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by Jack E. Pennington, Howard G. Hatch, Jr., and Norman R. Driscoll

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SUMMARY

A full-size pilot-controlled simulation of the docking of the Apollo command and service module with the lunar module has been completed by using a six-degree-of-freedom dynamic simulator. The study was designed to investigate the pilot's ability to complete a successful docking by using only visual information. Several thruster failures and three vehicle control modes were simulated.

Results indicated that, with adequate visual aids and with no thruster failures, docking by using the primary control mode is not a difficult maneuver. Control-system failures increased the terminal docking errors and tended to reduce the pilot's confidence in his ability to control the vehicle precisely.

INTRODUCTION

The Apollo project makes use of the lunar-orbit-rendezvous technique (refs. 1 and 2) to provide a relatively large payload capability for the Saturn V launch vehicle. One of the important phases of the lunar-orbit-rendezvous technique is the pilot-controlled rendezvous and docking of two space vehicles. Docking will take place during two phases of the Apollo lunar-landing mission: (a) transposition docking during the translunar trajectory (between earth and moon); and (b) lunar-orbit docking following the ascent of the lunar module (LM) from the lunar surface.

Earlier studies of simulated dockings (refs. 3 and 4) have shown that a pilot can dock satisfactorily with the Gemini vehicle or with a generalized vehicle. The Apollo pilot, like the Gemini pilot, will have problems of visual parallax, cross coupling between control forces, and low control power, but to a different extent. Also, the Apollo pilot will not be able to see the vehicle docking mechanism at contact. In cooperation with the Manned Spacecraft Center and North American Aviation, Inc., the problems of pilot control

with various failures and vehicle control modes were investigated in a full-size six-degree-of-freedom piloted simulation of the docking of the command and service module (CSM) with the lunar module (LM). The rendezvous docking simulator at the Langley Research Center (ref. 5) was used in this investigation.

This report includes the results of the CSM-active docking simulation with particular reference to the pilot's control capabilities and requirements. The areas investigated are: (a) effects of various thruster failures, (b) comparison of vehicle control modes, and (c) ability to complete a successful docking with the target tumbling. Results are expressed both as quantitative measurements of terminal docking conditions and as subjective opinions of test pilots and astronauts.

SYMBOLS

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). Factors relating the two systems are given in reference 6.

f	fuel consumption, pounds (kilograms)
F	reaction control system jet thrust, pounds (newtons)
F_X, F_Y, F_Z	translational forces along CSM body axis, pounds (newtons)
M_X, M_Y, M_Z	rotational torques about CSM body axis, foot-pounds (newton-meters)
I_{sp}	specific impulse, seconds
I_{XX}, I_{YY}, I_{ZZ}	principal moments of inertia, slug-foot^2 (meter-newton-second^2)
I_{XY}, I_{XZ}, I_{YZ}	products of inertia, slug-foot^2 (meter-newton-second^2)
l	reaction control system moment arm, feet (meters)
p,q,r	angular velocities about vehicle body axes, degrees/second
t	flight time, seconds
X,Y,Z	Cartesian coordinate system

x,y,z	longitudinal, lateral, and vertical displacement, feet (meters)
x_c,y_c,z_c	distance from CSM center of mass to thrust center, feet (meters)
x_o,y_o,z_o	distance from CSM center of mass to docking face, feet (meters)
x_s,y_s,z_s	distance from CSM center of mass to simulator drive point, feet (meters)
x_t	longitudinal distance from target center of mass to docking face
ϕ	angle of roll, degrees
θ	angle of pitch, degrees
ψ	angle of yaw, degrees

Subscripts:

B	CSM motion with respect to CSM body axis
D	CSM motion with respect to simulator drive center
I	CSM motion with respect to an inertially fixed axis system
R	target motion with respect to CSM body axis
T	target motion with respect to target body axis

Abbreviations:

CM	command module
CSM	command and service module
LM	lunar module
RCS	reaction control system
SM	service module

Derivatives with respect to time are denoted by dots over the variables.

DESCRIPTION OF APPARATUS

Mission Phases

Pilot-controlled docking will take place during two phases of the Apollo mission. (See ref. 7.) In the transposition phase (fig. 1), which takes place during the translunar trajectory, the CSM is the active vehicle and the combination of the LM and the Saturn IVB vehicle is the passive target. In the lunar-orbit docking phase, which takes place following the ascent of the LM from the lunar surface, either the CSM or the LM can be the active vehicle. The choice of active vehicle will depend upon such factors as available fuel, crew status, and any spacecraft malfunctions.

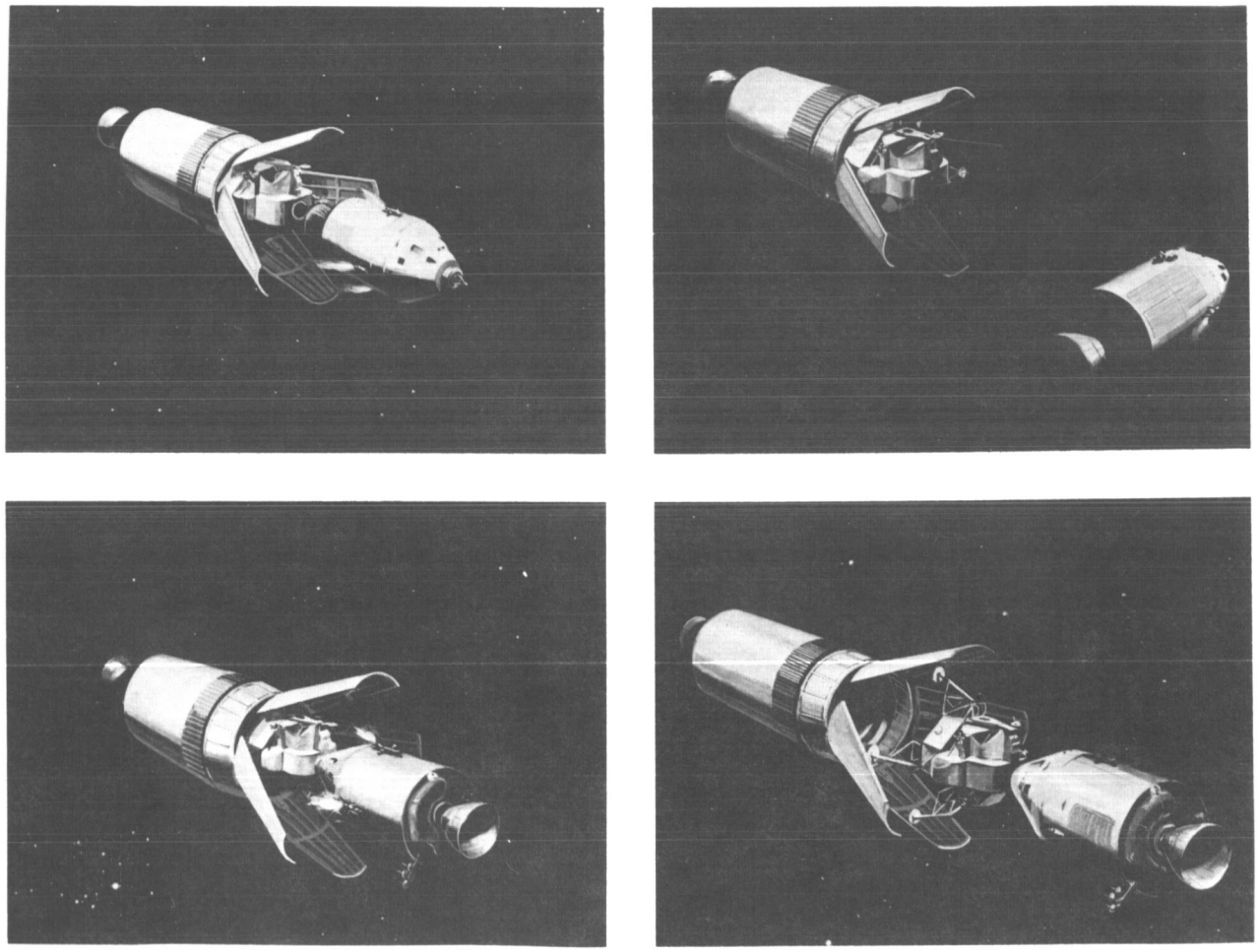


Figure 1.- Artist's conception of Apollo transposition maneuver. L-66-4527

The CSM-active docking operation in lunar orbit is much the same as the transposition docking operation except that the target is the ascent stage of the LM. In both phases the large mass and inertias of the CSM require accurate docking because of the loading limits of the latching mechanism and the low control power of the attitude system. The maximum design docking tolerances for both phases are $\pm 10^{\circ}$ in attitude, ±1 deg/sec in attitude rate, ±1 foot (0.3 m) in radial displacement, ±0.5 foot/sec (0.15 m/s) in lateral and vertical velocity, and 1 foot/sec (0.30 m/s) in longitudinal (closure) rate. An additional requirement to insure proper latching is that longitudinal velocity be greater than 0.1 foot/sec (0.03 m/s).

