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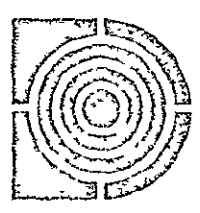
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May 1975



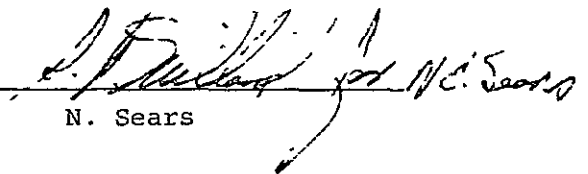
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ABSTRACT

The objective of the On-Orbit Flight Control Module is to provide rotational and translational control of the Space Shuttle orbiter in the Orbital Mission Phases, which are external tank separation, orbit insertion, on-orbit and de-orbit. A candidate design and its implementation are presented in this document. The program provides a versatile control system structure while maintaining uniform communications with other programs, sensors, and control effectors by using an executive routine/functional subroutine format.

Section 1 describes the software functional requirements using block diagrams where feasible, and input-output tables. Section 2 describes the software implementation of each function using equations and structured flowcharts. This section relates on a one-for-one basis with the material in Section 1. Section 3 contains a glossary of all symbols used to define the requirements. The Appendices of Section 4 contain material which is supportive in nature to the preceding sections or is too voluminous to be included therein.

FOREWORD

This document presents the second revision of the Space Shuttle digital flight control design base developed jointly by the Draper Laboratory Control and Flight Dynamics Division, the JSC Guidance and Control Systems Branch, and the Lockheed Houston Aerospace Systems Division. Detailed designs for the orbital flight phase are documented herein in accordance with Rockwell International Space Division, Procurement Data Requirement Description, Digital Autopilot Requirements Definition, number UA17. This report replaces the parallel material in The Charles Stark Draper Laboratory, Inc. document R-793, Book 1-Volume IV, Functional Subsystem Software Requirements Document, Flight Control, Vertical Flight Test, Revised August 1974. Sections have been renumbered to reflect the more limited scope of the present document.

This publication describes the design of the Flight Control software in its present state of development. Its primary intent is to provide a reference to the algorithms incorporated in the control laws. The organizational structure of the software is undergoing significant revision; therefore, material pertinent to this aspect should be considered a snapshot of an evolving process.

Point designs and algorithms are presented for the Flight Control module which may be categorized into Digital Autopilot (DAP) drivers, a Reaction Control System (RCS) DAP, a Thrust Vector Control (TVC) DAP and a state estimator.

Each driver has the function of providing to either the RCS DAP or the TVC DAP drive signals which have been processed from raw controller inputs or other data external to the Flight Control module.

The RCS DAP contains designs for the phase plane and jet selection. A single phase plane control law is employed which treats the no disturbance acceleration case as the limit of the finite disturbance acceleration case. The nominal and vernier jet selection is based on logical

equations that produce an on-off state for each jet as output while accommodating hi-lo, jet fail, tail or nose, translation, and off-axis coupling compensation options. Its major design feature is the capability to satisfy the fail-operational fail-safe requirement.

The TVC DAP design is presented for both the linear engine gimbal servo and the latest model of the nonlinear servo. The digital compensation was designed in consideration of bending, slosh, tail-wags-dog, stability margins, transient response, closed-loop guidance, sample period, thrust misalignment and engine failures.

The state estimator has two separate filters which produce somewhat independent estimates for rate and acceleration without use of the nonlinear trap concept.

In addition to revisions of existing designs, this report contains the first version of failure detection and identification logic which responds to failures in the control effectors.

The sections of the Flight Control module described in this document, with the exception of the jet selection algorithms, certain drive routines and the failure detection and identification logic, have been structured and are being run on the Statement Level Simulator (SLS) which is being developed at the Draper Laboratory for the testing of flight programs that are written in HAL (Higher Assembly Language).

