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APOLLO EXPERIENCE REPORT - CREW STATION INTEGRATION

Volume III - Spacecraft Hand Controller Development

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16. Abstract

The development of hand controllers has evolved from the basic mechanical linkage technique used in the Mercury spacecraft to the total fly-by-wire three-axis switching device used to control the Apollo spacecraft. The evolving developmental process is described in this report.

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APOLLO EXPERIENCE REPORT

EDITORIAL COMMITTEE

FOREWORD

        This technical note documents experience gained in the area of spacecraft crew station design and operations during the Apollo Program. Emphasis is given to the time period ranging from early 1964 up to, and including, the Apollo lunar landing mission of July 1969. This time period covers three important phases of the Apollo Program: the design phase, hardware construction, and mission operations.

        This technical note consists of five volumes. Volume I, "Crew Station Design and Development," gives an overview of the total crew station integration task. Volumes II, III, IV, and V are specialized volumes, each of which is devoted to a basic functional area within the Apollo crew station. The subject of each volume is indicated by its title, as follows.

        Volume II, "Crew Station Displays and Controls"

        Volume III, "Spacecraft Hand Controller Development"

        Volume IV, "Stowage and the Support Team Concept"

        Volume V, "Lighting Considerations"

                                                    Louis D. Allen
                                                    Lyndon B. Johnson Space Center

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APOLLO EXPERIENCE REPORT

CREW STATION INTEGRATION

VOLUME I I I — SPACECRAFT HAND CONTROLLER DEVELOPMENT

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SUMMARY

During the development of control techniques for Project Mercury, rudder pedals were determined to be unsuitable for control in the yaw axis because of crew station and environmental interface problems. These conditions led to the development of the three-axis fly-by-wire hand controller used for the Apollo manned spacecraft.

To establish a guideline for the complex parameters of a three-axis controller, a functional specification was developed that established the mechanical forces and electrical functions of the Apollo spacecraft hand controllers. This specification also established a commonality requirement between the command module and the lunar module hand controllers and identified human engineering requirements.

INTRODUCTION

The Apollo spacecraft attitude (rotational) and translational hand controllers provided a linkage from the crewman to the stabilization and control system (SCS) that enabled the crewman to override the automatic control mode and manually insert pulse, direct, or proportional commands in the pitch, roll, and yaw axes or any combination of these axes. The six hand controllers that existed during the Apollo Program included the command module (CM) Block I rotational hand controller (RHC), the CM Block II RHC, the CM Block I translational hand controller (THC), the CM Block II THC, the lunar module (LM) attitude controller assembly (ACA), and the LM thrust and translation control assembly (TTCA).

The Apollo spacecraft hand controllers represent the state of the art in hand controller design as it has evolved through the manned space-flight programs. Initially, rudder pedals were envisioned for the Mercury spacecraft yaw axis, with a two-axis hand controller for the pitch and roll axes. However, high g-loads, restricted leg movement within the space suit, and weight and space limitations forced the design of a three-axis attitude controller (fig. 1). For the Mercury spacecraft, the controller basically consisted of a set of linkages controlling variable valves on one set of thrusters with limit switches on the linkages for the fly-by-wire mode driving a second set of

thrusters. The Gemini spacecraft attitude and translational controller design (figs. 2 and 3) eliminated many of the mechanical linkages present in the Mercury design and provided a complete and improved fly-by-wire system. The Apollo spacecraft controllers represent an even more significant refinement.

During the development of the Apollo controls, a functional specification for attitude controllers was established to maintain the requirement for commonality between the CM rotational controller and the lunar module (LM) attitude controller and to provide a baseline for controller feel and function. This specification was first applied to the Apollo Block II CM RHC
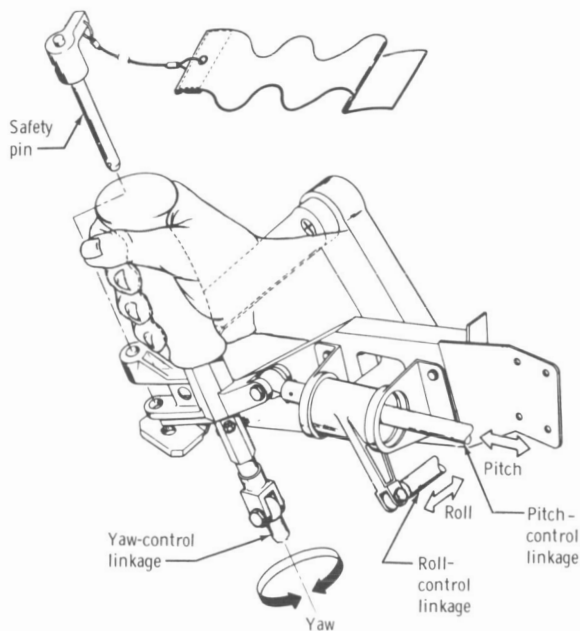

