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DYNAMIC SIMULATION OF LUNAR MODULE DOCKING WITH APOLLO COMMAND MODULE IN LUNAR ORBIT

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SUMMARY

A full-size pilot-controlled simulation of the Lunar-Orbit-Rendezvous docking of the lunar module (LM) with the command and service module (CSM) has been conducted on the six-degree-of-freedom Langley rendezvous docking simulator.

Docking the ascent stage of the LM with its top hatch to the CSM was studied, and pilots performed the maneuver with only visual observation of the target for guidance information. The objectives of the simulation were to determine if visual aids were needed to complete the docking and to determine the effects of lighting conditions, control mode, and pressure suit on the mission.

The results showed that the pilots could dock within specified tolerances if visual aids were used. The most desirable visual aids were a collimated reticle aid in the LM and an illuminated standoff cross in the CSM. The lighting conditions studied had no effect on docking when visual aids were used.

The most desirable control modes were the direct mode for translation control and rate command with attitude hold for attitude control. The direct attitude control mode was extremely difficult. When the pilot was wearing a pressurized suit, he found that control was degraded somewhat.

INTRODUCTION

One concept for lunar orbit rendezvous docking (ref. 1) between the lunar module (LM) and the command and service module (CSM) is for the LM to be the active vehicle and dock with its top hatch to the CSM. In this maneuver the LM will approach the CSM with the LM pilot looking forward out the triangular front window. At a range of 50 feet (15 m) or so, the pilot will rotate the LM 90°, lean back, and, looking through a small overhead window, will approach the CSM with the LM top hatch forward, and complete the docking in this orientation.

To study a pilot's ability to complete the final docking alinement and the top hatch docking with only out-of-the-window visual cues for guidance information, the Langley Research Center conducted a full-scale piloted simulation utilizing the six-degree-of-freedom Langley rendezvous docking simulator.

The objectives of the simulation program were to determine if visual aids were necessary to complete a docking and to determine the effect on docking accuracies of lighting conditions, control modes, and flight in a fully pressurized suit.

SYMBOLS

p,q,r angular velocities about vehicle body axes, degrees/second

x,y,z longitudinal, lateral, and vertical displacement of CM docking probe with respect to LM docking hatch, meters (feet)

$\dot{x},\dot{y},\dot{z}$ longitudinal, lateral, and vertical velocities of LM center of mass, meters/second (ft/sec)

t flight time, seconds

m_A mass of altitude fuel used, kilograms

m_t mass of translation fuel used, kilograms

ϕ angle of roll, degrees

θ angle of pitch, degrees

ψ angle of yaw, degrees

Designations:

CM command module

CSM command and service module

LM lunar module

RCS reaction control system

DESCRIPTION OF APPARATUS

Simulator

An overall view of the Langley rendezvous docking simulator is shown in figure 1. This view shows the Gemini model installed. (For a description of the simulator, see ref. 2.) The simulator consists of an overhead carriage and cable-suspended gimbal system. The carriage is electrically driven and provides three degrees of freedom in translation. The gimbal is hydraulically driven and provides three degrees of freedom in rotation. Thus, the pilot flies the vehicle in six-degree-of-freedom motion which is controlled in a closed-loop fashion through a ground-based analog computer. The operating volume of the simulator is 210 feet horizontally (65 m) by 15 feet laterally (4.6 m) by 40 feet vertically (12.2 m). Since this facility allows the use of full-size target models, the pilot is presented three-dimensional, real-world visual information.

Because the LM is much larger than the Gemini spacecraft, the whole vehicle would not fit in the gimbal system. However, as will be shown, the entire LM configuration was not needed for this simulation.

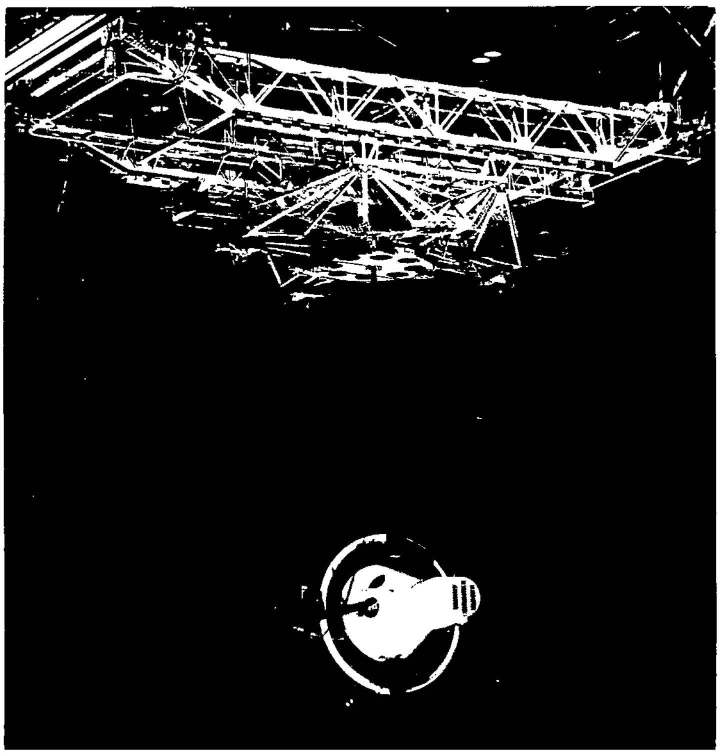

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Figure 1.- Langley rendezvous docking simulator (Gemini configuration).

LM/CSM Docking Configuration

Figure 2 is a schematic drawing of the LM docked with the CSM. For clarity, the LM descent stage has been added to the ascent stage. Actually, in lunar orbit, only the ascent stage would dock with the CSM. The crew compartment of the LM is located on the front of the ascent stage. The docking hatch is on top of the ascent stage. Since the pilot flies the LM from the crew compartment, only it and the top hatch were needed for this simulation.

