-Axis Control

Because the RCS thrusters are located 45° from the Y,Z-axes, the same 8 jets are used for both pitch and roll control. Referring to Fig. 4, it can be seen that pure pitch or pure roll rotations use four jets, while combined rotations occur about either the U- or V-axis, using only two thrusters. When a combined pitch-roll rotation occurs, control power over both axes is reduced by a factor of 2. Figure 17 indicates that there are two approaches to nulling multi-axis errors. It is possible to respond about both axes immediately with two jets, nulling the smaller error entirely, then nulling the remaining error with four jets. The second alternative is to reduce the larger error with four jets. When both errors are equal, both axes are nulled using two jets.

The latter method is intrinsic to U,V control axes and is also the minimum-integral-error path. It is more natural to the pilot as well. Should the pilot issue equal commands in pitch and roll and then sense that roll control is more urgent, he would increase roll deflection of the hand controller. With the second logic, roll control would increase immediately. In the first case, pitch error would be nulled entirely before full control power was applied to the critical axis.

Test Results

All LGC programming receives extensive digital and hybrid computer simulation testing at the MIT Instrumentation Laboratory prior to its release to NASA. The digital simulation provides trajectory computation and step-by-step execution of LGC coding in a batch processing mode\( ^{15} \). The real-time hybrid simulation provides a fixed-base cockpit environment, utilizing flight display hardware as well as IMU, radar, and LGC function simulators\( ^{16} \). Digital trajectory computations, combined with analog vehicle simulation and "window optics", enable mission design and verification studies, including star tracking and lunar landing, to be "flown" by MIT/IL personnel.

Figure 18 is representative of standard response of the Lunar Module to a sequence of manually commanded step inputs. CDU noise and jet switching delays are included in this digital simulation of the Descent configuration, with fully-loaded ascent propellant tanks and 90%-loaded descent propellant tanks. Four-degree-per-second commands are issued at 10-s intervals beginning at 15 seconds. The axis sequence is +P, +Q, -R, -R, -Q, -P, so the net angle change of a perfectly-controlled system is zero at the completion of the test. Fine scaling (40/s MCR) and narrow attitude deadband (0.3°) are used in this test. Figure 18 is a time history of LGC-estimated and actual rotational rates; the latter trace is marked by Xs.
A total of 6.72 kg of RCS propellant is used for this test sequence. This is 8.5% above the theoretical minimum; the excess can be attributed to attitude hold limit cycling and to corrections necessary to obtain the commanded rate.

Raising the commanded rate to 200°/s, similar performance is noted, although it takes four seconds to achieve the commanded rate with this configuration. The minimum angle traversed in achieving a rate, starting from and returning to zero rate, is

$$
\Delta \theta_{\text{min}} = \frac{\omega_{\text{max}}^2}{a},
$$

(6)

where $a$ is the rotational acceleration. For this case, $\Delta \theta_{\text{min}}$ is 80°; for the landing configuration, it is half that. It is clear that the Normal MCR is available only for large angle changes in either case.

Raising the attitude deadband to its wide setting (50°) has no effect on the rate initially obtained for maneuvers beginning in the Direct Rate mode; however, corrective firings commanded in the Pseudo-Auto mode are delayed, and limit cycle periods are increased by a factor of 17. In LM-Alone powered flight, the attitude deadband is fixed at 10°. It is 1.4° for CSM-Docked control.

Very small rates can be commanded with the LUMINARY rate command logic. A single count provides a commanded rate which is 0.5% of the MCR. Over long-term averages, the system will supply this low rate within the resolution of a minimum impulse. The fuel consumed in commanding small rates has a high percentage excess above the theoretical minimum; the total fuel expended is hardly larger than that required for attitude hold limit cycling. Because it is difficult to sense the deflection at which output voltage begins, and because it is difficult to perceive very low rates, it is unlikely that very-low-count rates will be commanded.