Figure 1. - Mercury spacecraft three-axis hand controller.
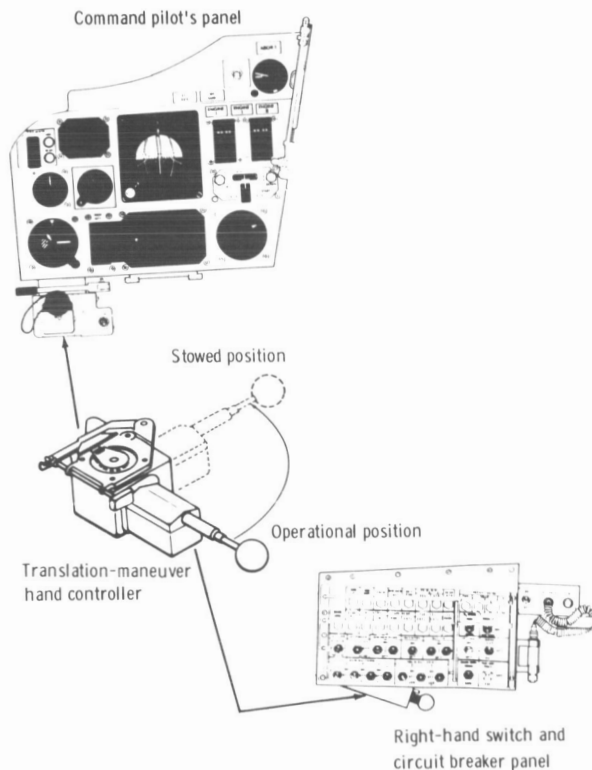

Figure 2. - Gemini spacecraft attitude controller.

Figure 3. - Gemini spacecraft translational-maneuver hand controller.

during the early developmental phases and to the LM attitude controller assembly (ACA) during the design phase. Two attitude controllers were installed in both the CM and LM to provide redundant controllers and additional control inputs during peak workload periods.

The CM translational controller assembly provided the crewmen with the capability to issue discrete manual commands in each axis (X, Y, and Z). It also provided abort-enable and autopilot-disable capability. The LM TTCA provided the crewmen with the capability to issue discrete manual commands in each axis (X, Y, and Z). It also provided a throttle mode for varying the thrust of the descent engine.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

DISCUSSION

Hand Controller Functional Specifications

During the development of the Apollo Block I hand controllers, the need for a functional specification to define and maintain the requirement for commonality between the CM and LM controllers became evident. Although this specification (appendix A) established the feel (i.e., force and deflection), control functions, soft stop requirements, and handle design, it was flexible enough to accommodate mechanization of each controller to its assigned task. The vendor requested and was granted three deviations to the specification (appendix B).

Much of the specification data was obtained by conducting laboratory simulations that evaluated different combinations of force and deflection characteristics. A single-axis tester, which consisted of a handgrip mounted on a variable-control device, was used as a measurement device for the simulation during which simple tracking tasks were performed by the crewmen. By changing the position of the tester handgrip, torque and displacement variations (including soft stops) could be made in any one axis. The mechanical setup of the tester could be converted to measure the torque at breakout, rate or torque increases from breakout to soft stop, the torque step at a constant deflection at the soft stop, the rate of torque increase from soft to hard stop, and the hysteresis.

Attitude Controllers on the CM

When the functional requirements specification was approved, a design freeze was imposed on the Block I attitude controller. This controller was redesigned to the specified requirements, and the new configuration became known as the Block II controller.

Block I RHC. - The Block I RHC was a small, simple, compact, three-axis controller with three switches and a linear transformer output (rotary variable-differential transformer (RVDT)) in each axis. A quick-disconnect dovetail mounting bracket and

a long cable permitted relocation of the controller within the spacecraft. The RHC, although designed for right-hand use only, could be transferred to the navigation station or to another crewman's couch. This handle was designed without space-craft communications push-to-talk switches (fig. 4 and table I). A mechanical locking pin extended through the handle of the Block I RHC into the RHC base; this pin prevented inadvertent RHC activation during nonoperating periods. Late in the design phase of the Block I RHC, soft stops were added to the roll axis only to provide the crewmen with a manual-override output in roll for lift-vector control during entry.

Figure 4.- Functions of the Block I CM rotational hand controller.

TABLE I.- BLOCK I RHC SPECIFICATIONS

Parameter	Value
RVDT input voltage, V ac, at 400 Hz, 1 W	26
RVDT output voltage, V ac, at 400 Hz, 1 W	0 to 4.2
Switch voltage, V dc	28 (+2, -3)
Switch inductive load, A	4
Switch resistive load, A	7
Maximum dimensions, cm (in.):	
Height	23.50 (9.25)
Length	14.63 (5.76)
Width	7.11 (2.80)
Cable length	467.4 (184.0)
Weight (including external cable and connector), kg (lb)	2.22 (4.9)

Block II RHC.- The force and displacement characteristics of the Block II RHC were an improvement over those of previous models. Although many operational problems occurred with the RHC, most were discovered and corrected by the vendor. Because of training requirements, seven early model rotational hand controllers were delivered. Several problems were experienced with these units during the training sessions. The most significant problem was multiaxis interference; that is, a maximum deflection in plus roll and minus pitch caused the pitch-sector gear to hit the frame and force the switch package and the RVDT out of calibration. An offset null resulted, and the pitch breakout switch remained closed. This problem was resolved by machining the frame for adequate clearance.