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SECTION 1

SOFTWARE FUNCTIONAL REQUIREMENTS

The functions of the Flight Control (FC) module, and additional FC-related functions performed externally to the module, are identified and described in this section. The description begins with an overview that relates the FC module to the other Guidance, Navigation and Control (GN&C) software major functions, defines its external interface, and identifies the functional groups within the FC module. The section then describes individual functions using analytic block diagrams which relate on a one-for-one basis with the actual flowcharts of Section 2. The input and output requirements for each module appear in tabular form. A glossary of the symbols used in this section to represent computer variables appears in Section 3.

1.1 Overview

The FC module, or FC, will control the attitude and translation of the Space Shuttle during orbital activities by using the Reaction Control System (RCS) and/or Thrust Vector Control (TVC) of the Orbital Maneuvering System (OMS) as effectors. The RCS consists of 38 nominal (900 pound thrust) fixed jets and 6 vernier (25 pound thrust) fixed jets. The OMS is a pair of 6000 pound thrust engines gimballed independently of each other in pitch and yaw. Figure 1.1-1 shows the relationship of FC to other GN&C major functions and to the shuttle sensors, effectors, controls and displays. The FC module is scheduled by the top-level Moding and Sequencing function of the applications software via the Flight Computer Operating System.

There are two rather independent sets of control laws for the RCS and for TVC, and FC divides the effector-peculiar algorithms into two digital autopilots (DAPs)—an RCS DAP and a TVC DAP—as shown in Figure 1.1-2. Only one DAP is in control at any given time, although the TVC DAP can request help from the RCS DAP for attitude control if necessary. The controlling DAP receives commands from one or possibly