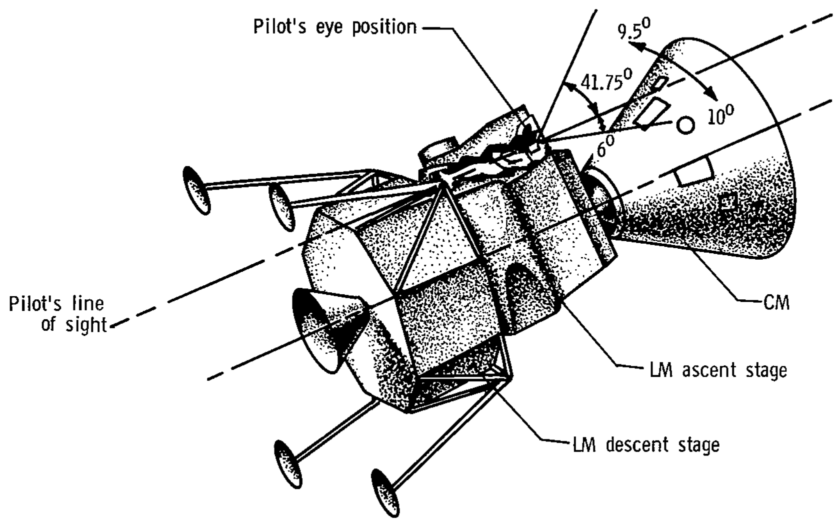


Figure 2.- Illustration of Apollo LM-CM docking.

The crew compartment and top hatch were mounted in the gimbal system as shown in figure 3, which is a view of the LM docking simulator. This view is equivalent to that in figure 2; the rest of the LM ascent stage would be located below the crew compartment.

Even though only part of the LM configuration was used in this simulation, every effort was made to duplicate the fields of view, interior arrangements, and motion that the complete LM would have. For instance, the center of gravity of the LM is located approximately in the middle of the ascent stage, and even though the gimbal drive axes were not about that point, an analog computer was programed to drive the system so that the LM simulator would rotate about the correct center of gravity.

Pilot Position in LM

In the actual LM, the pilot is positioned in his restraining harness as shown in figure 2; his line of sight out the top window is about 2 feet (0.6 m) to the left of and about 3 feet (0.9 m) above the LM center line. The top window is located about 1 foot (0.3 m) from the pilot's eyes and consists of two parallel panes of glass, 1 inch (2.5 cm) apart. The window area is 3/8 sq ft (0.035 sq m). The pilot's field of view, then, is 41.75°

forward, 6^{o} aft, 9.5^{o} right, and 10^{o} left. (See fig. 2.) With this field of view, the pilot cannot see the docking mechanism of either vehicle when they are docked or in close proximity to each other.

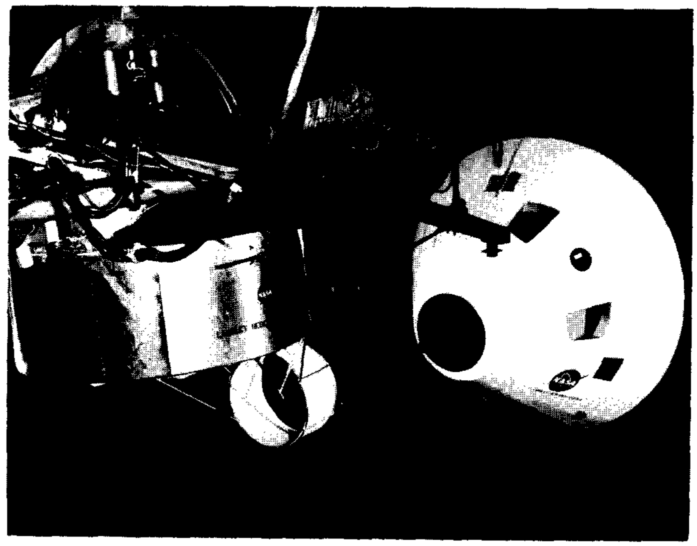


Figure 3.- Apollo LM docking simulator. L-64-9969

Figure 4 shows a pilot, positioned in the LM simulator and wearing a full pressure suit. Because of the way the LM was mounted in the gimbal system, the pilot was lying on his back relative to the hangar floor, so a couch was used to obtain correct body position instead of the normal LM restraint harness.

The LM pilot's proper position was such that his body was tilted back from the longitudinal axis of the LM by about 20^{o} to 30^{o}. In order to prevent the pilot from having a head-down position in the simulator, all runs were flown at a 20^{o} angle uphill. In addition to the 20^{o} to 30^{o} body slant, the pilot's head was tilted back 20^{o}. The tilt of the pilot's head was limited to 20^{o} because of pressure-suit restrictions.

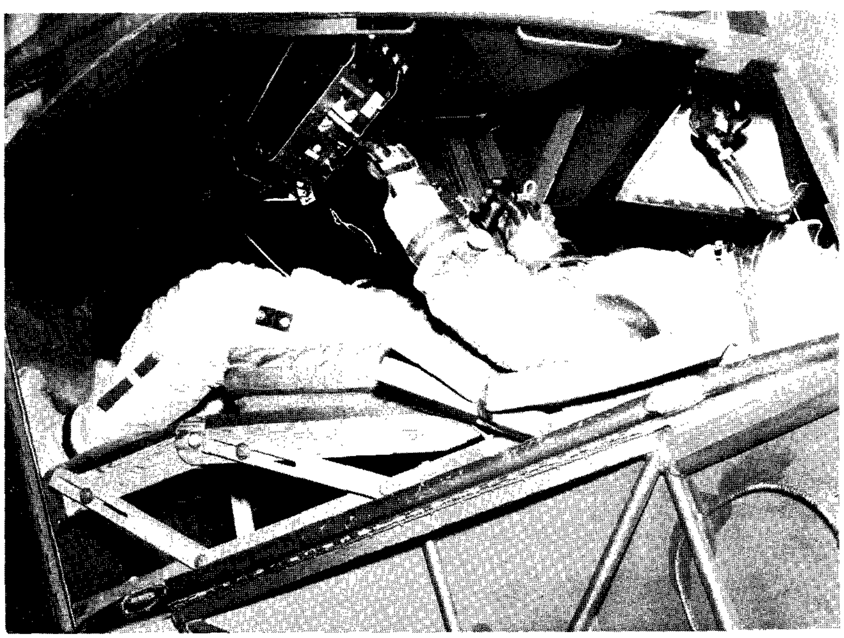


Figure 4.- Pilot in LM simulator. L-65-441

Thus, the pilot had to rotate his eyes up about as far as they would go in order to obtain the additional 40° or 50° needed to see straight out the top window.

LM Control System

The pilot flew the LM with two hand controllers: the attitude controller on his right and the translation controller on his left. The controllers were about 2 feet apart (0.6 m), 2 feet forward (0.6 m), and $1\frac{1}{2}$ feet below (0.5 m) the pilot's eye position. The controllers were oriented for flying the LM while looking forward out the front window. Thus, for example, when the pilot twisted the attitude controller handle to the right he yawed to the right while looking out the front window. However, when looking out the top window, this same vehicle motion looks like a roll to the left. There were similar apparent axis interchanges which the pilot had to remember each time he made either an attitude or a translation control input.