During preliminary training sessions with the Block II rotational hand controllers, the crewmen noted that the fuel-budgeting technique developed for the Gemini controller was not possible for the Apollo RHC. On the Gemini spacecraft, a minimum jet impulse could be obtained by quickly tapping the controller handle in the desired direction. A short engine pulse would result, and the controller handle would be returned by springs to the neutral position without further jet firings. When this technique was tried with the Apollo RHC, the handgrip overshot its neutral position in the opposite direction because it was underdamped, thus causing undesired jet firings. All hand controllers were tested by tapping the handle sufficiently for a right-roll impulse and monitoring the handle overshoot for a left-roll impulse. No overshoot impulse existed on the Gemini and Block I CM attitude controllers; however, in the Block II CM and LM attitude controllers, a negative-roll impulse was observed. Another test consisted of commanding a full-right-roll deflection to the soft stops, releasing the handle, and measuring the time required for the controller to reach and stay within the detent switches. The following test results were obtained.

Attitude controller tested	Response time, sec
Gemini	0.120
Apollo:	
Block I CM	.020
Block II CM	.200
LM	.400

The vendor engineering specification for the LM ACA required that the overshoot not exceed 1.0 second in roll and 0.5 second in pitch and yaw. The Apollo spacecraft computer compensated for the overshoot obtained by tapping the handle; therefore, the Block II hand controller did not require modification.

The final design for the CM RHC (fig. 5 and table II) consisted of 3 rotary variable-differential transformers and 18 microswitches; that is, one breakout switch and two direct switches beyond each soft stop (fig. 6). One of the two direct switches was redundant. The mechanical locking pins were redesigned within the RHC; two interlock switches were provided for electrical disablement. Scissor-type null-positioning springs were used in each axis to eliminate hysteresis and provide a reliable mechanical zero. A symmetrical handle, equipped with a push-to-talk switch, was designed for left- or right-hand operation.

Figure 5.- Functions of the Block II CM rotational hand controller.

TABLE II.- BLOCK II RHC SPECIFICATIONS

Parameter	Value
RVDT input voltage, V ac, at 400 Hz	26 ± 0.32
RVDT output voltage, V ac, at 400 Hz	0 to 4.58 ± 0.32
Switch voltage, V dc.	28
Switch inductive load (direct), A	5
Switch resistive load (breakout and push to test), A	3
Maximum dimensions, cm (in.):	
Height	27.28 (10.74)
Length	18.52 (7.29)
Width	7.70 (3.03)
Cable length	274.3 (108.0)
Weight (including external cable and connector), kg (lb)	3.6 (8)

Figure 6.- Block II rotational control.
Pitch torque plotted as a function
of deflection with increasing torque.
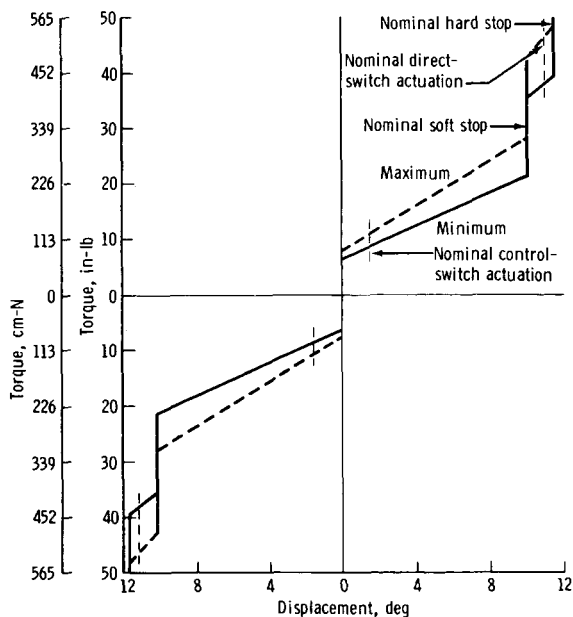

Figure 7.- Functions of the LM attitude
controller assembly.

The ACA on the LM

The basic design configuration of the
LM ACA (fig. 7 and table III) passed all
design verification and quality testing. As
problems occurred, they were corrected
within specification requirements. Costly
last-minute design changes were minimized,
and a high-quality hand controller package resulted. A rigid switch package was used for
each axis to avoid wire-bundle flexing. Each package contained 14 switches and a trans-
ducer, which was actuated through gear and linkage assemblies to the handle. To avoid
the torque buildup to switch actuation (as was experienced with the Gemini controller),
a force-feedback technique was developed for switch pairs so that, as one switch opened,
another closed, thus canceling any force buildup and undesirable feel at the handle.