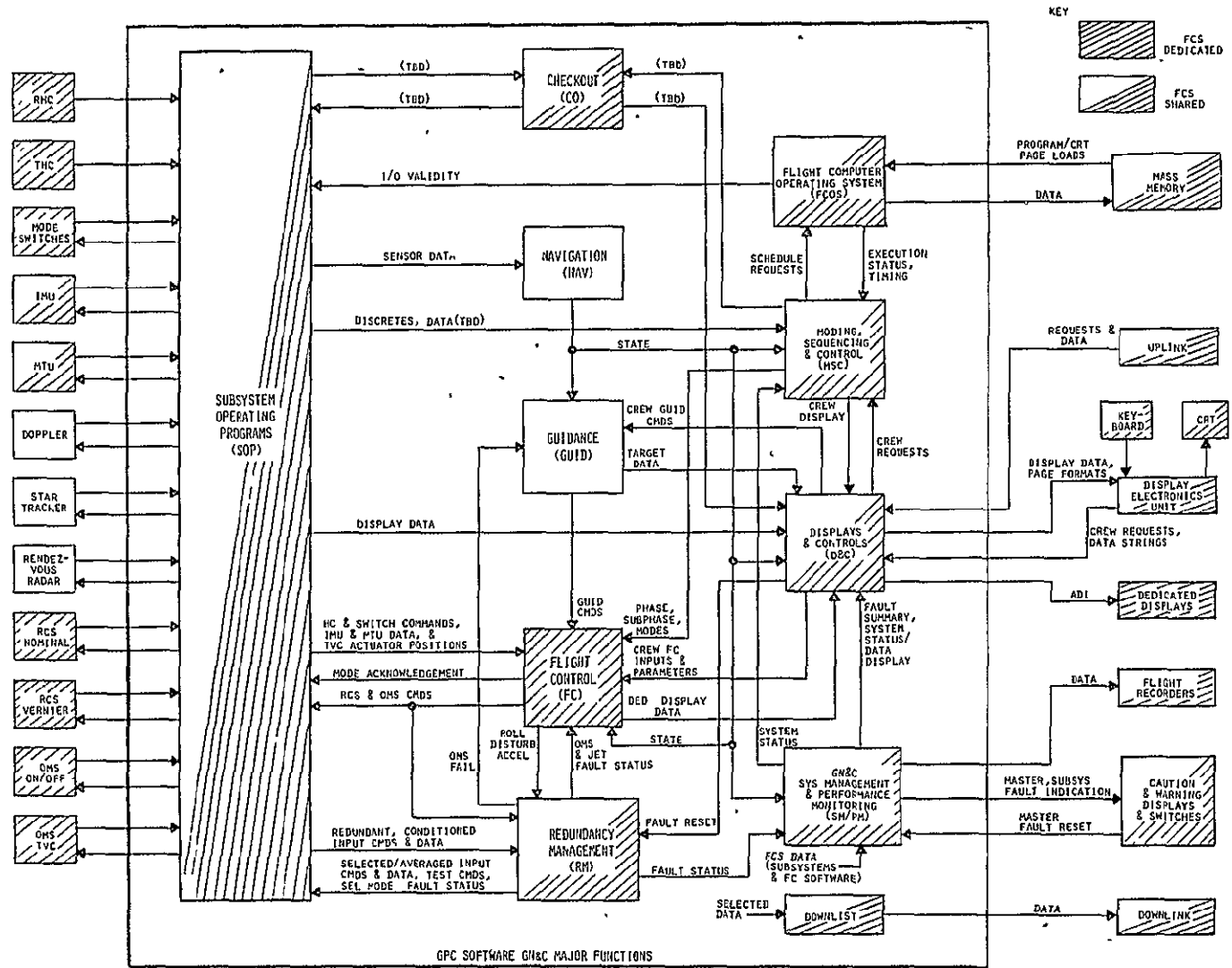


Figure 1.1-1. Relationship of FC module to other GN&C major functions.