Command and Service Module

The command and service module (CSM), which was the active vehicle in this study, is a two-part vehicle composed of the Apollo command module (CM) and the Apollo service module (SM). The SM reaction control system (RCS) consists of four independent, equally capable networks each made up of four reaction control engines or thrusters (one quad), tankage, and regulating components. Each RCS network is mounted on a panel near the forward end of the SM, as shown in figure 2. Two of the engines in each quad are used for roll control, and the other two are used for either pitch or yaw control, depending upon the location of the network. Different combinations of these thrusters provide translation control.

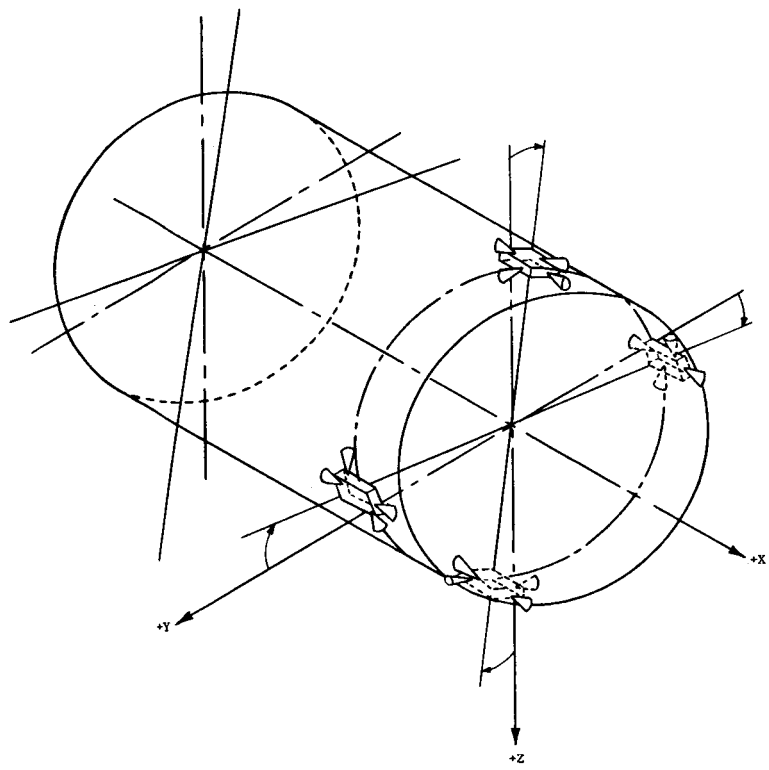


Figure 2.- Schematic drawing of Apollo service module showing RCS thruster locations.

Control Modes

Control of the CSM attitude during docking control modes by using the RCS is accomplished by selection of one of three functional modes of control: rate command with attitude hold, rate command without attitude hold, and direct (acceleration) command. The rate-command/attitude-hold control mode is the primary Apollo control mode; the latter two are secondary modes.

Rate-command mode.- In the rate-command mode (without attitude hold), movement of the attitude hand controller (fig. 3), actuated by the pilot's right hand, commands a spacecraft angular rate about each axis proportional to the displacement of the controller, up to a maximum of 0.85 deg/sec. With the hand controller centered, or at a neutral position, the spacecraft rate about each axis is damped within a rate dead band of 0.2 deg/sec.

Figure 3.- Pilot seated in cockpit. L-65-6460.1

Rate-command/attitude-hold mode.- With the attitude-hold circuit engaged, the spacecraft attitude is held within both an angular-rate dead band of 0.2 deg/sec and a small angular dead band (0.2 deg in the simulation), as long as the controller remains centered. When the controller is actuated, the attitude-hold circuit is automatically disengaged.

Direct control mode.- In the direct control mode, the jets are fired directly by movement of the attitude hand controller actuated by the pilot's right hand. Angular

acceleration is the maximum provided by the thrusters for the period of hand-controller deflection. The Apollo pilot can obtain direct attitude control either by individual axis selection at the control panel, which in turn energizes switches in the controller that are activated when the controller is deflected 2° from the center position, or by maximum deflection of the controller, which engages override switches located about 12° from center. In the simulation program, the individual-axis selection was not possible (the same mode was used for all three axes), and the direct control mode used the override switches.

In the direct control mode the Apollo pilot must compensate for cross coupling of angular rates, which would be automatically damped if the rate-command mode were used. In addition to the normal inertial coupling of angular rates which occurs when more than one angular rate exists, significant coupling is caused by the relation of the control jets to the center of mass of the CSM. Firing of the translation jets which are not directed through the mass center produces significant torques about all three axes. The attitude-disturbance torques in pitch and yaw, introduced by vertical and lateral translation thrust, equal about one-fourth of the torques produced by the attitude thrusters.

Translation control.- Translation control is similar to the direct control mode in that deflection of the three-axis translation controller (fig. 3), actuated by the pilot's left hand, fires the translation thrusters directly (after signal processing), with no velocity-feedback signals provided.

Simulation Facility and Operation

The CSM-active docking facility involved a full-size model of the pilot's compartment and nose section of the Apollo command module, associated drive systems, a jet selection and controller interface unit, a general-purpose analog computer, and a full-size model of the LM ascent stage. The design, operation, and capabilities of the facility are described in detail in reference 5. The model (fig. 4) was driven in six degrees of dynamic freedom.

The large size of the Apollo command module (12-foot (3.7-m) diameter) prevented placing a model of the entire CM in the simulator gimbal system (with 7-foot-diameter (2.1-m) capability); therefore, only the command (docking) pilot's compartment was placed in the gimbal system. This cutout part of the CM provided the correct field of view for the simulator pilot. Inside the cockpit was mounted a gunsight, used as a collimated sight, and two side-arm controllers located on either side of the seat. Moving either controller transmitted signals to the jet selection and controller interface unit which simulated the proper control jets. A more complete description of the interface unit is given in appendix A.