The requirements for internal logic functions for the pitch and roll axes and
direct thruster control increased the number of switches to 14 per axis. The internal
switch logic, coupled with the multiple power paths to the controller, complicated
failure-isolation procedures; therefore, special external isolation switches were added
for rapid controller disablement. The increased number of switches did, however,
offer more capability for isolating a failed switch. Because of the requirement to stow
the controllers during certain intravehicular activities and during ingress and egress,
the controllers were mounted to foldable armrests. This design feature required a
number of refinements since it introduced problems including interference, wire-bundle
flexing, and inadvertent switch closures during stowage. Additional problems
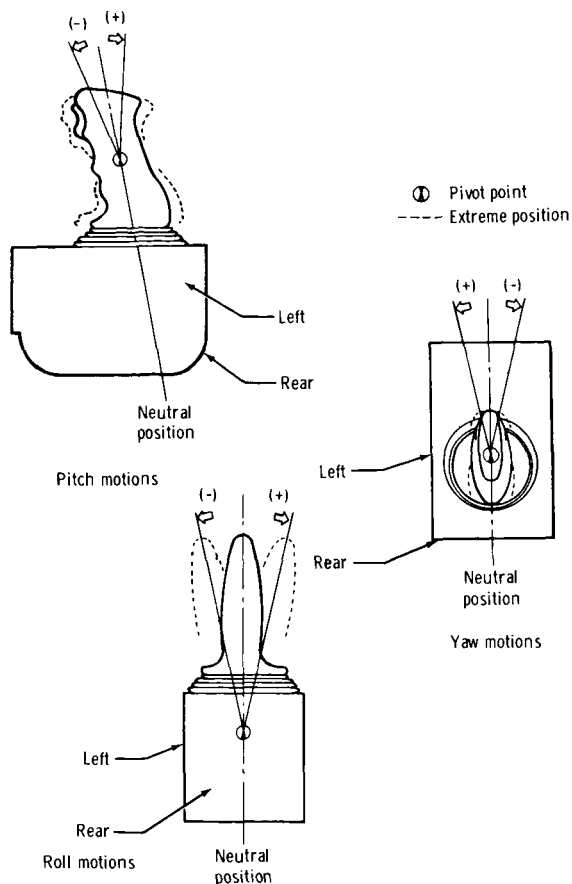
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concerning excessive cable length, cable routing, stowage mechanization, and controller-vehicle interface were alleviated before the first manned mission.

TABLE III. - LUNAR MODULE ACA SPECIFICATIONS

Parameter	Value
Linear-transformer output voltage to soft stop, V ac, at 800 Hz, 1.5 W	0 to 2.87 ± 0.07
Switch voltage, V dc	28 (+2, -3)
Switch inductive load, A	1
Switch resistive load, mA	500
Maximum dimensions, cm (in.):	
Height	25.55 (10.06)
Length	16.99 (6.69)
Width	10.16 (4.00)
Cable length	91.44 (36.00)
Weight (including external cables and connectors), kg (lb)	2.04 (4.50)

The 14 switches and the RVDT within the LM ACA performed the following functions. As the control handle was moved from neutral (fig. 8), the detent switches closed, preparing the system for a pulse-direct firing of the jets. At 2° to 3° deflection, the pulse-direct switches closed, and the appropriate reaction control system (RCS) jets fired. At a displacement of approximately 10°, the soft stops separated the pulse-direct mode from the manual-override mode. Movement of the handle beyond the soft-stop position closed the four manual-override switches, which caused direct firing of all four jets. The RVDT output was variable (0 to 3 volts, 800 hertz), either in or out of phase with respect to direction, from null to the soft stops.
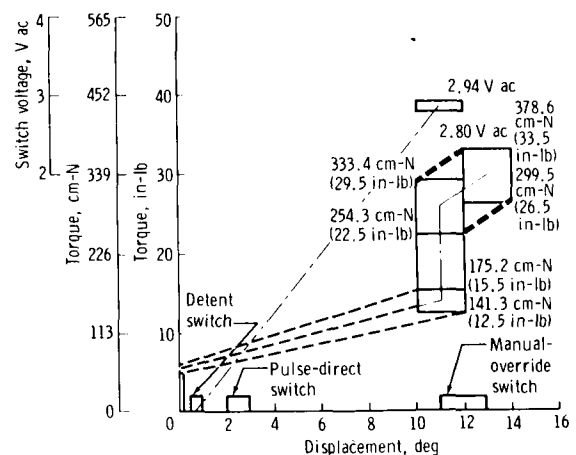

Figure 8.- Lunar module ACA roll-axis torque, voltage, and switch requirements plotted as a function of displacement.

Translational Hand Controllers on the CM

Two translational hand controllers were installed in the Apollo Block I spacecraft for redundancy. During the Block II redesign, redundant switching was incorporated in the controller so that the separate backup controller was eliminated.

Block I THC.- The Block I THC was a simple T-handle displacement-type control with two microswitches each in the X-, Y-, and Z-axes. The autopilot-disable and launch-abort modes were initiated, respectively, by clockwise or counterclockwise rotation of the T-handle grip from 12° to 17°. A problem existed in these modes in the CM THC because a greater force was required to rotate the handle out of the disable or abort mode than out of detent. This situation, which caused the handle to go beyond detent into the opposite mode, was annoying but was not an operational problem.