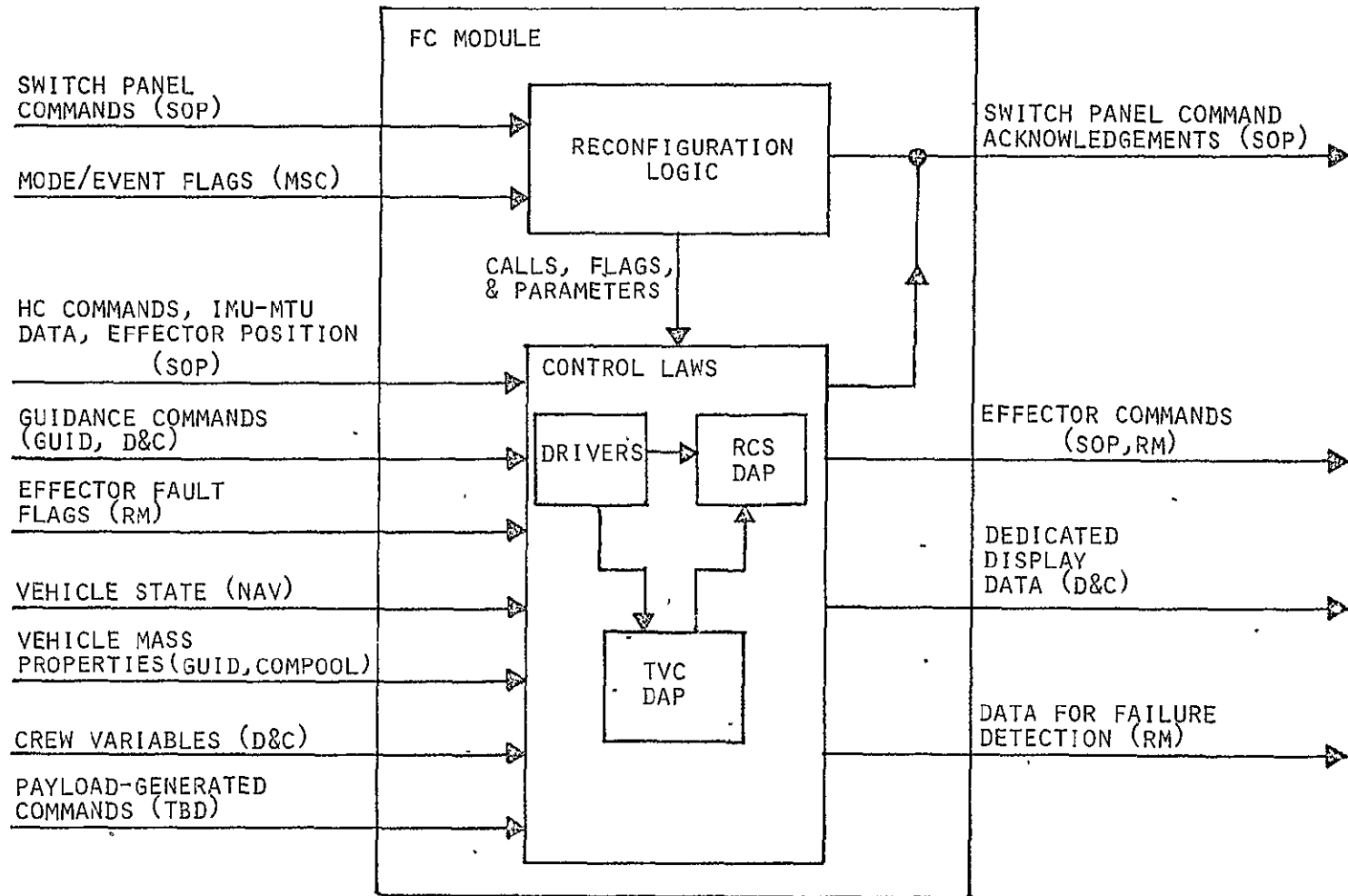


Figure 1.1-2. Functional relationship of reconfiguration logic and control laws for the FC module.

two of a set of driver routines, whose general function is to translate the externally supplied commands and data into a standard command set acceptable by the particular DAP. Selection of the driver(s) and controlling DAP is the responsibility of the Reconfiguration Logic which calls the appropriate routines in response to crew inputs and external software flags. Additional reconfiguration, within the called routines, is performed through the passage of flags and adjustment of parameters used in the control laws.

Inputs and outputs of FC are described in Tables 1.1-1 and 1.1-2 respectively. Within these tables, the inputs and outputs are grouped under headings that correspond to the input/output interface labels of Figure 1.1-2. The "type" column of the tables uses the following abbreviations:

- A(1) - Array of order 1
- V(1) - Vector of order 1
- M(1,j) - Matrix of 1 rows, j columns
- S - Scalar
- I - Integer
- B - Boolean

The detection and identification of failures of the control effectors is performed by code in the Redundancy Management module (Figure 1.1-1). The routine, titled OMS/RCS Failure Detection and Identification (FDI), is described in this document since its implementation is proceeding parallel to the flight control design. Based upon FDI-derived data, the FC module may make internal changes to its execution.

1.2 Reconfiguration Logic

1.2.1 Supervisor

The FC module is invoked regularly by the FCOS. The Reconfiguration Logic at the top level maintains and interrogates flags and indices, and determines the appropriate selection and sequence for invoking the second-level, or "driver", routines, each of which performs a specific function to supply commands to the TVC or RCS DAP.

Table 1.1-1. Input parameters for the FC module.