Three attitude-control modes were used in the simulation: rate command, rate command with attitude hold, and direct (on-off). In the rate command mode, movement of the attitude hand controller produced a spacecraft rate about each axis proportional to the displacement of the controller up to a maximum of 20 deg/sec at full deflection. With the hand controller centered, or at a neutral position, the spacecraft rate about each axis was damped to within 0.75 deg/sec. The rate command with attitude hold mode was similar to the rate command mode except that with the hand controller centered the spacecraft was held within both a 0.75 deg/sec rate deadband and a 0.3 degree position deadband. A small number of flights were made in the rate command mode with a 0.2 deg/sec deadband. In the direct control mode the angular acceleration was the maximum provided by the reaction control system (RCS) for the period of hand-controller deflection. Table I shows the LM parameters used in the simulation. Translation control was similar to the direct attitude control mode in that maximum acceleration was applied for the duration of translation controller deflection.

Computer Program

A general-purpose analog computer closed the loop between the pilot and the simulator. The pilot's control inputs were transformed from the LM body-axis system to an inertially fixed axis system alined with the axes of the drive system; these inputs were then integrated to give velocity and position. The velocity and position commands were fed to the simulator drive systems which moved the LM model.

In the equations of motion used in this simulation, it was assumed that the target was stable and that the mass, center of gravity, and inertia of the LM did not change because of the small amount of fuel used compared with the vehicle mass.

In addition, orbital mechanics effects were neglected. A series of tests were conducted on the simulator and it was determined that the orbital mechanics effects were insignificant for the ranges covered in this report. The main reason for the insignificance is that the drifts created by orbital mechanics effects are much smaller than the drifts created by pilot control inputs, and since the pilots continually applied control inputs in a closed-loop fashion the orbital drifts were hardly detectable.

PROCEDURE AND CASES STUDIED

Simulation Procedure

Docking flights were made with initial offsets from 30 feet longitudinally, up to 5 feet 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, if high rates were present at the end of rendezvous, the pilot would arrest these rates before initiating the docking. Second, if the pilot corrected initial displacement, he would induce small attitude and translation rates.

Six National Aeronautics and Space Administration (NASA) test pilots and 12 astronauts took part in the simulated flights. Their flight background and experience were instrumental in evaluating the control task, simulator response, piloting techniques, and visual aids.

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) pilot comments. Time histories of control inputs, velocities, and attitudes were shown on continuous charts for each flight.

Since final docking accuracies could be measured and digitally recorded at the end of each flight, most of the quantitative data are expressed in terms of final displacement errors, final rates, flight time, and fuel use. Displacement errors were measured between the center of mass of the spacecraft and the center line of the target at the termination of a docking flight – the termination point being defined as the point at which the longitudinal distance x between vehicles became zero.

Two additional computations were performed on the digital readout data from the analog computer. The velocity and position error of the docking hatch of the LM relative to the docking probe of the CM was calculated from the center-of-mass data, and then the terminal velocities, position errors, fuel use, and flight times were averaged for each set of related flights. These calculations permitted evaluation of the docking accuracy relative to the design docking tolerances of ±1 foot (0.3 m) radial $\left(\sqrt{y^2 + z^2}\right)$ error, ±10° attitude error, 0.5 fps (0.15 m/sec) lateral and vertical rates $\dot{y}$ and $\dot{z}$, and 0.1 to 1.0 fps (0.03 to 0.3 m/sec) closure rate $\dot{x}$.

The third type of data obtained, pilot comments, were transcribed during and following the data flights.

Cases Studied

For the docking maneuver simulated, the cockpit was not instrumented; therefore, the pilot obtained all information (range, range rate, attitude, and so forth) from the visual cues afforded by the CSM targets (and visual aids) alone. Four phases of the docking simulation included the study of (1) requirements for visual aids to increase the pilot's precision and confidence, (2) effects of lighting conditions, (3) effects of control modes on terminal docking accuracies, and (4) effects of a fully pressurized suit on pilot control capability.

RESULTS

Preliminary Studies and Docking Orientation

Initial simulation flights showed that docking the LM with its top hatch to the CSM was very difficult. Two expedient methods of alleviating some of the visual and control problems were tried. First, a mirror was installed in the cockpit so that the pilot would not have to lean back and look over his head while controlling the vehicle. Second, the controller logic was modified so that the controller input and the vehicle motion seen in the mirror would be consistent (a roll attitude input would produce an apparent roll attitude change, by yawing the vehicle). Both changes were abandoned early in the program because the change in the controller logic would tend to reduce the reliability of the actual flight systems, and as pilots became more accustomed to the task, they found that it was possible to adapt to the standard controller logic and view directly out the top window.

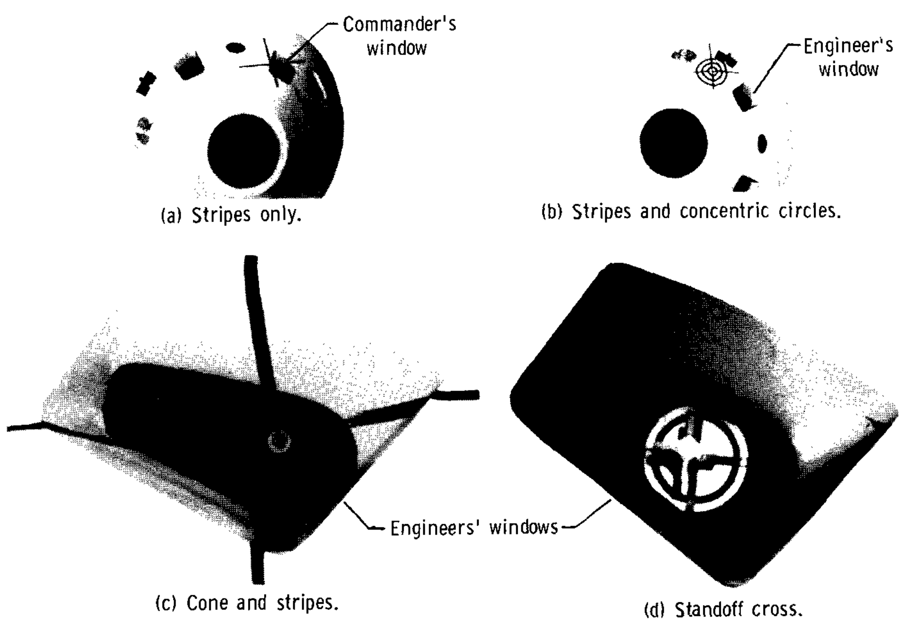
During the program, three CSM docking roll orientations were used. In the first roll orientation, with the vehicles docked, the LM pilot was looking into the CSM command pilot's docking window. However, shortly after the program began, this roll orientation was changed by 90° because other studies showed there would be harmful jet impingement on the radar antennas in this position. The second roll orientation was such that the LM pilot's line of sight intersected the CSM at a point below the square window on the engineer's side of the CSM. Finally, it was mutually agreed to change to the third roll orientation in which the LM pilot's line of sight intersected the CSM at the engineer's docking window in order to make use of visual alinement aids mounted on or inside the engineer's window. This orientation (illustrated in fig. 2) was used in the remainder of the flights.