The translational modes were actuated by a 0.89-centimeter (0.35 inch) displacement in or out for the X-axis and a 6° deflection of the handle for Y- or Z-axis. The crewman's push-to-talk intercom switch was installed in the top of the T-handle, and a mechanical sliding lock to arm the THC was located on the top cover of the handle (fig. 9 and table IV).

Block II THC.- The Block II THC was mounted on the left armrest of the commander's (CDR's) couch on a dovetail mounting bracket. As in the Block I design, the T-handle rotation provided the CDR with the capability to initiate an abort
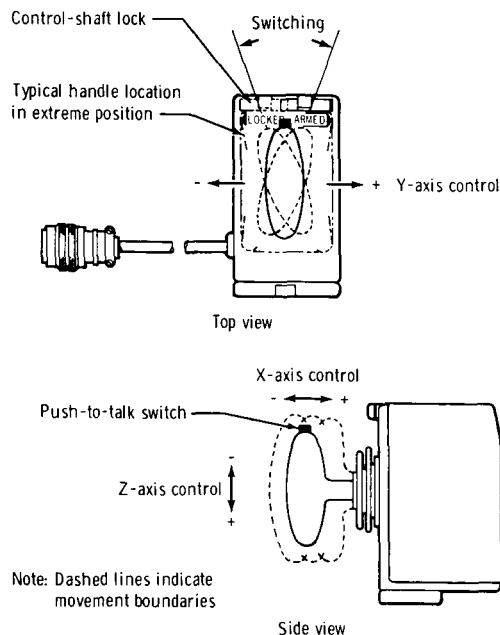

Figure 9.- Functions of the Block I CM THC.

TABLE IV.- BLOCK I THC SPECIFICATIONS

Parameter	Value
Input voltage to switches, V dc	28 ± 3
Switch ratings:	
Sensitive switches	
Maximum resistive load, A . . .	5
Maximum inductive load, A . . .	3
Nominal operating load, mA . . .	100 to 500
Push-to-talk switch	
Maximum resistive load, A . . .	3
Maximum inductive load, A . . .	1
Nominal operating load, mA . . .	250
Maximum dimensions, cm (in.):	
Height	14.83 (5.84)
Length (grip extended)	17.78 (7.00)
Width	7.70 (3.03)
Cable length	467 ± 5 (184 ± 2)
Weight (including cable), kg (lb) . . .	2.38 (5.25)

or to override the autopilot mode. Rotating the T-handle counterclockwise initiated an abort during the launch sequence. Rotating the handle clockwise disabled the CM computer and engaged the SCS backup configuration selected or switched from SCS automatic thrust vector control (TVC) to manual TVC, depending on the position of panel switches. The overshoot problem of the Block I THC was corrected in the Block II design. A vertical or horizontal deflection of the T-handle in or out by 1.27 centimeters (0.5 inch) provided the CMP with manual control in translation of the Z-, Y-, or X-axis or any combination of those axes (fig. 10 and table V).
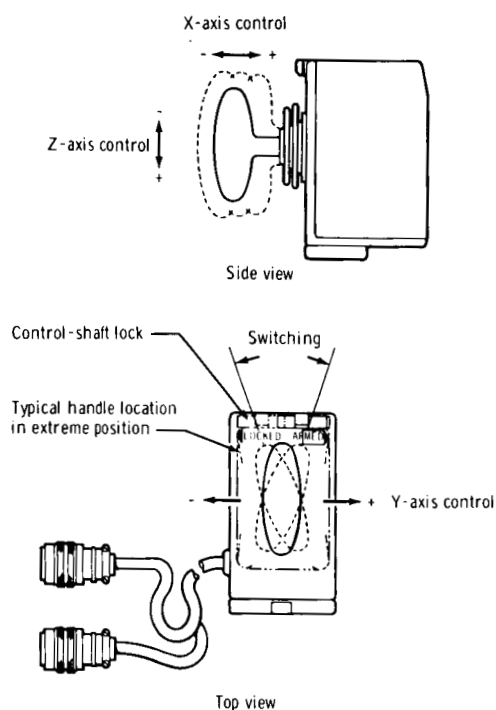
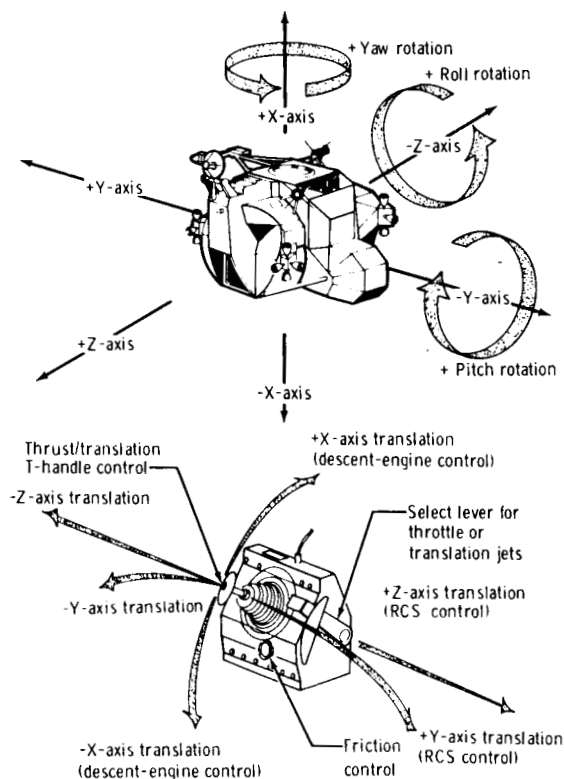Figure 10. - Functions of the Block II CM THC.