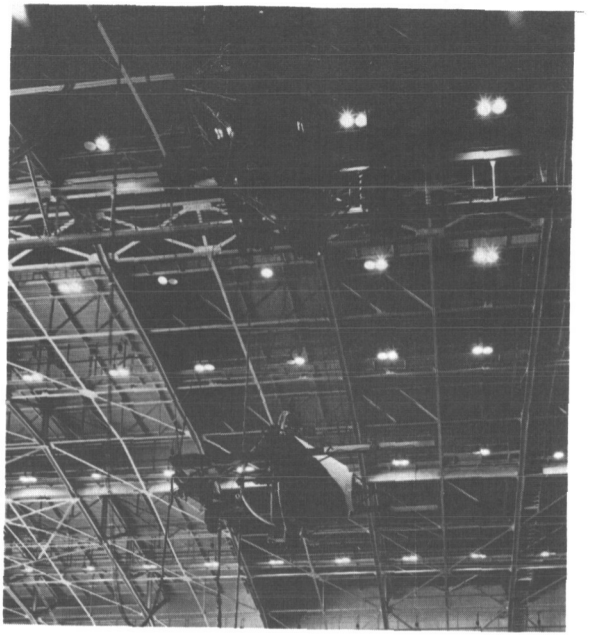


Figure 4.- Photograph of rendezvous docking facility. L-66-1432

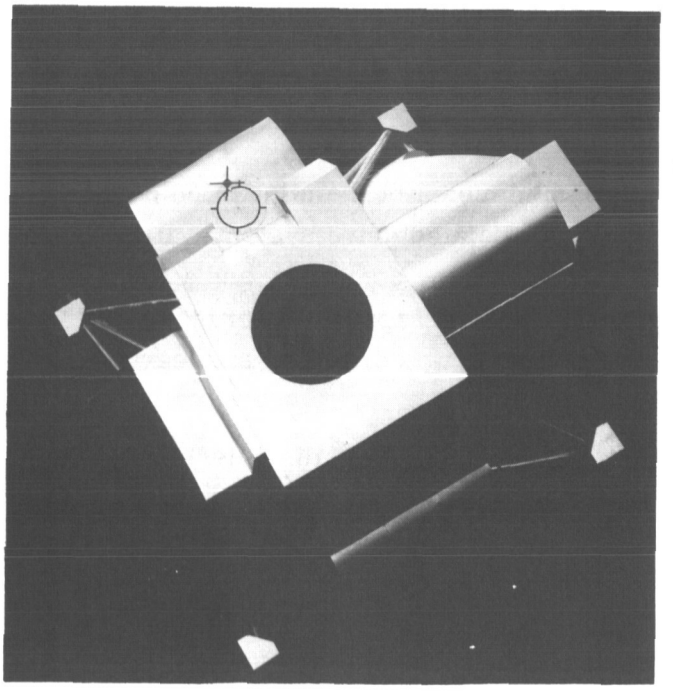
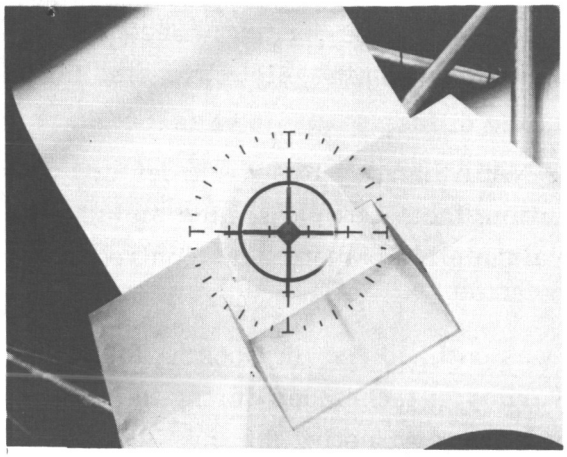


Figure 5.- LM docking target. L-66-2111

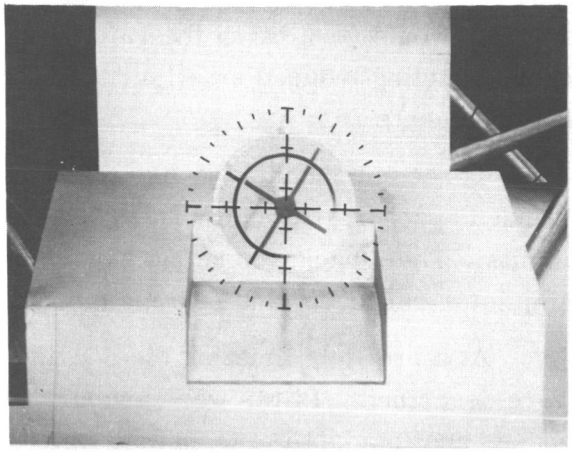
The target (fig. 5) was a full-size model of the ascent stage of the lunar module suspended from the ceiling. It was painted diffusive aluminum (about 76 percent reflectivity) and did not have latching facilities. High-intensity flashing xenon lamps (210 lumen-seconds output) were placed on the target to determine the effects of glare, such as that which might be caused by LM reaction-control jets, on the pilot's control of docking. The pilot's design eye position, which was about 23 inches (0.6 m) to the left of and 40 inches (1.0 m) above the CSM center line, prevented the pilot from seeing the LM docking hatch when the vehicles were less than about 10 feet (3.0 m) apart; therefore, a visual aid was mounted on the LM target along the pilot's line of sight to assist in vehicle alinement. Translation and attitude errors were zero when the cross on the aid was centered against the rear disk and the collimated reticle in the cockpit was superimposed on the cross. Figure 6 shows the pilot's view of the aid with various displacement errors.

Mathematical Model and Equations of Motion

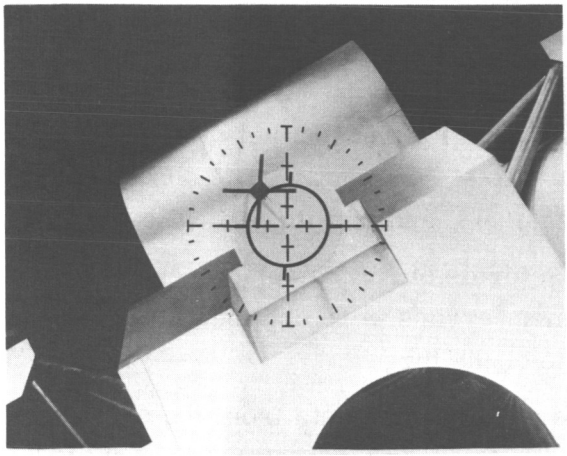
A general-purpose analog computer closed the loop between the pilot and the simulator. The computer transformed and integrated the control-jet inputs to provide velocity and position commands for the simulator drive system. Because of the small amount of fuel used compared with the vehicle mass, it was assumed in the simulation that the CSM mass and the



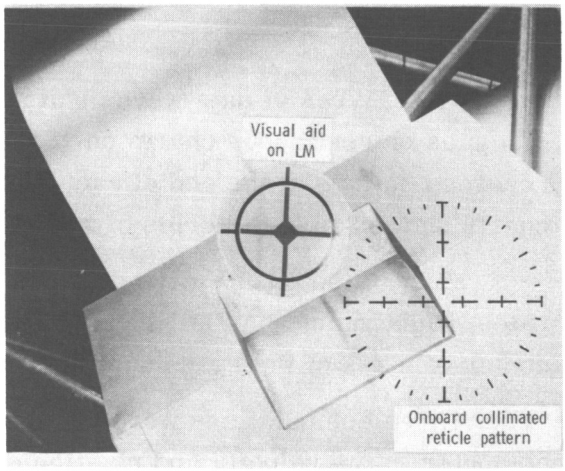
(a) No errors. Vehicles correctly alined.



(b) Roll attitude error. No translation error.



(c) CSM translated to right and below target.



(d) CSM pitched down and yawed right relative to target.

Figure 6.- Pilot's view of visual docking aid with various displacement errors.

L-66-4528.1

center of mass did not change. In addition, orbital mechanics effects were neglected because of short distances and low rates used. The equations of motion used in the docking simulation are given in appendix B.

PROCEDURE AND DATA ANALYSIS

Simulation Procedure

Docking flights were made with initial offsets of 55 feet (16.8 m) longitudinally, up to 5 feet (1.5 m) vertically and laterally, and from 5° to 10° displacement about all three axes from a wings-level/straight-ahead attitude. No initial rates were used for two reasons. First, in earlier flights it was found that if high initial rates were used,

the pilot would first bring the rates near zero before initiating the docking. Second, the cross coupling induced small attitude and translation rates when the pilot corrected initial displacements.

Three astronauts and five test pilots from the NASA Langley Research Center and Manned Spacecraft Center and North American Aviation, Inc., took part in the simulated flights. Their background and experience were invaluable in evaluating the control task, simulator response, and piloting techniques.

At a preflight briefing the docking maneuver was outlined and the docking tolerances were described. Pilots were encouraged to try a variety of techniques during the training phases and to adapt the technique which was most satisfactory, noting that minimum fuel usage and maximum accuracy were not necessarily compatible. Pilots were instructed to reach a compromise.