Visual Aid Study

From the pilot comments and the amount of training required (on the order of 12 to 20 flights), it was apparent that the unusual way of flying the LM for docking was difficult for the pilots. Consequently, the first part of the simulation program was to investigate possible visual aids, which would make the task easier for them.

Two types of visual aids were used in the simulation. The first type was mounted on the LM and served to define the pilot's line of sight. In some flights the pilot used illuminated crosshairs, which were scribed on the inner and outer panes of the docking window. In other flights the pilot used a collimated sight. With either the scribed lines or the sight, the pilot saw a cross superimposed on an object he viewed out the window. The sight was more convenient because it projected a reticle to infinity and the pilot did not have to refocus his eyes when looking from the lines to the target.

The second type of aid, mounted on or inside the CSM target, included several configurations. These configurations, shown in figure 5, were used in conjunction with the aid of the LM to help the pilot determine relative alinement between the two vehicles. The stripes-only aid (fig. 5(a)) utilized lines painted on the outside surface of the CM. When using the stripes-only aid, the pilot would rotate the LM until the cross (or reticle) on the LM-mounted aid was superimposed on the CSM stripes. He then observed the aspect of the CSM either by looking at the whole vehicle or at the window by the stripes.



(a) Stripes only.

(b) Stripes and concentric circles.

(c) Cone and stripes.

(d) Standoff cross.

Figure 5.- Visual aids for docking. L-67-933

By remembering how these look from prior training when the two vehicles were properly alined, the pilot could get a rough estimate of any error in alinement. When the docking roll orientation was changed 90° (to the second orientation), concentric circles (fig. 5(b)) were mounted along the pilot's line of sight; these, too, were on the CSM surface and gave the pilot only a rough estimate of relative alinement. Although the pilots could dock under these circumstances, they preferred a more positive way of determining alinement.

A three-dimensional aid was needed to give the pilot a positive alinement cue, but it could not be mounted on the outside of the CSM. For this reason, the final (third) docking orientation was established to permit the LM pilot to look almost directly in the CSM engineer's window, behind which there is adequate room to mount visual aids. The first three-dimensional visual aid used inside the CSM was a concentrically ringed convex cone. (See fig. 5(c).) The cone was used in conjunction with the stripes, and when the pilot superimposed the LM cross on the CSM cross he could use the rings on the cone for an aspect, or displacement, cue. There was a gap in the middle of the projected reticle cross so that the pilot could see the cone clearly. Thus, during an approach, the pilots kept the crosses superimposed by using attitude control and the cone alined by using translation control. Several other cones of different sizes and apex angles were used. It was found that the cone shown in figure 5(c) was good for long ranges and that a smaller cone with less taper was good for close ranges. For this reason, a double cone would be best. The cone shown in figure 5(c) has an apex angle of 20°.

The final aid used was the standoff cross (fig. 5(d)). This cross was a small version of the aid that has been proposed for mounting on the LM for use by the CSM pilot (ref. 3). This aid gave the pilot a very clear indication of alinement – both attitude and translation.

Table II summarizes the configurations and cases studied in the remainder of the docking study.

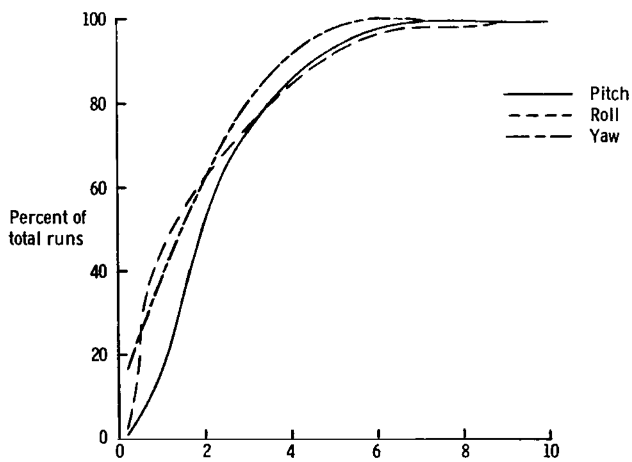
Table III (case 1) presents the results for flights made using the rate-command—attitude-control mode and with no visual aids on either the LM (onboard) or the CM (target). The table indicates that only 10 of the 16 flights ended with terminal conditions within the docking tolerances of ± 1 foot (± 0.3 m) in radial error, $\pm 10^{\circ}$ in attitude error, 0.1 to 1.0 fps (0.03 to 0.3 m/sec) closure rate, and 0.5 fps (0.15 m/sec) lateral and vertical rates. In the six unsuccessful flights, the parameters out of tolerance were attitude, radial position, or both which indicates that the pilots had the vehicle under control, but that they lacked adequate visual cues. The large number of out-of-tolerance flights and the large dispersion in terminal attitude, radial position, and angular rates, indicated by the standard deviation σ (see ref. 4), could not be tolerated for such a critical task. Thus, the succeeding flights (cases 2 to 5) were devoted to evaluating visual aid techniques which could provide adequate visual cues and increase the docking accuracy.

Table IV (case 2) presents the results for flights in which pilots used the crosshair scribed on the LM window and the cone-and-stripes aid on the target. (See fig. 5(c).) The table shows a marked improvement in almost all terminal conditions and in percent of flights in tolerance. This clearly indicates that the pilot can satisfactorily control the spacecraft if he can be given an indication of the type of correction needed. This indication was provided by the visual aids.