Figure 11. - Functions of the LM TTCA.

The TTCA on the LM

The two LM thrust and translation controller assemblies provided the LM crewmen with manual translational control of all three axes, with deflection of the T-handle by actuation of detent switches. The feeling of stiffness with deflection of the controller handle was due to the use of moving switch packages and graphite-type lubricants. By sliding a lever on the side of the controller, control in the X-axis (fig. 11) became a manual-throttle mode for the descent engine. A soft stop was designed at 53° deflection of the throttle handle, which represented a 0- to 53-percent thrust of the descent engine for fine control during landing maneuvers. Beyond the soft stop were 10° of handle deflection for controlling 53 to 100 percent of the descent-engine

thrust. The amount of frictional drag on the handle in the throttle mode (fig. 12) could be varied by an external knob on the lower left side of the controller.
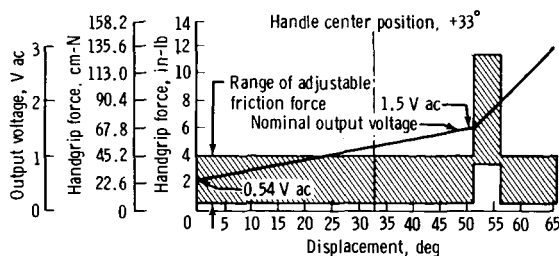

Figure 12. - Handgrip force and output voltage plotted as a function of displacement on the LM TTCA in the throttle-control mode. When the handgrip is moved through the 51° to 56° position in either direction, the minimum jump in friction is 33.9 cm-N (3 in-lb).

TABLE V. - BLOCK II THC SPECIFICATIONS

Parameter	Value
Input voltage to switches, V dc . . .	28 (+2, -3)
Switch ratings:	
Z-, Y-, and X-axis switch resistive loads, A	2
Clockwise rotary switch resistive loads, A	2
Counterclockwise rotary switch resistive loads, A . . .	2
Maximum dimensions, cm (in.):	
Height	16.03 (6.31)
Length (grip extended)	18.69 (7.36)
Width	9.73 (3.83)
Cable length (including connectors)	229 (90)
Weight (including cable), kg (lb)	2.7 (6)

CONCLUDING REMARKS

It was demonstrated in the Apollo Program, as in Project Mercury and the Gemini Program, that the three-axis hand controller is very adaptable to the spacecraft environment. However, it was not conclusively established that a three-axis controller would be acceptable in a shuttle-type vehicle when used in a dual mode as both an atmospheric and nonatmospheric control device. The functional specification for attitude controllers developed during the Apollo Program provides flightcrew operational design requirements for use in spacecraft applications.

For future programs, the amount of internal electrical components and logic should be minimized as was done in the design of the command module rotational hand controllers (as opposed to the design used in the lunar module attitude controller assembly). Internal components should be minimized or transferred to external black boxes to reduce the possibility of massive internal failures and to permit a straight-forward approach for normal or emergency powerdown of controllers; that is, by reducing the power-signal paths at the controller interface.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, September 13, 1974
956-23-00-00-72

APPENDIX A

FUNCTIONAL SPECIFICATIONS FOR APOLLO HAND CONTROLLERS

SCOPE AND CLASSIFICATION

This specification establishes the basic functional characteristics required for the hand controllers to be used in the Apollo command module and lunar module and is applicable to any three-axis attitude side-arm controller used for manual control of space vehicle attitudes (pitch, roll, and yaw).

REQUIREMENTS

Controller Forces

The data showing torque plotted as a function of deflection in figures A-1 to A-3 represent the required force characteristics in the pitch, roll, and yaw axes, respectively. These characteristics include breakout, gradient, soft stops, and maximum forces. The hysteresis inherent in each controller shall be held to within ±10 percent of the breakout spring force so that the actual measured forces fall within the bands shown in figures A-1 to A-3.

Controller Deflections

The deflections for roll, pitch, and yaw shall be as shown in figure A-4. Nominally, the soft stops shall be encountered at ±10° and the hard stops at ±11.5° in all axes.

Controller Axes

The axes shall be as shown in figure A-5. The pitch axis shall be at the palm of the hand; the yaw axis, through the hand perpendicular to the pitch pivot; and the roll-axis pivot, 10.16 (-0.0, +2.54) centimeters (4.00 (-0.0, +1.0) inches) below and perpendicular to the normal pitch axis.