The impulse response of the LUMINARY manual rate command system plotted in Fig. 19 is nonlinear and contains transportation lag. The 10°/s impulse, lasting from 0.1 to 0.5 second, is a saturating input. Vehicle response would be identical for any commanded rate greater than the maximum achieved rate. Response is obtained by "bang-bang" firing.
of the RCS thrusters, with no coast time before thrust reversal. There is no response to the 0.1-s impulse; initialization lag obscures the input. For longer saturating impulses, lasting T sec (in 0.1-s increments), the maximum angular rate is approximately,

$$\omega_{\text{max}} \approx a(T - 1)$$  \hspace{1cm} (7)

and the net angle change is

$$\Delta \theta \approx a(T - 1)^2$$  \hspace{1cm} (8)

The smallest angle change obtained with the heavy Descent configuration in digital simulations is 0.068°; with landing inertias, this increment is doubled. Thus, the availability of small attitude changes is not dependent on low ACA sensitivity. Using saturating inputs, the change occurs in a nearly time-optimal process. The angle change is independent of controller deflection, depending only on the duration of the command.

Ramp inputs are not especially useful in controlling the Lunar Module. Because numerous small pulses are commanded, the ramp input is inefficient. If, however, a slow ramp is commanded, the Direct Rate mode is not used, and there is initial delay as the Pseudo-Auto phase point drives toward a switching curve. Command buildup and vehicle response are quadratic and quantized. If the ACA deflection is then reversed, there is a lag as the attitude error shifts from one switching boundary to the opposite. These effects are apparent in the time history of Fig. 20, and the phase trajectory of Fig. 21 (linear ACA scaling was used in this test).

![Figure 20 Response to a Ramp Input](image)

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![Figure 21 Response to a Ramp Input Phase Trajectory](image)

If an entire 8-jet system is failed-off undetected, response is sluggish. The state estimator overestimates jet effectiveness, and the thrusters are turned off prematurely. The response is overdamped, but no jets are fired against the desired rotation.

Detecting the failures, the jet-effectiveness estimate is corrected and the response emulates standard performance with reduced rotational acceleration.

A jet failed-on is not likely to go undetected for any length of time. If it occurs in powered flight, the bias acceleration estimate feels its effect, and the offset is nulled by the descent engine or by shifting the phase plane logic for improved RCS control. In coasting flight, bias accelerations are not estimated, but the failure is more apparent. If the jet is left on, the autopilot opposes the jet, but reinitializations of attitude reference caused by manual control will allow a small drift.

Two of the features of the LUMINARY manual rate command are brought to bear with an undetected on-failure. The Direct Rate mode alone allows a high drift rate, due in part to the skip logic. The Pseudo-Auto mode is required to keep the drift rate low (on the order of 1°/s). With a U- or V-jet on-failure the U,V errors are chattering out-of-phase, preventing a normal mode switch from Direct Rate control to Pseudo-Auto or automatic attitude hold. The mode switches when the 4-s time limit is reached.

The LGC is not programmed for a detected on-failure. Because an on-failure wastes fuel, the offending jet must be disabled. Disabling the jet informs the computer that the jet is no longer available for control, resulting in a detected off-failure.

Error in the mass estimate ("mass mismatch") can be likened in its effects to the damping of a
linear system. The RCS jet effectiveness estimate is programmed as a function of the vehicle mass estimate. If the estimate is high, the jets are commanded on for a period that is longer than necessary; the opposite occurs with low estimates. In the latter case, response is over-damped, requiring many short firings. High mass estimate introduces overshoot. As the estimate becomes larger, the response becomes oscillatory, eventually entering a high amplitude limit cycle at about 150 percent of actual mass.