Data Reduction and Analysis

Three types of data were obtained in the simulations: (1) data recorded as time histories on continuous charts on 16 data channels, (2) digital readouts of all outputs recorded on tape at the end of each run, and (3) the pilots' comments. The continuous charts showed time histories of velocities, displacements, and fuel throughout each flight.

Most of the quantitative data are expressed in terms of final displacement errors, rates, flight time, and fuel usage. Final displacement errors were obtained between the center of mass of the spacecraft and the center line of the target.

Three computations were performed on the digital readout data from the analog computer. The velocity and position error of the nose of the spacecraft was calculated from the center-of-mass data, and then the terminal velocities, position errors, fuel use, and flight time were averaged for each set of related flights. The standard deviation σ was calculated by using the following equation from reference 8:

$$\sigma = \left[\frac{1}{n - 1} \sum_{n=1}^{i} \left(a_i - \bar{a}\right)^2\right]^{1/2}$$

where n is the number of flights, a_i is the data obtained in the ith flight, and $\bar{a}$ is the average of n data points.

Pilot comments and ratings were obtained at the end of a series of flights in a particular configuration. Pilots were asked first, to give a numerical rating of the control task by using the form shown in table I, which is based on the Cooper rating system in

reference 9 and, second, to make qualitative comments concerning the configuration flown. Pilot comments have been included wherever possible in this report.

Cases Studied

For the docking maneuver simulated, the pilot obtained all information (range, range rate, attitude, and so forth) from just the visual cues afforded by the LM target. The objectives of the study were to investigate: (1) docking accuracies with each of the three control modes, (2) effects of various jet failures, and (3) differences between day and night lighting conditions. The cases studied are listed in table II.

The simulated electrical bus failure results in failure of half the 16 RCS jets. Three jets are failed in two adjacent quads (one jet in the positive X-position and one jet in the negative X-position are not failed); one jet in each of the other two quads is failed such that opposite quads have jets in the same X-position failed.

All the cases listed in table II were flown with the primary (rotational priority) jet-select logic (see appendix A) except the one titled "one quad – secondary," for which the secondary (equal priority) jet-select logic was used.

Target (LM ascent stage) tumbling rates up to 0.5 deg/sec were simulated in the lunar-orbit docking configuration. Rates of 0.17 deg/sec were simulated in the transposition docking (LM and S-IVB target) configuration. The primary difference between the lunar-orbit and the transposition docking with the stable target was the smaller mass and inertia and, therefore, greater control power of the CSM in the lunar-orbit phase. With the target tumbling, the transposition docking was more difficult than the lunar-orbit docking because of the much larger distance between the target center of mass and the docking face. Thus, for the same tumbling rates, the docking face of the target moved at a significantly higher rate in the transposition phase than in the lunar-orbit docking phase. The vehicle parameters are listed in the following table:

Parameter	Lunar-orbit phase	Transposition phase
$\dot{p}$, deg/sec^2	9.8	5.1
$\dot{q}$, deg/sec^2	1.5	1.1
$\dot{r}$, deg/sec^2	1.5	1.1
F, lbf (N)	100 (445)	100 (445)
I_{sp}, sec	290	290
l, ft (m)	6.96 (2.12)	6.96 (2.12)
x_o, ft (m)	14.60 (4.45)	15.11 (4.61)
y_o, ft (m)	-0.93 (-0.28)	-1.66 (-0.51)
z_o, ft (m)	-0.22 (-0.07)	-0.025 (-0.008)

Parameter	Lunar-orbit phase	Transposition phase
x_c, ft (m)	1.67 (0.51)	2.18 (0.66)
y_c, ft (m)	-0.93 (-0.28)	-1.66 (-0.51)
z_c, ft (m)	-0.22 (-0.07)	-0.025 (-0.008)
x_s, ft (m)	9.17 (2.80)	9.68 (2.95)
y_s, ft (m)	-1.72 (-0.52)	-2.45 (-0.75)
z_s, ft (m)	-1.89 (-0.58)	-0.64 (-0.20)
x_t, ft (m)	5.91 (1.8)	26.45 (8.1)
$\ddot{x}_B$, ft/sec^2 (m/s^2) . . .	0.4 (0.12)	0.2 (0.06)
$\ddot{y}_B$, ft/sec^2 (m/s^2) . . .	0.2 (0.06)	0.1 (0.03)
$\ddot{z}_B$, ft/sec^2 (m/s^2) . . .	0.2 (0.06)	0.1 (0.03)

RESULTS AND DISCUSSION

Comparison of Rate-Command/Attitude-Hold and Direct Control Modes

Table III shows the results of flights made with the primary Apollo control mode (rate command/attitude hold) in the lunar-orbit docking configuration with no thruster failures. All these flights were successful and the terminal conditions were well within design tolerances. Table IV shows the results of flights made in the same configuration except the pilot used the direct control mode instead of the rate-command/attitude-hold control mode.

Using the direct control mode (table IV) pilots were confident of their ability to control the CSM, but only 89 percent of the flights were successful. The angular acceleration about the roll (X) axis, which was four to five times as large as the acceleration about the other two axes, made precise roll control difficult. A more desirable acceleration level would result if two rather than four jets were fired for roll. All the unsuccessful flights were caused by a roll angular rate which was greater than the design tolerance level of 1 deg/sec. Fuel usage was generally less but varied more widely in this mode than in the more precise rate-command/attitude-hold mode. The control task would probably have been somewhat easier if the on-off switches had been located near the center (breakout) point instead of at maximum deflection, but this feature was not investigated in this study.

Effects of Failure One Quad of Reaction Control System

Table V shows the results of flights made with the rate-command/attitude-hold mode in the lunar-orbit docking configuration with one RCS quad failed. Flight conditions

were the same as those reported in table III except for the thruster failure. Pilots noted that except for slightly reduced control power, a single quad failure had no significant effect. The attitude-hold feature of the control system prevented any attitude change caused by cross coupling from translation thrusts.

Comparison of Rate-Command/Attitude-Hold and Rate-Command Control Modes

Table VI shows the results of flights made with the rate-command control mode in the lunar-orbit docking configuration with one RCS quad failed. Flight conditions differed from those reported in table V only in the attitude control mode used. As would be expected, when the rate-command mode was used rather than the rate-command/attitude-hold mode, there was a decrease in control precision. Therefore, the results show a slight decrease in the amount of fuel required and an increase in terminal errors because a precise attitude was not held. Pilot comments and the poorer Cooper rating given the system verify these results. Even with the less precise control system, pilots were able to complete almost all runs within the docking tolerances.

Comparison of Jet-Select Logics

All the results except those shown in table VII were obtained from flights made using the primary jet-select logic (appendix A). Conditions for the flights reported in table VII were the same as those for the flights reported in table VI except for the jet-select logic. The results indicate, and the pilots agreed, that there was no significant difference between the two jet-select logics.

Comparison of Day and Night Flights

Table VIII shows the results of night flights made with the rate-command/attitude-hold mode in the lunar-orbit docking configuration with no thruster failures. These flight conditions are the same as those of table III except that the flights in table III were made during the day.

Although the hangar was darkened as much as possible, the night flights (table VIII) did not represent completely dark conditions. Ambient lights made all the LM features visible at maximum ranges; therefore, it might be well to consider the conditions only degraded from sunlight conditions. However, the fact that the pilots tended to concentrate on the visual aid mounted on the LM for visual cues indicates that the loss of target aspect under completely dark conditions should not be a major problem.

The high-intensity strobe lights used to represent the LM reaction control jet glare were annoying but did not appreciably affect the pilot's control task or the terminal conditions. All night flights were within docking tolerances.

Comparison of Lunar-Orbit and Transposition Docking Configurations

Table IX shows the results of flights made with the rate-command/attitude-hold mode in the transposition docking configuration with no thruster failures. The only significant difference between these flights and those made in the lunar-orbit docking configuration (table III) was an increase in the fuel expended. More fuel was required to control the vehicle in the transposition configuration because it is considerably larger and heavier than in the lunar-orbit docking configuration. The difference in the Cooper ratings given by the pilots to the two configurations (tables III and IX) is probably due to different pilots who flew the configurations. It should be noted that the Cooper ratings show a trend rather than an exact numerical ranking because every pilot did not fly every configuration. The pilot ratings and quantitative results given in the tables generally agree in that the more adverse the pilot rating was, the less accurate the terminal condition and the smaller the percentage of success. Pilots who flew both configurations noted that the reduced control power in the transposition phase was noticeable but not detrimental.