Relative Location of Controller Axes

Controller axes relative to the pilot axes. - As shown in figure A-5, the controller axes in the installed position shall be alined relative to the corresponding pilot-labeled vehicle axes so that the controller input axes are obvious to the pilot.

Controller axes relative to the centerline of the forearm. - The normal position of the controller yaw axis shall be such that the vertical angle between this axis and the centerline of the forearm is 110° ± 5° to allow for normal positioning of the hand (fig. A-5).

Control-Systems Mode-Actuation Points Within Controller Deflections

Proportional output. - The proportional output shall be active through the entire controller deflections (±10°) except for the dead band at neutral. This dead band shall not exceed ±1° handle deflection (mechanical dead band). The proportional output shall always fall outside the mechanical dead band of the controller to prevent inadvertent inputs.

Direct-mode actuation. - The direct mode shall be actuated at 25 percent (2.5° ± 1°) of total normal deflection in all axes.

Emergency direct-mode actuation. - The emergency direct mode shall be actuated at a point beyond the soft stops and before contacting the hard stops.

Pulse-mode actuation. - The pulse mode shall be actuated at the same point as the direct mode.

Handgrip

The desired handgrip shape shall be as shown in figure A-5. Deviations to this shape (to accommodate switching, etc.) shall be submitted to the NASA Lyndon B. Johnson Space Center (formerly the Manned Spacecraft Center) for written approval or disapproval.
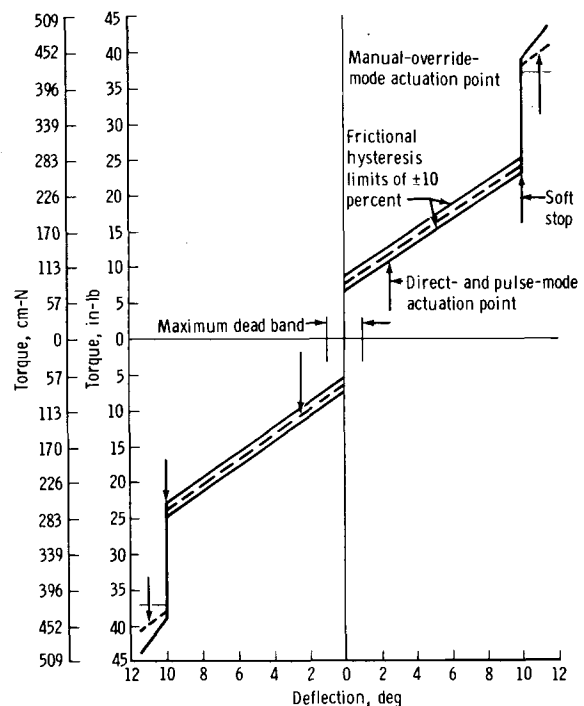

Figure A-1.- Pitch torque plotted as a function of deflection.
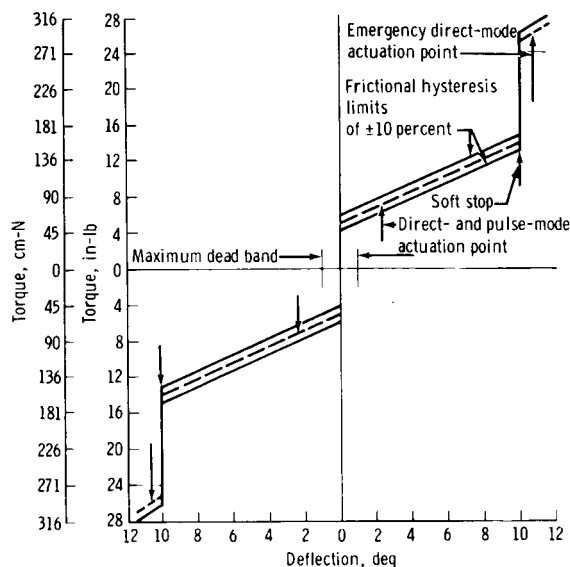
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Figure A-2. - Roll torque plotted as a function of deflection and measured at 10.478 centimeters (4.125 inches) above roll pivot (i.e., at pitch pivot).
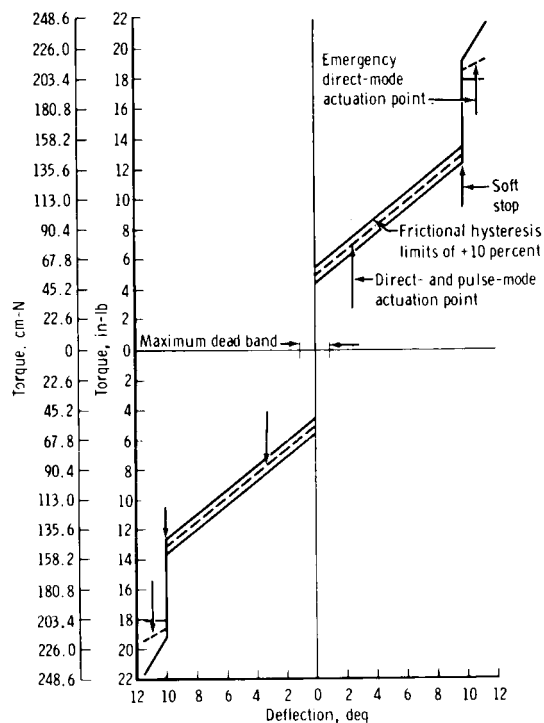