Manual Control of the Lunar Landing

Rate Command

The most challenging manual task of the lunar mission is landing the Lunar Module on the moon. The maneuver is comparable to a helicopter landing on earth, but the differences are at least as significant as the similarities. The LM's rotational control power is only a fraction of helicopter control power. Translational control is obtained by tilting the main engine thrust vector, which entails tilting the whole spacecraft. In hover, thrust magnitude is one-sixth what it would be on earth. The vehicle must be rotated six times as far to obtain an equal translational acceleration. There are no significant aerodynamic effects during the landing; neither the beneficial effects of dihedral and directional stability, nor the disturbing effects of adverse coupling and turbulence, are present. Visibility is restricted in the Lunar Module, and external motion cues are more difficult to obtain than in a bubble-canopied helicopter. The main engine depletes its propellant within 2 minutes of the beginning of manual control, forcing the landing to be made quickly.

The LM is well-instrumented, providing all the flight status information necessary for a successful landing. In addition to the FDAI, there are meters indicating horizontal velocity components, attitude, altitude rate, and thrust. The second crew member can call additional information on the DSKY, including total horizontal velocity, mass estimate, and the slant range to the landing site. Although the main engine can be throttled manually, rate-of-descent can be maintained by the LGC, with the astronaut specifying sink rate through a "click" switch. The latter allows the pilot to concentrate on control of attitude and horizontal translation.

A nominal manual landing sequence begins at an altitude of 500 feet. Forward velocity and sink rate are 58 ft/s and 15 ft/s, respectively. The Lunar Module is pitched up 20°. The astronaut switches from the approach-phase program (P64) to the rate-of-descent landing program (P65) by turning the mode selector switch from AUTO to ATT HOLD. In most instances, it is not difficult for the astronaut to guide the spacecraft from this point to touchdown, provided there are no obstacles to be avoided. Lateral velocity, roll angle, and yaw angle are small and may not need adjustment. Rate-of-descent is gradually decreased to 3 ft/s with the R-O-D switch, positive pitch angle is maintained to null the forward velocity, and the vehicle is then aligned with the local vertical for a low-rate descent to the surface. In such an instance, the landing maneuver is a programmed sequence requiring negligible control.

The real landing is somewhat different. Even small angle and velocity biases propagate into velocity and position errors and must be controlled.

If an alternate landing site is desired, angles and velocity components must be perturbed to shape the trajectory, then nulled before touchdown.

The difficulty of the landing task can be appreciated by considering a simple dynamic model. The pilot must control 2 components each of angle, velocity, and position with angle rate command. Neglecting human pilot and angle rate-loop dynamics, it is necessary to close 2 control loops around triple integrators to land at a point. A control loop closure of this sort is unstable for any gain unless second-order compensation or inner-loop closures can be provided. Second-order compensation may be beyond the pilot's compensatory capability, and positive control of angle and velocity must be exercised; therefore, inner-loop closures are mandatory. It is easily demonstrated that angle and velocity closures, indicated in Fig. 22a, provide stable poles for the position closure. The last closure must have low gain to remain stable.

![Figure 22 Linearized Models of Position Control Loops](image)

This simplification yields an optimistic estimate of system stability. Realistic linear modelling of the position control system should include additional dynamic terms, as in Fig. 22b. Simulating the angle rate-loop as a second-order linear system adds 2 poles and a zero to the innermost loop. The simplest form of a human pilot describing function includes a time delay, which in turn can be approximated by a stable pole and a non-minimum-phase zero. Stable position-loop closures also can be obtained for this more complex model, although outer-loop gain must be reduced.

Although landing the Lunar Module is a multi-variable control task, it appears that the pilot commands these variables sequentially. Crout's data(6) show few multi-axis rate commands, and MIT's simulation experience agrees. In order to fly to a crossrange target, two techniques are used. If the lateral distance is small, a hover technique is used. In this case, the yaw axis is
ignored, and the pilot sideslips to the landing site. For greater crossrange, the technique is closer to flying an aircraft. As shown in Fig. 8, the pilot rolls the spacecraft to establish a side velocity and then nulls the roll angle. Next, the vehicle is yawed to the direction of motion, and the craft flies to the target with negligible side velocity. In an aircraft, directional stability and rudder control would have coordinated the turn.