When a collimated sight was used onboard the LM instead of the scribed lines on the window, the results (table V, case 3) showed no appreciable difference. The difference in fuel use and the percent of flights within tolerance was considered to be due to the varied experience of the pilots rather than to the visual aids. All pilots agreed that, although their accuracy in completing the docking task was similar with either the scribed lines or the collimated sight, they preferred the collimated sight. Because the reticle was projected at infinity, (1) the pilot did not have to refocus his eyes when looking from the reticle to the aid on the target; and (2) the reticle did not appear to move if the pilot moved his head. Thus, the collimated sight is more desirable than the scribed lines on the LM window.

Table VI (case 4) presents the results for flights made with the collimated reticle onboard the LM and with the standoff cross aid in the CSM window. A comparison of table VI with the data in table V shows little difference in the results between the cone-and-stripes aid on the CSM, and the standoff cross aid on the CSM. This small difference could be expected because the pilots split on their preference for the aids on the target. Most pilots preferred the standoff cross because it provided both attitude and translation cues and was similar to the aid on the LM. Some pilots preferred the cone-and-stripes aid mainly because the large vertical stripe on the outside of the CSM provided a better roll cue than the standoff cross. However, the standoff cross did provide an adequate roll alinement cue. Thus, it would appear that either the cone-and-stripes aid or the standoff cross aid would provide the pilot with adequate information for docking control. (Perhaps the best possible aid would be the standoff cross inside the CM with a roll reference stripe on the outside surface.)

The distribution of the terminal conditions for flights with collimated sight and standoff cross (table VI, case 4) is shown in figures 6(a) to 6(e)



(a) Terminal attitude error.

Figure 6.- Flight terminal conditions.

as a function of the number (percentage) of flights. Figure 6(a) shows that the majority of the terminal attitude errors were well within the 10° docking tolerance. The attitude fuel usage (fig. 6(b)) was much higher than the translation fuel usage because of the automatic damping system used in conjunction with the rate command attitude control mode.

The CSM standoff cross and the LM collimated reticle were used for the other phases of the docking simulation (cases 5 to 8 in table II).

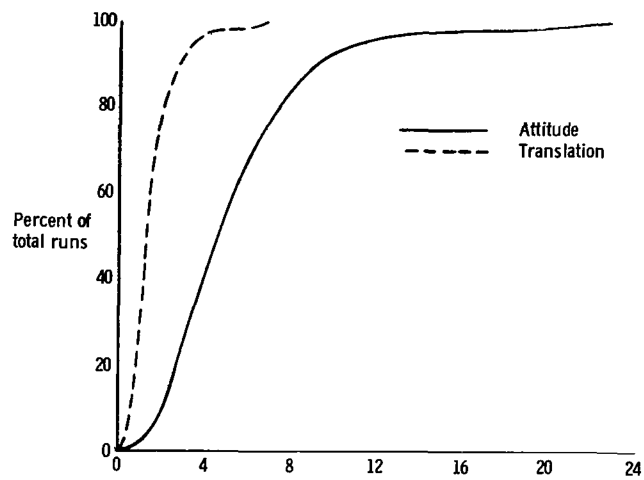
Lighting Studies

The object of the second phase of the simulation was to determine the difference in difficulty of docking under daytime and nighttime lighting conditions. Under the nighttime lighting conditions only the CSM visual aid was illuminated, thus, the pilot could not use the body of the CSM for aspect or orientation cues.

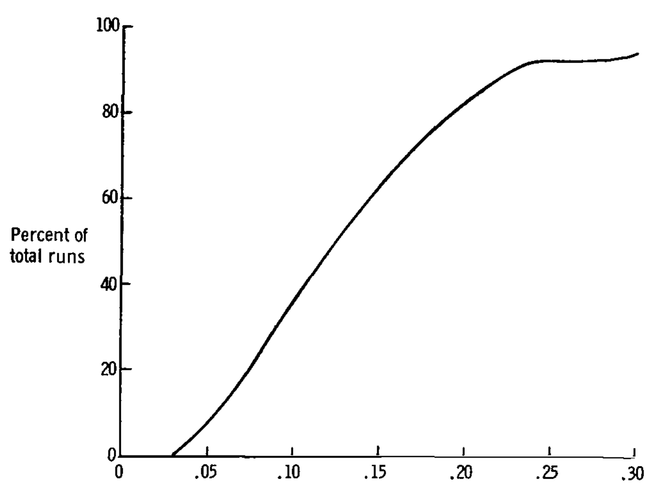
For some of the night flights, four high-intensity strobe lights (235 lumen-seconds) were placed on the target at the thruster location to represent the glare of the LM reaction control jets. The lights annoyed the pilots somewhat, but did not noticeably affect the docking accuracies; therefore, the results of these flights are combined with the results of all other night flights in table VII.

For some of the flights a floodlight was placed above the LM docking window to illuminate the CSM target during the approach. The results and the pilot comments indicated that the floodlight was an aid during the approach, but did not affect terminal accuracies; the results of these flights are also included in table VII.

A comparison of the results of the day and night flights (tables V and VII) show no significant difference between the terminal conditions. The



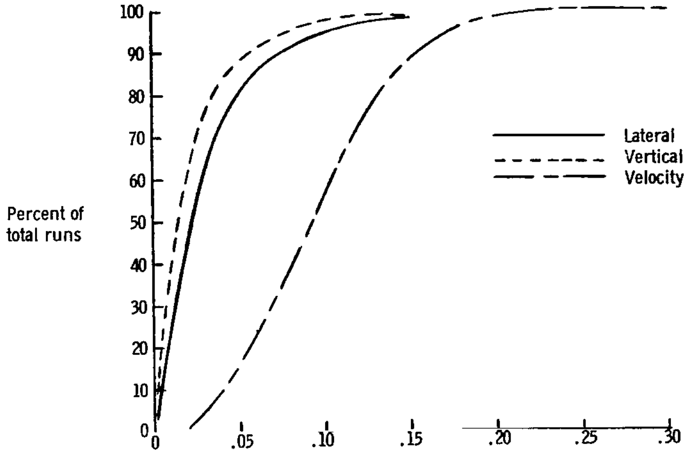
(b) Fuel use.