Name	Description	Source	Type	Range	Units	Sample Rate (Hz)	Update Rate Req'd (Hz)
<u>SWITCH PANEL COMMANDS</u>							
WIDE_NARROW_DB_SW	Phase plane deadband select	SOP	A(3)B	0, 1	(none)	25	TBD
ROT_HI_LO_SW	Rotation controller gradient, discrete rate, pulse size and discrete acceleration level select	SOP	A(3)B	0, 1	(none)	25	TBD
TRANS_HI_LO_SW	Translation pulse size and discrete acceleration level select	SOP	A(3)B	0, 1	(none)	25	TBD
ROT_OPTION	Manual rotation submode select	SOP	A(3)I	1, 2, 3	(none)	25	TBD
TRANS_OPTION	Manual translation submode select	SOP	A(3)B	0, 1	(none)	25	TBD
NOM_VERNIER_SW	RCS nominal/vernier jet select	SOP	B	0, 1	(none)	25	TBD
NORMAL_VIEW_SW	HC axis system select (based on HC identity and desired axes)	SOP	B	0, 1	(none)	25	TBD
PURE_NONPURE_SW	RCS pure moment/cross coupling select	SOP	B	0, 1	(none)	25	TBD
INERTIAL_LOCAL_SW	Barbecue mode inertial/local vertical axis system select	SOP	B	0, 1	(none)	25	TBD

Table 1.1-1. Input parameters for the FC module (Cont.).

Name	Description	Source	Type	Range	Units	Sample Rate (Hz)	Update Rate Req'd. (Hz)
<u>MODE/EVENT FLAGS</u>							
RCS_ROTATION	RCS rotation mode enable	MSC	B	0, 1	(none)	25	TBD
RCS_ROT_AUTO_MANUAL	RCS rotation auto/manual select	MSC	B	0, 1	(none)	25	TBD
ATT_MNVR	Auto attitude maneuver mode enable	MSC	B	0, 1	(none)	25	TBD
TWO_THREE_AXIS	Two or three axis select for auto attitude maneuver	MSC	B	0, 1	(none)	25	TBD
OMS_PRETHRUST	OMS prethrust alignment mode enable	MSC	B	0, 1	(none)	25	TBD
LCL_VERT_ATT	Local vertical auto attitude maneuver mode enable	MSC	B	0, 1	(none)	25	TBD
PAYLOAD_MANIP	Payload manipulation mode enable	MSC	B	0, 1	(none)	25	TBD
POINTING	Pointing mode enable	MSC	B	0, 1	(none)	25	TBD
POINTING_OPTIONS	Pointing options select	MSC	I	TBD	(none)	25	TBD
BBQ	Barbecue mode enable	MSC	B	0, 1	(none)	25	TBD
RCS_TRANSLATION	RCS translation mode enable	MSC	B	0, 1	(none)	25	TBD
RCS_TRANS_AUTO_MANUAL	RCS translation auto/manual select	MSC	B	0, 1	(none)	25	TBD

Table 1.1-1. Input parameters for the FC module (Cont.).

Name	Description	Source	Type	Range	Units	Sample Rate (Hz)	Update Rate Req'd. (Hz)
<u>MODE/EVENT FLAGS (Continued)</u>							
OMS_ARM_REQ	OMS arming request	MSC	A(2)B	0, 1	(none)	25	TBD
OMS_ON_REQ	OMS turn-on request	MSC	A(2)B	0, 1	(none)	25	25
TVC_AUTO_ MANUAL	TVC auto/manual select	MSC	B	0, 1	(none)	25	TBD
<u>HC COMMANDS</u>							
RHC	Rotational hand controller deflection	SOP	A(3)S	(TBD)	deg	25	TBD
THC	Translational hand controller command	SOP	A(3)I	-1, 0, 1	(none)	25	TBD
<u>GUIDANCE COMMANDS</u>							
GA_ COMMANDED	Commanded terminal IMU gimbal angles	GUID or D&C	A(3)S	-180 < x ≤ 180	deg	25	no requirement
OMEGA_C	Commanded body angle rate	GUID	V(3)S	(TBD)	deg/s	25	25
POINTING_ VECTOR_CMD	Unit vector specifying commanded pointing direction, including initial OMS thrust direction, in stable member axes	GUID or D&C	V(3)S	±1	(none)	25	no requirement

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Table 1.1-1. Input parameters for the FC module (Cont.).