An Advanced Manual Control System for Lunar Landing

Within the framework of the present LGC program, manual control for the lunar landing can be improved. Necessary data are already maintained within the program, and new coding is minimal. The purpose of the improved mode is to reduce the number of variables that must be actively controlled by the pilot, through closing additional feedback paths within the guidance computer and by redirecting the output of the hand controller. In several respects, LM response would be closer to the characteristics of an aircraft. As a result, the new logic has been christened the "Airplane Mode", shown in Fig. 23.

![Diagram of airplane mode control system]

Figure 23 Manual Attitude Control for Lunar Landing

There are 3 major attributes of the Airplane Mode: directional stability, coordinated turns, and attitude command. The Airplane Mode can be requested or rejected by the crew through the DSKY using "extended verbs" (an extended verb is a 2-digit number that orders the computer to take a specific action, e.g., change a display, incorporate radar data, restart, etc.). The mode is available only during the manual landing programs (P66 or P67). The three characteristics could be implemented separately, although the first two are complementary and should be programmed together.

Directional stability is obtained by biasing the yaw attitude error. Forward and lateral horizontal velocities, $V_{YH}$ and $V_{ZH}$, which are displayed to the crew on a cross-needle meter, determine the sideslip angle. Setting the yaw bias to the sine of the sideslip angle provides a correction of the proper sign which is conservative at large angles. For pitch and roll angles near zero, the yaw bias angle is,

$$\phi_B = \sqrt{V_{YH}^2 + V_{ZH}^2} \quad (9)$$

As RCS jets cease command yaw in response to $\phi_B$.

If yaw rate is made equal to the rate-of-change of flight azimuth, the turn is coordinated. For nearly vertical attitude, the yaw rate error bias is

$$\phi_B = \frac{a_x \sin \psi}{V_{ZH}} \quad (10)$$

where $a_x$ is the specific force caused by the descent engine, and $\psi$ is the body-referenced roll angle.

These relations bear some discussion. They should be applied for the range of pitch and roll angles used in the lunar landing (less than 30°). They are applied only in forward flight ($V_{ZH} > 1$ ft/s) and for horizontal velocity greater than 6 ft/s; therefore, in near-hover, small velocity or roll angle changes do not cause sudden yaw changes. $\phi_B$ couples the side force and yaw moment equations-of-motion, and lag in the $V_{YH}$ estimate destabilizes the yaw control loop. A suitable attenuation applied to $\phi_B$ assures stability, although yaw response is then delayed. Without yaw rate bias, $\phi_B$ would realign the LM’s Z-axis to the plane of translation by any small impulsive during a steady turn. Firings of both signs would occur, wasting fuel. Biasing the yaw rate error by Eq. (10) eliminates the problem, establishing a rate when the spacecraft is rolled and removing it when the roll angle is null. The yaw rate bias does not affect the stability of the lateral equations-of-motion.

Directional stability and coordinated turn logic remove the need to control yaw, simplifying the crossrange maneuver. Once headed in the proper direction, the pilot need not control along his flight path. The ability to yaw the spacecraft manually for observation is maintained, as neither $\phi_B$ nor $\phi_B$ is honored in the Direct Rate mode. When control passes to the Pseudo-Auto mode, $\phi_B$ opposes manual command, so such maneuvers should not be prolonged.

Attitude command in pitch and roll relieves the pilot of much work in flying and hover modes. As shown in Fig. 22c, the pilot need not consciously close the attitude-loop for system stability. With attitude command, steady-state ACA deflection commands linear acceleration. When the controller is released, the vehicle returns to the vertical and maintains constant horizontal velocity.