Effect of Multiple Thruster Failures

With a single electrical bus failure (table X) 23 runs were attempted, but 14 of them were halted because of simulator limits. Only 7 of the 9 runs completed were successful. Successful docking was possible from some initial conditions, but not from others.

The CSM was not completely uncontrollable; the vehicle could be stabilized, but maneuvering caused significant cross coupling and required large fuel expenditures. The adverse Cooper rating given this configuration (6.5) indicates the pilots' lack of confidence in docking with a bus failure.

Table XI shows the combined results of flights made with either two adjacent or two opposite RCS quads failed. Of the sixteen runs attempted, 11 were halted because of simulator limits; 2 of the 5 completed runs were out of tolerance. The configuration was completely unflyable with adjacent RCS quads failed. Both pilots succeeded in stabilizing the vehicle, but then the translation input caused an attitude disturbance, and a thrust applied to damp the attitude disturbance arrested the translation. Thus, the only net changes were in the amount of fuel used and in the pilot's disposition.

A limited amount of success was achieved with failure in opposite RCS quads. A large operating volume was required and the pilots had to make some maneuvers from an

attitude in which the target was not visible, but it was possible to maneuver the vehicle. The adverse Cooper rating given this configuration (9) indicates the pilots' lack of confidence.

Effects of Target Tumbling

Terminal errors and fuel usage were larger for flights in which pilots docked with the simulated target tumbling at a rate of 0.17 deg/sec (table XIV) than those for flights in which they docked with the stable target. Tumbling data in tables XII and XIV should be applied with caution because the fact that docking can be accomplished with the target tumbling at a given continuous rate does not necessarily imply that a cyclic rate of the same magnitude could be tolerated.

Pilots in the lunar-orbit docking configuration with the LM tumbling at a rate of 0.15 deg/sec (table XII) and in the transposition configuration with the LM tumbling at a rate of 0.17 deg/sec (table XIV) were confident that they could complete the docking, and all docking runs for these LM tumbling rates were successful. Either the rate-command or the direct control mode was found to be suitable. The choice of control mode would thus be based on pilot preference. The rate-command/attitude-hold mode was impractical because the CSM was required to rotate continuously in order to match the attitude of the LM target.

For the lunar-orbit docking configuration, terminal errors and fuel usage were higher at the higher tumbling rate of 0.25 deg/sec (table XIII). Of the 13 docking runs attempted, 12 were successful. The direct attitude control mode was required because the rate-command system damped to 0.20 deg/sec, a rate less than that needed to match the angular rates of the target.

A few flights were made for an LM tumbling rate of 0.50 deg/sec. As would be expected, pilot confidence decreased, and fuel usage and terminal errors increased. Results indicate that docking with tumbling rates in excess of about 0.2 deg/sec should be avoided because of excessive RCS fuel usage and difficult spacecraft control.

Visual Aspects of the Docking Simulation

All the data which have been presented are based upon flights made using a collimated reticle (gunsight) in the cockpit and the standoff cross aid (fig. 6) mounted on the LM target. Earlier docking studies (refs. 4 and 10) have shown that the visual aids strongly influence pilot confidence and docking accuracies because the pilot can control properly only if he has adequate visual cues. Pilots thought that both aids used in this study were satisfactory and provided adequate cues. The collimated reticle (gunsight) allowed the pilot some head movement and made it unnecessary for him to refocus his

eyes between the target and the reticle. A similar collimated sight will be on the Apollo CSM. The standoff cross provided precise alinement cues, particularly at close range, and could be scaled up or down to meet space or weight requirements of the spacecraft without significant degradation. One suggested improvement was to construct the standoff cross with a feature which would designate the 12 o'clock position. This feature will be incorporated on the visual aids for actual flight.

CONCLUSIONS

The results of the simulation of the Apollo command and service module (CSM) docking maneuver wherein the pilot used only visual information for spacecraft control indicate the following conclusions:

1. Pilots were confident of the docking maneuver during the day and under the dark conditions simulated when using any of the three control modes tested (rate command, rate command with atitude hold, and direct) with no thruster failures. Pilots could consistently dock within the design tolerances by using the rate-command/attitude-hold control mode. The rate-command/attitude-hold control mode was completely satisfactory with a stable target.

2. The direct control mode required care to keep the terminal angular rates below the design tolerance of 1 deg/sec. A more desirable acceleration level would result if two rather than four jets of the reaction control system were used for roll acceleration.

3. There were no problems in controlling the CSM with one quad of the reaction control system failed by using the rate command/attitude hold or the rate command control mode.

4. There was no apparent difference between the two jet-select logics tested.

5. Electrical bus failure or a failure of two quads in the reaction control system did not result in complete loss of control, but successful docking was not repeatable under all conditions. The large amount of fuel required to maneuver the CSM with these failures may pose a possible restraint to the CSM-active docking.

6. Pilots were able to complete successful dockings with target tumbling rates of 0.15 deg/sec in the lunar-orbit docking configuration and 0.17 deg/sec in the transposition configuration. Fewer successful dockings could be completed at higher tumbling rates. Rates in excess of about 0.2 deg/sec should be avoided because of the excessive amount of fuel required.

7. The visual aids used in the study were satisfactory. One suggested improvement was a feature which would designate the 12 o'clock position of the standoff cross.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 17, 1966,
125-19-01-0600-23.

APPENDIX A

DESCRIPTION OF INTERFACE UNIT

The interface unit, separate from the analog computer, was required to convert the alternating-current signals from the controller to direct-current signals, and to simulate control-system switching, priority logic, and thrust dynamics. The following sections describe in detail the various operations of the interface unit.

Characteristics of Simulated Reaction Control System Thruster

The thrust characteristics of a service-module reaction control system jet were approximated in the interface unit by the following equation:

$$T = 100\left(\Delta t + d_2 - d_1\right)$$

where T is the thrust impulse in pound-seconds (newton-seconds) and Δt is the duration of the electrical thrust command signal in milliseconds. The values used in the interface unit for the docking study were:

Δt_{min} = 20 milliseconds (minimum electrical pulse width)

d_1 = 12.5 milliseconds (thrust-on transport lag)

d_2 = 6 milliseconds (thrust-off transport lag)

Jet-Select Logic

Two different types of jet-select logic were used in the simulation. The primary logic provided that pitch and yaw commands had priority over translation commands, and translation commands had priority over roll commands. Thus, when a situation called for two opposing jets to fire, one due to a translation command and one due to a pitch or yaw command, the jet providing pitch or yaw would fire. The secondary (equal priority) logic provided that no axis or maneuver had priority. Thus, when a situation called for opposing jets to fire, both jets would fire, causing fuel consumption with no net motion.

Failure Selection

Sixteen switches corresponding to the jets of the reaction control system enabled selection of normal, failed-off (propellant values closed) or failed-on (propellant values open) conditions. These switches were used in combination in the simulation to represent quad and bus failures.

APPENDIX B

EQUATIONS OF MOTION

Four orthogonal, right-hand axis frames were incorporated in the simulation:

1. The B-axis frame (identified by subscript B) represented the body-axis system of the CSM, with the origin at the CSM center of mass.

2. The I-axis frame (identified by subscript I) was inertially stabilized in rotation, with the origin at the CSM center of mass.

3. The axes of the D-axis frame (identified by subscript D) were parallel to those of the I-axis frame but the center was located at the drive point of the simulator attitude (gimbal) system. The D- and I-frames were separated by the distances from the center of gravity to the gimbal center x_s, y_s, z_s.

4. The T-axis frame (identified by subscript T) represented the body-axis system of the target. For flights in which the target was stable, the axes of the T-frame were parallel to those of the I- and D-frames. The relative positions of the B-frame and T-frame determined the attitude and center-of-gravity errors between the CSM and the target. The nose (docking hatch) position and velocity errors were computed as part of a digital data-reduction program.