Name	Description	Source	Type	Range	Units	Sample Rate (Hz)	Update Rate Req'd. (Hz)
<u>GUIDANCE COMMANDS (Continued)</u>							
BODY_POINTING_VECTOR	Unit vector, in body axes, to be aligned with POINTING VECTOR CMD	GUID or D&C	V(3)S	±1	(none)	25	no requirement
DELTA_V_CMD	Commanded translational velocity change	GUID or D&C	V(3)S	(TBD)	m/s	25	no requirement
<u>PAYLOAD-GENERATED COMMANDS</u>							
(TBD)							
<u>IMU-MTU DATA</u>							
GIMBAL_ANGLES	IMU gimbal angles	SOP	A(3)S	-180<x ≤180	deg	25	25
DELTA_V	IMU accelerometer data; vehicle velocity change since previous sampling	SOP	V(3)S	(TBD)	m/s	25	TBD
TIME_OF_READING	IMU data time tag	SOP	S	(TBD)	s	25	25
<u>VEHICLE STATE</u>							
POSITION	Vehicle position in stable member coordinates, referred to geocenter	NAV	V(3)S	(TBD)	m	25	TBD

Table 1.1-1. Input parameters for the FC module (Cont.).

Name	Description	Source	Type	Range	Units	Sample Rate (Hz)	Update Rate Req'd. (Hz)
<u>VEHICLE MASS PROPERTIES</u>							
VEHICLE_CG	Vehicle center of gravity	COMPOOL	V(3)S	(TBD)	m	25	no requirement
<u>EFFECTOR FAULT FLAGS</u>							
JFAIL	RCS jet failure	RM	A(44)B	0, 1	(none)	25	25
OMS_FAIL_DETECT	OMS failure detected	RM	B	0, 1	(none)	25	25
OMS1_FAIL	OMS1 failure identified	RM	B	0, 1	(none)	25	25
OMS2_FAIL	OMS2 failure identified	RM	B	0, 1	(none)	25	25
<u>EFFECTOR POSITION</u>							
OMS1_YAW_PITCH	OMS1 gimbals yaw and pitch angles	SOP	A(2)S	(TBD)	deg	25	25
OMS2_YAW_PITCH	OMS2 gimbals yaw and pitch angles	SOP	A(2)S	(TBD)	deg	25	25
<u>CREW VARIABLES</u>							
DESIRED_MAGNITUDE_OF_BODY_RATE	Desired magnitude of body rate in automatic attitude maneuvers	D&C	S	0 to 5	deg/s	25	no requirement

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Table 1.1-1. Input parameters for the FC module (Cont.).

Name	Description	Source	Type	Range	Units	Sample Rate (Hz)	Update Rate Req'd. (Hz)
<u>CREW VARIABLES</u> (Continued)							
BARBECUE_ RATE	Desired barbecue-mode angular rate	D&C	S	(TBD)	deg/s	25	no require- ment
LO_PITCH_ TAIL_NOSE	Tail or nose jet select for low-level pitch rotation	D&C	B	0, 1	(none)	25	no require- ment
LO_YAW_ TAIL_NOSE	Tail or nose jet select for low-level yaw rotation	D&C	B	0, 1	(none)	25	no require- ment

Table 1.1-2. Output parameters for the FC module.