A review of the literature reveals that attitude command for the lunar landing has been tested at NASA FRC[9,11,12] although the testing was not as extensive as rate command testing. The limited numerical results and the comments of Mallick, Kuever, and Mattrang are generally favorable to attitude command[11]. Their negative observations are that pilots of the LLRV found the control less "natural", and that positive controller pressure is required to maintain non-zero attitude. The pilots did say, however, that attitude command is "easier to fly, especially near touchdown". The authors reach the same conclusion from analog-simulator and VTOL results, and add:

The greatest benefits from attitude control would seem to result from reduced initial training time to fly a craft so controlled, from the reduced continued pilot attention to control which results in reduced pilot fatigue over flights of long duration, and from more precise control under instrument flight conditions[11].

Since these design studies were made, the Lunar Module configuration has been defined, and a digital
control system has been introduced. The parameters varied in the FRC tests are now fixed, largely as a result of these tests. Those which can be changed now, e.g., ACA sensitivity and rate limiting, were not varied. Attitude command can be implemented in the LGC program by rescaling and rerouting the hand controller output in the present Q,R-axes control logic.

Conclusions and Recommendations

The Lunar Module rate command system provides rapid response to urgent inputs, as well as precise response to all commands. This is made possible by using Direct Rate and Pseudo-Auto modes of control and by computing RCS firing times as functions of vehicle inertia, bias acceleration, and rate. The sensitivity is gauged not by the size of the rate error but by the speed of hand controller deflection. Attitude errors are included in the control computation to limit drift about uncommanded axes and to provide integral compensation for rate control. Quadratic scaling of the ACA output minimizes the difficulty in commanding small rates, retaining high command rate capability. Improvement in the Lunar Module's handling qualities results in more precise landings and less fuel usage, in addition to better pilot ratings. The rate command mode provides acceptable response to commands in the face of jet failures and mass estimate errors.

In a sense, the LUMINARY rate command mode is a "second generation" system, for it draws upon analysis of extensive fixed-base and flight simulations of more basic control concepts. The earlier (SUNDANCE) version programmed in the Lunar Guidance Computer approximated these analog control systems. The LUMINARY manual mode is quintessentially digital, making forer use of the logical branching and nonlinearities which are so readily (and reliably) programmed in the digital computer. There are elements in the design which seem disturbing from a classical viewpoint: it is sampled and quantized, control torques are either on or off, there are transportation lags, there is no natural damping, the system limit cycles, and the signal flow varies from cycle to cycle.

The attitude control loop can be approximated by poles and zeros as long as it is buried within multiple loops, yet it defies linear approximation for closer examination. In spite of this, it is a logically straight-forward design whose response characteristics, though not sinusoids or exponentials, are easily predicted; they are simply powers of time. There lies the key to the design: the plant is simple, a pure integrator with negligible coupling.

Additional changes should be considered for advanced Lunar Module manual attitude control systems.

The Airplane Mode for lunar landing, which adds directional stability, coordinated turns, and attitude command, can be implemented by software changes alone. Such a system reduces the number of variables that must be actively controlled by the pilot.

The lags associated with the hand controller can be attacked in two ways. Fifty milliseconds could be saved by providing a separate interrupt for zeroing and enabling the ACA counters prior to the DAP interrupt. An additional 100 milliseconds could be saved if the ACA output were digital and if the ACA/LGC interface allowed parallel transmission of the output words.

One of the difficulties in commanding small rates is the pilot's inability to sense the onset of his control action. His only feedback is vehicle response. If the controller torque were supplanted or replaced by torque proportional to the actual output, e.g., by using the present ACA's voltage output to control a torque motor, the pilot could sense the output more quickly. A step increase in torque when output begins might suffice.

Increased control power during landing and decreased control power during docking are desirable but not mandatory changes. A 25% increase in RCS acceleration, accompanied by a moderate increase in controller scaling would aid handling qualities during the landing. To prevent over-control in a light Ascent configuration, a reduction in allowable minimum impulse or a second (lower) RCS thrust level would be a useful adjunct to this change.

References