A pitch, yaw, roll (θ, ψ, ϕ) order of rotation was used in transforming from the body-axis system to the inertial-axis system. The Euler transformation equations (ref. 11) used in the simulation were:

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix}_I = \begin{bmatrix} \cos\theta\cos\psi & \sin\theta\sin\phi - \cos\theta\sin\psi\cos\phi & \sin\theta\cos\phi + \cos\theta\sin\psi\sin\phi \\ \sin\psi & \cos\psi\cos\phi & -\cos\psi\sin\phi \\ -\sin\theta\cos\psi & \cos\theta\sin\phi + \sin\theta\sin\psi\cos\phi & \cos\phi\cos\theta - \sin\theta\sin\psi\sin\phi \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix}_B \tag{B1}$$

The translation velocity of the drive system was modified to compensate for the difference between the center of the drive system and the CSM center of mass as follows:

$$\dot{x}_D = \dot{x}_I + qz_s - ry_s \tag{B2}$$

$$\dot{y}_D = \dot{y}_I + rx_s - pz_s \tag{B3}$$

$$\dot{z}_D = \dot{z}_I + py_s - qx_s \tag{B4}$$

where x_s, y_s, and z_s are the coordinates of the drive center with respect to the CSM center of mass.

A second matrix is needed to transfer the position and velocity from the inertial system to the target system for error calculation:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix}_T = \begin{bmatrix} \cos\theta_T \cos\psi_T & \sin\psi_T & -\sin\theta_T \cos\psi_T \\ \sin\theta_T \sin\phi_T - \cos\theta_T \sin\psi_T \cos\phi_T & \cos\psi_T \cos\phi_T & \cos\theta_T \sin\phi_T + \sin\theta_T \sin\psi_T \cos\phi_T \\ \sin\theta_T \cos\phi_T + \cos\theta_T \sin\psi_T \sin\phi_T & -\cos\psi_T \sin\phi_T & \cos\phi_T \cos\theta_T - \sin\theta_T \sin\psi_T \sin\phi_T \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix}_I \tag{B5}$$

where θ_T, ψ_T, and ϕ_T define the attitude of the target axis relative to the inertial frame.

The moment equations, which assume rigid-body dynamics, are as follows:

$$\dot{p}_B I_{XX} = M_X + F_X y_c - F_Y z_c + I_{XY}\left(\dot{q}_B - p_B r_B\right) + I_{XZ}\left(p_B q_B + \dot{r}_B\right) \tag{B6}$$

$$\dot{q}_B I_{YY} = M_Y + F_Y z_c - F_Z x_c + \left(I_{ZZ} - I_{XX}\right) p_B r_B + I_{YZ}\dot{r} + I_{XY}\left(\dot{p}_B + q_B r_B\right) \tag{B7}$$

$$\dot{r}_B I_{ZZ} = M_Z + F_Z x_c - F_X y_c + \left(I_{XX} - I_{YY}\right) p_B r_B + I_{XY}\left(p_B{}^2 - q_B{}^2\right) + I_{XZ}\dot{p}_B + I_{YZ}\dot{q}_B \tag{B8}$$

The coordinates x_c, y_c, and z_c define the coordinate of the thrust center with respect to the center of mass.

The rotational cross-coupling terms which are not included in equations (B6) to (B8) are neglected because their effects are less than 1 percent of the vehicle control power. Other simplifying assumptions used for the study are: (1) no orbital effects; (2) constant mass for both vehicles; and (3) constant specific impulse.

If the target is tumbling, it is necessary to determine the relative angular velocities of the two vehicles in order to drive the simulator correctly. Equations (B6) to (B8) can, of course, be considered relative velocities for the nontumbling case. The relative angular velocities are given by:

$$p = p_B + p_R \tag{B9}$$

$$q = q_B + q_R \tag{B10}$$

$$r = r_B + r_R \tag{B11}$$

where p_B, q_B, and r_B are the velocities obtained by integrating equations (B6) to (B8). The terms p_R, q_R, and r_R are the components of the target angular rate about the CSM body axes. These rates are obtained from:

$$\begin{bmatrix} p_R \\ q_R \\ r_R \end{bmatrix} = \begin{bmatrix} A \end{bmatrix} \begin{bmatrix} B \end{bmatrix} \begin{bmatrix} p_T \\ q_T \\ r_T \end{bmatrix} \tag{B12}$$

where matrix $\begin{bmatrix} A \end{bmatrix}$ is the inverse of the matrix in equation (B1), and matrix $\begin{bmatrix} B \end{bmatrix}$ is the inverse of the matrix in equation (B5).

With the relative angular velocities available, the inertial (Euler) angular rates are computed from:

$$\dot{\psi} = q \sin \phi + r \cos \phi \tag{B13}$$

$$\dot{\theta} = (q \cos \phi - r \sin \phi)/\cos \psi \tag{B14}$$

$$\dot{\phi} = p - \dot{\theta} \sin \psi \tag{B15}$$

The Euler angular rates in equations (B13) to (B15) are integrated to obtain the Euler angle commands for the simulator gimbal system.

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TABLE I.- PILOT OPINION RATING SCHEDULE

[From ref. 9]

Operation	Adjective rating	Numerical rating	Description	Primary mission accomplished
Normal	Satisfactory	1	Excellent, includes optimum	Yes
		2	Good, pleasant to fly	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes
Emergency	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes
		5	Unacceptable for normal operation	Doubtful
		6	Acceptable for emergency condition only	Doubtful
None	Unacceptable	7	Unacceptable even for emergency condition	No
		8	Unacceptable – dangerous	No
		9	Unacceptable – uncontrollable	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No

TABLE II.- DOCKING CASES STUDIED

Attitude control mode	Failure	Lighting	Docking configuration	Results given in table –
Rate command/attitude hold	None	Day	Lunar orbit	III
Direct	None	Day	Lunar orbit	IV
Rate command/attitude hold	One quad	Day	Lunar orbit	V
Rate command	One quad	Day	Lunar orbit	VI
Rate command	One quad – secondary	Day	Lunar orbit	VII
Rate command/attitude hold	None	Night	Lunar orbit	VIII
Rate command/attitude hold	None	Day	Transposition	IX
Rate command/attitude hold	Bus	Day	Lunar orbit	X
Rate command/attitude hold	Two quads	Day	Lunar orbit	XI
Direct or rate command	Target tumbling	Day	Lunar orbit	XII, XIII
Direct or rate command	Target tumbling	Day	Transposition	XIV

TABLE III.- TERMINAL CONDITIONS OF DAY FLIGHTS IN LUNAR-ORBIT DOCKING CONFIGURATION WITH NO FAILURE FOR RATE-COMMAND/ATTITUDE-HOLD CONTROL MODE

[26 flights; all flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute value	Mean absolute value
f	7.91	4.44	20.03	7.91
t	166	24	211	166
Displacements				
y	-0.07	0.14	0.38	0.12
z	-.03	.11	.29	.09
ϕ	.55	1.08	4.20	.81
θ	-.11	.64	1.30	.49
ψ	-.15	.92	2.24	.71
Rates				
$\dot{x}$	0.42	0.08	0.72	0.42
$\dot{y}$	-.02	.07	.18	.06
$\dot{z}$	-.03	.06	.30	.04
p	0	.09	.20	.07
q	.01	.05	.14	.03
r	.01	.06	.14	.05

Pilot comments: The rate-command/attitude-hold control mode was a first-class one. The translation control had good positive response and about the right amount of authority. The dead band of this control mode was so tight that there were no perturbations and there was no noticeable oscillation of the vehicle. The attitude dead band, rate dead band, and maximum proportional rate command available were very acceptable.

The CSM docking maneuver was a slow, relatively simple piloting task. A sufficient amount of control power was available in all degrees of freedom, and vehicle response characteristics were compatible with the conditioned reflexes of a trained aircraft pilot. General visibility, although restricted, was adequate for accomplishing the maneuver.