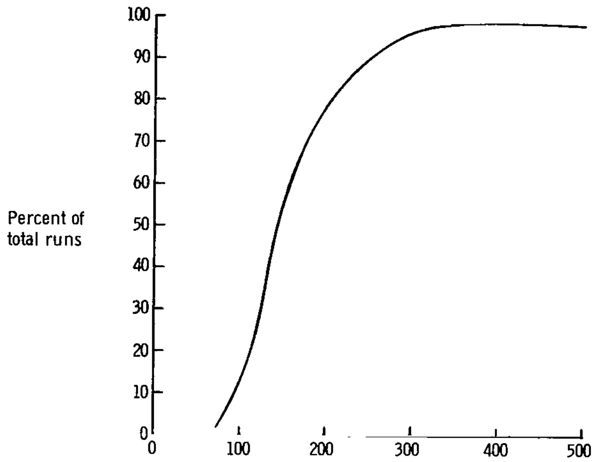
(c) Terminal radial position error.

Figure 6.- Continued.

explanation is that even during daytime conditions, the shape and large size of the Apollo target make it difficult to obtain aspect cues at close range, thus, the LM pilot must still rely primarily on the CSM-mounted aid. The lack of visual cues from the overall CM is confirmed by the pilot comments. Thus, it appears that the primary effect of docking under nighttime conditions would possibly be to lower the pilot's confidence and also to make it more difficult to obtain alinement cues at long ranges. At short ranges, near contact, the pilot would use the same cues and have approximately the same docking accuracies as would be expected for daytime flights. (In addition, any visual aid used would have to be self-illuminated in order to provide usable cues at night.)



(d) Terminal velocity.



(e) Flight time.

Figure 6.- Concluded.

Control Mode Studies

The third phase of the LM-active docking study investigated the effects of vehicle control modes on the pilot's ability to control the docking. All flights were made during the day with the collimated sight in the LM and with the standoff cross in the CSM target. The data for the rate command control mode are presented in table VI. The data for the rate-command—attitude-hold mode and the direct (on-off) attitude control mode are presented in table VIII (case 6) and table IX (case 7), respectively.

It would be expected that the rate-command—attitude-hold mode, which is the primary (nominal) control system for the lunar module, would be easier to fly and would provide the best terminal conditions because it permits precise attitude control. Pilot comments and terminal displacement errors presented in table VIII confirm these expectations. It is somewhat surprising to note, then, that 4 of the 33 flights using this control mode were unsuccessful. An examination of the four unsuccessful flights showed that three had angular rates at contact which were greater than the 5 deg/sec limit. The problem was that maximum deflection of the attitude controller commanded an angular rate of 20 deg/sec; therefore, if the pilot made any last-second attitude corrections (which was true in the case of the unsuccessful flights), the angular rate could easily be out of tolerance. To avoid this situation, it will be necessary to train the LM pilots in the proper procedures for control just prior to contact.

For the flights reported in table VI(a) the rate command control system damped the spacecraft angular rate about each axis to within a 0.75 deg/sec deadband when the pilot released the attitude controller. Near the end of the study, a small number of flights were made with a 0.20 deg/sec deadband. The pilots noted (table VIII(b)) that the lower deadband made the task considerably easier to fly. Thus, it appears that it may be possible to increase the docking accuracy and to reduce the pilot's workload just by reducing the width of the rate deadband.

Pressure Suit Studies

A pressure suit was used in 24 flights. The suit used was an early Gemini model fitted for use with constant-flow compressed air. Figure 4 shows the pilot positioned in the cockpit wearing the pressure suit.

Prior to the flights there was some concern that the pressure suit might not permit adequate visibility, but the flights showed that visibility was a lesser problem than that presented by the limited grip and actuation of the pressurized glove. Pilots had difficulty sensing controller actuation and had to make a definite effort when either opening or closing their grip or when changing wrist position. More recent suits have been modified to correct these problems.

Table X shows the terminal conditions and pilot comments concerning the pressure suit flights made using the rate-command—attitude-control mode. The pilots could perform the docking maneuver while wearing a fully pressurized suit, but could not perform consistently, and terminal errors were higher than in the flights without pressurized suits (table VI). A few flights were made with the direct attitude control mode. As would be expected, the pressurized suit made the task more difficult in the direct mode also; in fact, pilot comments indicate that a docking maneuver made in a pressurized suit and with the direct (on-off) control mode presented an extremely undesirable situation to the pilot and the effort required for this maneuver is near the limit of the pilot's ability to maintain satisfactory control of the LM ascent stage.

Although this study has demonstrated that the pressurized suit does degrade the pilot's docking control, it appears that the extent of degradation will be a function of suit design. Newer suits will undoubtedly give the pilot more freedom than the suit used in this simulation.

CONCLUSIONS

A study of the piloted simulation of the docking of the Lunar Module (LM) with the Apollo Command and Service Module (CSM) has yielded the following conclusions:

1. Docking the LM with its top hatch to the CSM is possible and can be performed more easily when visual aids are available to the LM pilot. Although the pilot can be trained to control the LM by looking through the overhead docking window, extensive training is required to achieve proficiency. (The pilots who fly the lunar mission will have achieved this high proficiency by virtue of several years of flight preparation activity.)

2. Of the target-mounted visual aids studied, LM pilots preferred either an illuminated three-dimensional cross in the engineer's window of the CSM, or a truncated cone in the engineer's window with stripes for roll reference on the outside surface of the CSM. A collimated sight mounted in the LM was found to be more desirable than crosshairs scribed directly on the LM docking window. However, either LM aid provided adequate information.

3. There was no noticeable effect of lighting conditions when the three-dimensional visual aids were used. High-intensity flashing lights used to represent the reaction control system jet glare were annoying, but pilots felt that a successful docking could be made with the jets flashing. There was no significant difference between results of day and night flights, because at close range (near contact) the pilot had to rely primarily on the target-mounted aid rather than on the target itself.

4. In a study of the control modes, the rate-command—attitude-hold mode (the nominal control mode) provided excellent attitude control. The rate command mode was more difficult than the rate-command—attitude-hold mode because the rate command system did not hold the vehicle attitude; however, terminal errors in the rate command mode or in the rate-command—attitude-hold were about the same. The direct attitude control was found to be difficult, but was deemed acceptable as an emergency mode.

5. When the pilot was wearing a pressurized suit, he found that control in all modes was degraded somewhat. Docking in the direct control mode while wearing a pressurized suit presented an extremely undesirable situation to the pilot, and the effort required for this maneuver is near the limit of the pilot's ability to maintain satisfactory control.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 23, 1967,
125-19-01-06-23.

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3. Pennington, Jack E.; Hatch, Howard G., Jr.; and Driscoll, Norman R.: A Full-Size Pilot-Controlled Docking Simulation of the Apollo Command and Service Module With the Lunar Module. NASA TN D-3688, 1966.