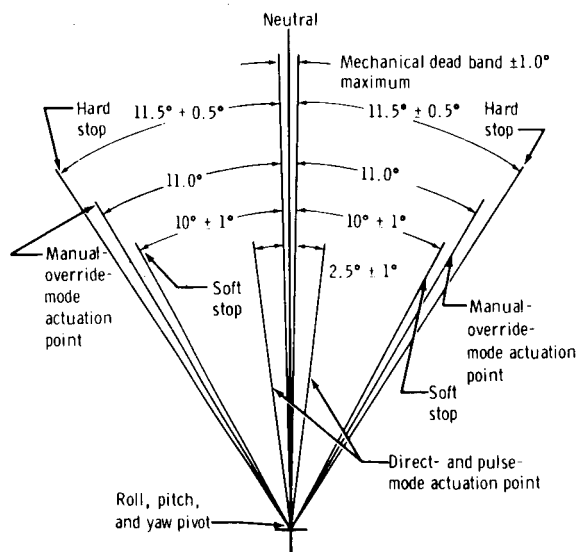Figure A-3. - Yaw torque plotted as a function of deflection.
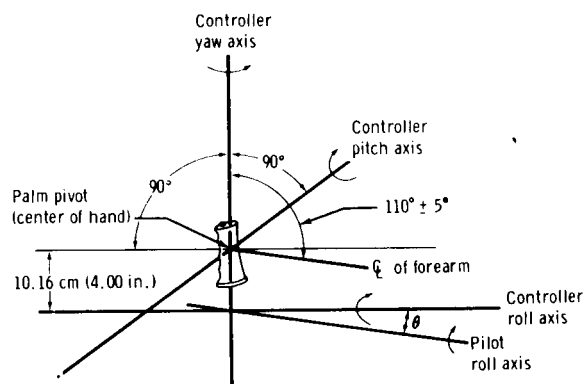

Figure A-4. - Deflections for roll, pitch, and yaw.

Figure A-5. - Controller axes with respect to crewman. The angle θ should be established such that the controller input axes are obvious to the pilot.

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APPENDIX B
APPROVED DEVIATIONS TO HAND CONTROLLER
FUNCTIONAL SPECIFICATIONS

Deviation 1

The force tolerance shall be such that, when measured in an increasing force direction, the maximum deviation from the nominal force value at any given point along the force-and-deflection curve (figs. A-1 to A-3) shall not exceed ±20 percent of the nominal force values. When measured in a decreasing force direction, the force shall not be less than 60 percent of the force value. The rationale for this request is explained in the following discussion.

The tolerance curve defined in the specification does not appear to be necessary to give the handle the proper feel and may indeed be undesirable because of the following penalties that are inherent in the mechanization. By holding the up and down forces to a tight tolerance, the breakout force is held to an even tighter tolerance so that the nonlinearities of the up- and down-force gradients should not cause the measured forces to fall outside the tolerance band. This tolerance and the high load limit (136 kilograms (300 pounds)) require the manufacturer to use special precision components, which raise the per-unit cost.

Deviation 2

The proportional output shall be active through the entire controller deflection (±10°) except for the dead band at neutral. This dead band (mechanical and electrical) shall not exceed a controller deflection of 1.75° ± 0.25° (when measured in an increasing force direction). The proportional output shall always fall outside the dead band of the controller to prevent inadvertent inputs. The following discussion explains the rationale for this request.

The intent of the specification is to cause the vehicle to start to rotate at 1° of increasing handle deflection and to slow, as close as possible, to a dead stop as the handle passes through 1° of decreasing handle deflection.

Although moving the electrical breakout point in toward the neutral point will decrease the handle deflection necessary to start the vehicle rotating, it will not reduce the vehicle rates below the dead band rates (without having to command an opposite rate). Extensive modifications to either the system or the controller or both must be made with resultant undesirable side effects (weight increase, volume increase, reliability decrease, cost increase, and peculiar operating characteristics). The requested 1.75° allowable deflection represents a compromise between the Block I value of 2.5° and the Block II specification of 1.0°.

Deviation 3

The direct mode shall be actuated at 17.5 percent ($1.75° \pm 0.25°$ as measured in an increasing force direction) of total normal deflection in all axes. The rationale for this request is discussed in the following paragraph.

Changing the location of the direct- and pulse-mode actuation point to $1.75° \pm 0.25°$ also allows the breakout switches to perform these switching functions. The change reduces the total count of internal control switches from the 16 switches required by the specification to 12 switches. Reducing the total switch count allows the rotational-control volume to be reduced by approximately 120×10^{-5} cubic meters (73 cubic inches) and the box weight to be reduced by approximately 0.45 kilogram (1 pound).

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."
—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

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