The average Cooper rating given by the four pilots who flew this configuration was 2.0.

TABLE IV.- TERMINAL CONDITIONS OF DAY FLIGHTS IN LUNAR-ORBIT DOCKING CONFIGURATION WITH NO FAILURE FOR DIRECT CONTROL MODE

[19 flights; 17 flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute value	Mean absolute value
f	9.07	2.56	15.61	9.07
t	211	87	448	211
Displacements				
y	0.09	0.20	0.49	0.18
z	-.02	.20	.49	.14
ϕ	.25	1.38	3.02	1.11
θ	-1.07	1.28	3.90	1.22
ψ	.26	1.88	4.30	1.37
Rates				
$\dot{x}$	0.45	0.13	0.62	0.45
$\dot{y}$	.07	.11	.32	.09
$\dot{z}$	.02	.05	.17	.03
p	-.05	.79	2.95	.43
q	0	.16	.53	.11
r	.02	.24	.55	.19

Pilot comments: The effect of the center-of-gravity position on attitude excursions incurred with translation inputs became quite evident. Since the center of gravity was rearward of a plane containing the four quads, a translation input caused an attitude acceleration and was quite bothersome.

The importance of the standoff cross visual aid on the LM and the collimated reticle on the CSM became quite obvious for this degraded control mode. One pilot obtained best results by keeping his eyes fixed on the standoff cross and occasionally referring to the collimated reticle. Hence, translation control was more of a problem than attitude control for this pilot, who gave this configuration a Cooper rating of 4.

Roll response was slightly oversensitive in this configuration and, as a result, the maneuver was generally accomplished with a noticeable roll rate.

Control was positive and easily accomplished and could have been rated good, but lack of attitude hold required a bit more work, so a satisfactory rating was selected.

The average Cooper rating given by the three pilots who flew this configuration was 3.3.

TABLE V.- TERMINAL CONDITIONS OF DAY FLIGHTS IN LUNAR-ORBIT DOCKING CONFIGURATION WITH ONE RCS QUAD FAILED FOR RATE-COMMAND/ATTITUDE-HOLD CONTROL MODE

[19 flights; all flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute value	Mean absolute value
f	11.32	4.21	21.50	11.32
t	231	50	309	231
Displacements				
y	0.07	0.09	0.24	0.10
z	-.07	.15	.34	.13
ϕ	-.29	.58	1.70	.46
θ	-.39	.40	1.10	.49
ψ	.75	.63	1.94	.77
Rates				
$\dot{x}$	0.38	0.17	0.82	0.38
$\dot{y}$	0	.07	.13	.05
$\dot{z}$	.01	.04	.12	.03
p	.02	.06	.11	.06
q	0	.06	.11	.04
r	-.02	.05	.13	.04

Pilot comments: The rate-command/attitude-hold control mode was very easy to fly. The attitude-hold feature of the control system maintained a stable attitude even with one quad failed.

A single RCS quad failure was difficult to detect through qualitative assessment of the handling characteristics. Cross-coupling effects were, in general, masked by the rate-command/attitude-hold control mode. A pilot who is thoroughly familiar with the response characteristics of the CSM might notice the reduced control power in the X-direction and in the plane of the failed quad.

The average Cooper rating given by the three pilots who flew this configuration was 2.3.

TABLE VI.- TERMINAL CONDITION OF DAY FLIGHTS IN LUNAR-ORBIT DOCKING CONFIGURATION WITH ONE RCS QUAD FAILED FOR RATE-COMMAND CONTROL MODE AND PRIMARY LOGIC

[25 flights; 24 flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute value	Mean absolute value
f	14.76	6.27	26.89	14.76
t	201	65	422	221
Displacements				
y	0.02	0.20	0.71	0.13
z	0	.18	.41	.15
ϕ	.50	1.33	3.58	1.13
θ	-1.08	1.88	4.32	1.80
ψ	-.40	1.57	5.04	1.19
Rates				
$\dot{x}$	0.37	0.10	0.61	0.37
$\dot{y}$	.01	.11	.31	.08
$\dot{z}$	-.01	.06	.15	.04
p	-.06	.31	1.07	.18
q	.05	.17	.48	.13
r	-.02	.17	.48	.12

Pilot comments: A single RCS quad failure was difficult to detect through qualitative assessment of the handling characteristics if the pilot was flying the rate-command control mode. Cross coupling occurred, but did not constitute a significant control problem; it did, however, increase fuel consumption.

The rate-command/attitude-hold control mode with either primary or secondary jet-select logic would be preferable to the rate-command control mode. Knowing which quad had failed, before docking, would not aid in the control task.

A single quad failure presents no marginal control tasks to the pilot provided no other failures are present.

Failure of one quad introduces two problems - cross coupling and sluggish response in the affected axes. This sluggish response required that a considerable amount of lead time be used for close-in alinement, especially for translation alinement commands involving the failed quad.

The average Cooper rating given by the four pilots who flew this configuration was 3.2.

TABLE VII.- TERMINAL CONDITIONS OF DAY FLIGHTS IN LUNAR-ORBIT DOCKING CONFIGURATION WITH ONE RCS QUAD FAILED FOR RATE-COMMAND CONTROL MODE AND SECONDARY LOGIC

[17 flights; all flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute value	Mean absolute value
f	14.12	3.97	25.73	14.12
t	219	66	408	219
Displacements				
y	0.15	0.20	0.59	0.19
z	.05	.24	.81	.14
ϕ	.10	1.24	2.40	.95
θ	-.63	1.31	2.88	1.15
ψ	.68	1.85	3.42	1.67
Rates				
$\dot{x}$	0.37	0.13	0.59	0.37
$\dot{y}$	0	.04	.10	.03
$\dot{z}$	-.01	.04	.11	.03
p	.02	.17	.24	.16
q	.05	.12	.20	.11
r	-.01	.10	.18	.08

Pilot comments: These runs were completely controllable and easy to fly. The "mildly unpleasant characteristic" in the numerical rating was an attitude excursion with a translation command in the positive X-direction which probably would not have been noticed if the rate-command/attitude-hold control mode had been used.

There was no significant difference between the two jet-select logics.

The average Cooper rating given by the three pilots who flew this configuration was 3.0.

TABLE VIII.- TERMINAL CONDITIONS OF NIGHT FLIGHTS IN LUNAR-ORBIT DOCKING CONFIGURATION WITH NO FAILURE FOR RATE-COMMAND/ATTITUDE-HOLD CONTROL MODE

[12 flights; all flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute value	Mean absolute value
f	10.17	2.67	14.63	10.17
t	192	38	250	192
Displacements				
y	0.04	0.09	0.25	0.07
z	.02	.09	.19	.07
ϕ	-.04	.44	.80	.35
θ	.18	.52	1.18	.44
ψ	.62	.79	1.92	.74
Rates				
$\dot{x}$	0.36	0.06	0.47	0.36
$\dot{y}$	.02	.05	.12	.04
$\dot{z}$	-.03	.04	.11	.03
p	.03	.05	.09	.04
q	.01	.03	.06	.02
r	0	.04	.08	.03

Pilot comments: The average Cooper rating given by the two pilots who flew this configuration was 2.5.

TABLE IX.- TERMINAL CONDITIONS OF DAY FLIGHTS IN TRANSPOSITION DOCKING CONFIGURATION WITH NO FAILURE FOR RATE-COMMAND/ATTITUDE-HOLD CONTROL MODE

[17 flights; all flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute value	Mean absolute value
f	15.44	3.45	21.62	15.44
t	188	46	282	188
Displacements				
y	-0.03	0.24	0.69	0.20
z	-.01	.13	.27	.10
ϕ	.40	.71	1.28	.69
θ	-.82	1.71	4.40	1.48
ψ	.24	.82	1.54	.69
Rates				
$\dot{x}$	0.37	0.21	0.49	0.42
$\dot{y}$	-.01	.03	.05	.02
$\dot{z}$	.01	.03	.06	.03
p	.01	.04	.11	.03
q	.03	.10	.40	.04
r	0	.02	.05	.02

Pilot comments: Attitude and translation control appeared sluggish as compared with the control in the lunar-orbit docking configuration. The lower control power was quite obvious, but presented no significant problems.