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TABLE I.- LM PARAMETERS AND SIMULATION ASSUMPTIONS

Parameters:	
Linear acceleration	0.439 m/sec^2
Angular acceleration –	
Roll	22.8 deg/sec^2
Pitch	25.8 deg/sec^2
Yaw	46.8 deg/sec^2
Specific impulse	303 sec
Distance from c.g. to thrust center –	
Δx	8.6 cm
Δy	-2.5 cm
Δz	3.0 cm
Distance from c.g. to docking probe	1.588 m

Assumptions:

Stabilized target (CSM)

No orbital (gravity gradient) effects

Constant mass and inertia

TABLE II.- CASES STUDIED

Case	LM aid	CSM aid	Control mode	Lighting	Pressure suit	Results, table no.
1	None	None	Rate command	Day	No	III
2	Scribed lines	Cone and stripes	Rate command	Day	No	IV
3	Reticle	Cone and stripes	Rate command	Day	No	V
4	Reticle	Standoff cross	Rate command	Day	No	VI
5	Reticle	Standoff cross	Rate command	Night	No	VII
6	Reticle	Standoff cross	Rate-command—attitude-hold control	Day	No	VIII
7	Reticle	Standoff cross	Direct	Day	No	IX
8	Reticle	Standoff cross	Rate command	Day	Yes	X

TABLE III.- RESULTS OF FLIGHTS USING NO AIDS

[Number of flights – 16; flights in tolerance – 62 percent]

Variable	Units	Mean error	Standard deviation	Maximum absolute error	Mean absolute error
y	m	0.018	0.229	0.500	0.177
z	m	-.037	.180	.482	.128
ϕ	deg	2.56	3.86	11.00	3.05
θ	deg	1.48	5.30	8.90	4.42
ψ	deg	2.13	8.47	19.92	6.02
$\dot{x}$	m/sec	.137	.061	.271	.137
$\dot{y}$	m/sec	-.009	.037	.079	.027
$\dot{z}$	m/sec	0	.055	.107	.046
p	deg/sec	-.02	.49	.92	.24
q	deg/sec	.17	1.10	3.85	.57
r	deg/sec	-.01	.45	1.02	.33
m_t	kg	.98	.49	1.94	.98
m_A	kg	2.80	1.40	5.29	2.80
t	sec	129.3	30.3	185.1	129.3

TABLE IV.- RESULTS OF FLIGHTS USING CONE AND STRIPES ON CSM AND CROSSHAIRS ON LM WINDOW

[Number of flights – 38; flights in tolerance – 97 percent]

Variable	Units	Mean error	Standard deviation	Maximum absolute error	Mean absolute error
y	m	-0.137	0.128	0.326	0.171
z	m	-.015	.116	.329	.088
ϕ	deg	.56	1.76	4.58	1.27
θ	deg	-.17	2.94	10.06	2.26
ψ	deg	-.19	3.37	8.90	2.50
$\dot{x}$	m/sec	.107	.058	.201	.107
$\dot{y}$	m/sec	-.012	.037	.119	.027
$\dot{z}$	m/sec	.012	.040	.134	.030
p	deg/sec	.31	1.26	6.25	.58
q	deg/sec	-.03	.90	3.85	.39
r	deg/sec	-.10	.66	3.59	.31
m_t	kg	1.90	2.33	7.24	1.90
m_A	kg	5.47	3.32	13.10	5.47
t	sec	173.1	106.0	445.0	173.1

TABLE V.- RESULTS OF FLIGHTS USING CONE AND STRIPES

ON CSM AND RETICLE IN LM

[Number of flights – 59; flights in tolerance – 93 percent]

(a) Terminal conditions

Variable	Units	Mean error	Standard deviation	Maximum absolute error	Mean absolute error
y	m	-0.122	0.125	0.308	0.149
z	m	-.006	.122	.634	.082
ϕ	deg	.01	1.95	7.92	1.17
θ	deg	-.98	3.11	10.16	2.49
ψ	deg	-.08	2.97	10.40	2.21
$\dot{x}$	m/sec	.091	.030	.165	.091
$\dot{y}$	m/sec	-.009	.030	.098	.024
$\dot{z}$	m/sec	-.003	.034	.094	.024
p	deg/sec	.05	.37	.99	.29
q	deg/sec	-.31	1.15	5.32	.62
r	deg/sec	-.09	1.49	9.04	.75
m_t	kg	.53	.61	3.54	.53
m_A	kg	3.43	2.00	7.36	3.43
t	sec	159.6	60.0	341.3	159.6

(b) Pilot comments

"The striped cone and window cross were preferred as the CM-mounted docking aid. This aid was easier to see further out than was the standoff cross."

"Roll attitude stripes on the CM exterior are desirable if they add no cost or complexity. They can serve also as a marginal alinement reference in case the standoff cross is disabled."

"As far as I am concerned, the reticle is superior to the crosshair [on LM window], so it is a worthwhile investment."

"The probe [cone] is not adequate at long distances."

"I like the reticle better but it is somewhat of a luxury item."

"The pilot task was considerably eased . . . by use of the [collimated] sight, and focusing problems were not apparent as they were with the crosshairs."

TABLE VI.- RESULTS OF FLIGHTS USING STANDOFF CROSS ON CSM AND RETICLE IN LM

[Number of flights – 60; flights in tolerance – 97 percent]

(a) Terminal conditions

Variable	Units	Mean error	Standard deviation	Maximum absolute error	Mean absolute error
y	m	-0.015	0.104	0.222	0.082
z	m	.046	.116	.317	.098
ϕ	deg	1.20	2.41	8.62	1.98
θ	deg	.57	2.65	6.54	2.24
ψ	deg	.25	2.24	5.12	1.79
$\dot{x}$	m/sec	.098	.043	.226	.098
$\dot{y}$	m/sec	-.006	.043	.158	.030
$\dot{z}$	m/sec	-.012	.037	.152	.024
p	deg/sec	.08	.36	.91	.29
q	deg/sec	.05	1.57	8.34	.71
r	deg/sec	.02	.75	3.72	.49
m_t	kg	1.61	1.20	6.67	1.61
m_A	kg	5.67	3.97	22.13	5.67
t	sec	162.40	82.8	590.5	162.40

(b) Pilot comments

"Some type of three-dimensional alinement aid is needed. The aid most preferred is the standoff cross."

"Roll attitude can be determined close-in from the standoff cross. Gross roll alinement can be obtained from running light pattern at greater distances."