The average Cooper rating given by the two pilots who flew this configuration was 1.5.

TABLE X.- TERMINAL CONDITIONS OF DAY FLIGHTS IN LUNAR-ORBIT DOCKING CONFIGURATION WITH A BUS FAILURE FOR RATE-COMMAND/ATTITUDE-HOLD CONTROL MODE

[9 flights; 7 flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute value	Mean absolute value
f	43.79	33.24	100.00	43.79
t	355	428	1390	355
Displacements				
y	-0.06	0.49	0.80	0.37
z	.16	.89	2.13	.57
ϕ	-1.71	3.07	7.38	2.20
θ	1.67	4.48	10.18	3.80
ψ	-.85	5.20	13.44	3.36
Rates				
$\dot{x}$	0.43	0.20	0.73	0.43
$\dot{y}$	-.02	.06	.12	.04
$\dot{z}$	0	.07	.13	.05
p	-.08	.71	1.66	.40
q	.04	.15	.31	.10
r	.14	.34	1.02	.18

Pilot comments: This configuration does not result in complete loss of control; however, successful docking was not repeatable from all initial positions. It may be possible to develop pilot techniques that would accomplish the maneuver under all conditions, but until these techniques are demonstrated to the satisfaction of the Apollo flight crew, electrical bus failure should be considered as a constraint against CSM-active docking.

The CSM was marginally controllable with a single bus failure - given time, patience, and fuel. Redesign of the dual bus concept may be in order.

The poor controllability, plus the large attitude maneuvers which were required to control translation and which caused the pilot to lose sight of the LM, made large close-in corrections difficult and possibly dangerous.

The average Cooper rating given by the two pilots who flew this configuration was 6.5.

TABLE XI.- TERMINAL CONDITIONS OF DAY FLIGHTS IN LUNAR-ORBIT DOCKING CONFIGURATION WITH TWO RCS QUADS FAILED FOR RATE-COMMAND/ATTITUDE-HOLD CONTROL MODE

[5 flights; 3 flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute value	Mean absolute value
f	9.41	3.30	14.08	9.41
t	111	19	140	111
Displacements				
y	-1.18	2.65	5.91	1.31
z	.79	1.94	4.24	1.05
ϕ	.58	1.56	2.64	1.29
θ	-3.04	4.51	9.90	3.35
ψ	.83	6.49	10.66	4.85
Rates				
$\dot{x}$	0.58	0.24	0.79	0.58
$\dot{y}$	.01	.03	.05	.02
$\dot{z}$	.04	.06	.12	.04
p	.16	.54	1.07	.34
q	-.05	.08	.13	.08
r	-.22	.32	.66	.27

Pilot comments: The control system damping made this configuration impossible to fly. Controlling the vehicle in direct attitude mode would be a last resort. Perhaps, with unlimited freedom of motion, pilot techniques could be developed to accomplish the docking maneuver.

With adjacent quads failed it is impossible to translate into the target. With two opposite quads failed, two degrees of freedom are lost.

Both pilots who flew this configuration gave it a Cooper rating of 9.

TABLE XII.- TERMINAL CONDITIONS OF DAY FLIGHTS IN LUNAR-ORBIT DOCKING CONFIGURATION WITH TARGET TUMBLING AT A RATE OF 0.15 DEG/SEC FOR DIRECT OR RATE-COMMAND CONTROL MODE

[14 flights; all flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute value	Mean absolute value
f	12.09	3.55	20.70	12.09
t	122	38	182	122
Displacements				
y	0.06	0.21	0.60	0.15
z	-.10	.28	.69	.20
ϕ	.31	.89	1.80	.75
θ	-1.16	1.74	4.98	1.51
ψ	.32	2.03	4.86	1.40
Rates				
$\dot{x}$	0.45	0.09	0.57	0.45
$\dot{y}$	-.02	.04	.10	.03
$\dot{z}$	-.01	.06	.10	.05
p	-.02	.24	.52	.20
q	.01	.22	.53	.16
r	.03	.28	.70	.21

Pilot comments: Translation position was the biggest problem, as in the direct control mode runs without LM tumbling. The main attention was devoted to the standoff cross, with less attention given to the reticle. In order to prevent the target from tumbling away, the apparent translation rates had to be arrested early and rapidly, the reticle superimposed on the standoff cross by means of attitude commands, and a positive translation command in the x-direction made, all in rapid sequence. Attitude control was no particular problem when the direct control mode was used. Since a tumbling LM target necessitated sustained CSM angular rates, the rates were adjusted by pulsing the rotational hand controller in the direct control mode rather than by maintaining a constant input in the rate-command mode. Since closure rate fell off as a run progressed, positive translation commands in the x-direction had to made several times during a run. Each time a positive command was made in the x-direction, adjustments were required of the other two translation rates and of all three attitude rates. No abnormal flight control techniques were required.

The average Cooper rating given by the two pilots who flew this configuration was 5.0.

TABLE XIII.- TERMINAL CONDITIONS OF DAY FLIGHTS IN LUNAR-ORBIT DOCKING CONFIGURATION WITH TARGET TUMBLING AT A RATE OF 0.25 DEG/SEC FOR DIRECT OR RATE-COMMAND CONTROL MODE

[13 flights; 12 flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute value	Mean absolute value
f	26.05	8.41	48.09	26.05
t	112	21	167	112
Displacements				
y	0.22	0.19	0.65	0.24
z	-.28	.43	.87	.43
ϕ	.76	1.66	3.84	1.47
θ	-.02	1.85	2.98	1.57
ψ	1.36	3.06	6.82	2.72
Rates				
$\dot{x}$	0.50	0.12	0.67	0.50
$\dot{y}$	-.07	.13	.44	.10
$\dot{z}$	.03	.11	.23	.08
p	-.20	.81	2.45	.53
q	-.10	.15	.30	.15
r	.09	.29	.72	.23

Pilot comments: Successful docking can generally, although not consistently, be made with the LM target tumbling at 0.25 deg/sec.

Although docking was accomplished with target tumbling rates up to 0.5 deg/sec, fuel requirements for rates in excess of 0.15 deg/sec were quite large and flight control was considered marginal for rates in excess of 0.25 deg/sec.

The average Cooper rating given by the two pilots who flew this configuration was 5.0.

TABLE XIV.- TERMINAL CONDITIONS OF DAY FLIGHTS IN TRANSPOSITION DOCKING CONFIGURATION WITH TARGET TUMBLING AT A RATE OF 0.17 DEG/SEC FOR DIRECT OR RATE-COMMAND CONTROL MODE

[13 flights; all flights in tolerance]

Parameter	Mean value	Standard deviation	Maximum absolute error	Mean absolute error
f	23.21	5.06	35.19	23.21
t	115	18	141	115
Displacements				
y	-0.01	0.18	0.38	0.13
z	.03	.29	.51	.25
ϕ	.05	1.75	3.50	1.25
θ	-.49	1.32	3.38	1.11
ψ	.39	1.89	3.34	1.50
Rates				
$\dot{x}$	0.55	0.09	0.70	0.55
$\dot{y}$	-.03	.04	.07	.04
$\dot{z}$	.01	.06	.11	.05
p	0	.21	.47	.16
q	-.06	.16	.46	.11
r	-.04	.16	.33	.13

Pilot comments: Within the constraints of the docking simulator, it appears that the transposition docking maneuver is feasible with target tumbling rates up to 0.17 deg/sec, the highest rate evaluated. The decision as to which control mode would be best appears to be based on pilot preference, as the direct mode was no more difficult to fly than the rate-command mode.

Vehicle response to rotational inputs in the transposition configuration was slow, but not restrictively slow; however, most attitude inputs were maximum.

Continuous rotational and translational commands were required, and high fuel consumption resulted. This high fuel consumption was the limiting factor, since the CSM was completely under control with respect to the target at all times.

Both pilots who flew this configuration gave it a Cooper rating of 4.0.

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