"It would appear that the standoff cross concept incorporates all the advantages of the aids previously evaluated plus several of its own."

TABLE VII.- RESULTS OF NIGHT FLIGHTS USING STANDOFF CROSS ON CSM AND RETICLE IN LM

[Number of flights – 21; flights in tolerance – 100 percent]

(a) Terminal conditions

Variable	Units	Mean error	Standard deviation	Maximum absolute error	Mean absolute error
y	m	0	0.076	0.149	0.055
z	m	0	.128	.268	.107
ϕ	deg	.28	2.04	4.16	1.61
θ	deg	.95	2.58	5.30	2.10
ψ	deg	-.43	2.39	5.28	1.97
$\dot{x}$	m/sec	.122	.073	.314	.122
$\dot{y}$	m/sec	-.018	.043	.122	.034
$\dot{z}$	m/sec	-.009	.043	.098	.037
p	deg/sec	.01	.34	.97	.26
q	deg/sec	-.27	1.19	4.65	.67
r	deg/sec	.07	.52	.97	.42
m_t	kg	1.63	.83	4.26	1.63
m_A	kg	5.27	3.18	12.21	5.27
t	sec	179.2	71.6	346.3	179.2

(b) Pilot comments

"A LM-mounted floodlight is an aid to darkside docking but is not a necessity."

"With the LM headlight on [at night], the perspective of the entire CM gave much better depth perception and closing rate estimation."

"Flashing [RCS strobe] lights are disturbing only when you are out a ways."

"At 0.165 m/sec closure rate it felt like the vehicle was 'hurtling' in."

"In day runs the CSM can be used for gross alinement and the aid for fine [alinement]; but at night, with no light on CSM, the aid must be used for both gross and fine alinement, and it is difficult."

"Day and night runs are of equal difficulty."

TABLE VIII.- RESULTS OF FLIGHT USING RATE-COMMAND—ATTITUDE-HOLD CONTROL MODE

[Number of flights – 33; flights in tolerance – 88 percent]

(a) Terminal conditions

Variable	Units	Mean error	Standard deviation	Maximum absolute error	Mean absolute error
z	m	0.070		0.399	0.082
ϕ	deg	1.50	2.86	7.96	2.62
θ	deg	.08	2.42	5.44	2.02
ψ	deg	-1.21	1.93	6.12	1.81
$\dot{x}$	m/sec	.140	.061	.204	.140
$\dot{y}$	m/sec	-.012	.040	.128	.030
$\dot{z}$	m/sec	0	.101	.070	.024
p	deg/sec	.30	1.84	7.93	.63
q	deg/sec	.38	1.61	8.68	.49
r	deg/sec	.05	.88	4.42	.37
m_t	kg	.78	.36	1.64	.78
m_A	kg	3.39	2.49	10.14	3.39
t	sec	138.7	36.4	236.4	138.7

(b) Pilot comments

"Rate command with attitude hold provides excellent attitude control."

"Rate command with attitude hold is much easier to fly than rate command. Once the attitude is 'on,' all you have to worry about is translation, and attitude maneuvers are much less numerous."

"The 0.2 deg/sec rate deadband was much easier to fly than was the 0.75 deg/sec rate deadband. More attitude control inputs were required as the deadband became sloppier. The deadbands were evaluated in the rate command control mode. Since the 0.75 deg/sec rate deadband was quite close to the maximum allowable rate for docking of 1 deg/sec in each axis, more control inputs were required of the pilot to maintain the proper attitude. In addition, the pilot had to be 'on' in attitude and not maneuver in attitude when close to the target. The 0.75 deg/sec rate deadband should be considered as a backup only."

"Rate command mode with a 0.75 deg/sec deadband is much harder to fly than the rate command—attitude hold mode."

"The control power in translation (0.396 m/sec^2) was higher than desirable for precise translation control. Translation control inputs by the pilot were essentially bang-bang."

TABLE IX.- RESULTS OF FLIGHTS USING DIRECT ATTITUDE CONTROL MODE

[Number of flights – 18; flights in tolerance – 78 percent]

(a) Terminal conditions

Variable	Units	Mean error	Standard deviation	Maximum absolute error	Mean absolute error
y	m	0.046	0.110	0.256	0.088
z	m	-.027	.149	.408	.104
ϕ	deg	.67	4.66	11.28	3.59
θ	deg	.12		7.14	3.16
ψ	deg	2.49	3.62	9.86	3.72
$\dot{x}$	m/sec	.122	.061	.241	.122
$\dot{y}$	m/sec	-.009	.030	.098	.021
$\dot{z}$	m/sec	-.027	.052	.146	.049
p	deg/sec	.37	1.07	3.54	.66
q	deg/sec	-.57	1.17	3.35	.88
r	deg/sec	-.14	1.68	4.75	1.12
m_t	kg	1.52	1.47	5.52	1.52
m_A	kg	2.30	2.28	9.75	2.30
t	sec	186.1	35.7	488.1	186.1

(b) Pilot comments

"In direct [attitude control mode], using the switches at the end of throw is a problem, especially for pitch up."

"Three-axis direct is hairy and should be used only as a last-ditch effort."

TABLE X.- RESULTS OF FLIGHTS MADE USING PRESSURE SUIT

[Number of flights – 18; flights in tolerance – 67 percent]

(a) Terminal conditions

Variable	Units	Mean error	Standard deviation	Maximum absolute error	Mean absolute error
y	m	-0.235	0.107	0.436	0.235
z	m	.091	.219	.442	.192
ϕ	deg	2.92	5.74	14.36	4.83
θ	deg	.10	2.71	6.34	2.17
ψ	deg	-3.92	4.26	12.38	4.01
$\dot{x}$	m/sec	.113	.061	.232	.113
$\dot{y}$	m/sec	-.015	.037	.088	.030
$\dot{z}$	m/sec	0	.034	.137	.037
p	deg/sec	.16	.34	.85	.29
q	deg/sec	.92	2.60	7.52	1.46
r	deg/sec	-.17	.64	2.22	.40
m_t	kg	1.62	.80	3.85	1.62
m_A	kg	6.32	3.59	15.29	6.32
t	sec	146.8	53.4	242.0	146.8

(b) Pilot comments

"There is some difficulty [in wearing a pressure suit] because it is hard to tell how large an input is applied by feeling the controller. The primary indication is seeing motion of the vehicle. I don't seem to be having any other problem except with the controller."

NASA-Langley, 1967 —— 32 L-5210

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