Name	Description	Destination	Type	Range	Units	Update Rate (Hz)	Sample Rate Req'd. (Hz)
<u>EFFECTOR COMMANDS</u>							
JONLST	RCS jet on command	SOP, RM	A(44)B	0, 1	(none)	25	25
OMS1_ON_CMD	OMS1 on command	SOP, RM	B	0, 1	(none)	25	25
OMS2_ON_CMD	OMS2 on command	SOP, RM	B	0, 1	(none)	25	25
OMS1_YAW_PITCH_ERROR	OMS1 yaw and pitch position errors	SOP, RM	A(2)S	(TBD)	deg	25	25
OMS2_YAW_PITCH_ERROR	OMS2 yaw and pitch position errors	SOP, RM	A(2)S	(TBD)	deg	25	25
<u>DEDICATED DISPLAY DATA</u>							
RATE_ERROR	Angular rate error in body axes	D&C	A(3)S	(TBD)	deg/s	25	TBD
VEHICLE_RATE	Vehicle attitude rate in body axes	D&C	A(3)S	(TBD)	deg/s	25	TBD
DESIRED_VEHICLE_ATTITUDE	Desired terminal IMU gimbals angles	D&C	A(3)S	(TBD)	deg	25	TBD
<u>SWITCH PANEL COMMAND ACKNOWLEDGMENTS</u>							
WIDE_NARROW_DB_ACK	Phase plane deadband select acknowledge	SOP	A(3)B	0, 1	(none)	25	TBD

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Table 1.1-2. Output parameters for the FC module (Cont.)

Name	Description	Destination	Type	Range	Units	Update Rate (Hz)	Sample Rate Req'd. (Hz)
<u>SWITCH PANEL COMMAND ACKNOWLEDGMENTS (Continued)</u>							
ROT_HI_LO_ACK	Rotation level select acknowledge	SOP	A(3)B	0, 1	(none)	25	TBD
TRANS_HI_LO_ACK	Translation level select acknowledge	SOP	A(3)B	0, 1	(none)	25	TBD
ROT_OPTION_ACK	Manual rotation submode select acknowledge	SOP	A(3)I	0, 1, 2, 3	(none)	25	TBD
TRANS_OPTION_ACK	Manual translation submode select acknowledge	SOP	A(3)I	0, 1	(none)	25	TBD
NOM_VERNIER_ACK	RCS nominal/vernier jet select acknowledge	SOP	B	0, 1	(none)	25	TBD
NORMAL_VIEW_ACK	HC axis system select acknowledge	SOP	B	0, 1	(none)	25	TBD
PURE_NONPURE_ACK	RCS pure moment/cross coupling select acknowledge	SOP	B	0, 1	(none)	25	TBD
INERTIAL_LOCAL_ACK	Barbecue mode inertial/local vertical axis system select acknowledge	SOP	B	0, 1	(none)	25	TBD
<u>DATA FOR FAILURE DETECTION</u>							
ROLL_ANGULAR_DISTURBANCE_ACCELERATION	Roll angular disturbance acceleration	RM	S	(TBD)	deg/s ²	25	25

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The primary task of the supervisor software is to interrogate the states of flags which are in general set/cleared by the upper-level applications software associated with crew interface and mission sequencing. For example, when the crew has commanded that an OMS burn be initiated, the major mode associated with the orbital maneuver operations will set the OMS_ARM_REQ and OMS_ON_REQ flags, causing the FC Reconfiguration Logic software to invoke the TVC DAP and its appropriate driver and to terminate nominal use of the RCS DAP. The supervisory reconfiguration software is also responsible for certain initialization actions and clean-up actions as modes of the FC change (from TVC to RCS or from automatic to manual, for example). The following lists the major Reconfiguration Logic functions in the sequence performed:

- (1) Initialization (if first entry or restart)
- (2) Input interface
- (3) Panel switch interpretation
- (4) State estimation, part 1
- (5) Driver call(s)
- (6) TVC or RCS DAP execution
- (7) State estimation, part 2

The first time FC is executed upon entry into the Orbital Mission Phase, an initialization will be performed. Fixed parameters which are derived from pad-loaded constants are computed and stored (it may be later decided, however, that this function should be performed preflight, rather than on-line). A restart flag may also be set externally because of certain external software, operating system, or hardware problems which would call for setting FC variables to initial values. Parameters that are initialized include integrator outputs, filter nodes and certain flags, which apply to the entire FC program. Other parameters which apply to subsets of the FC program will be re-initialized at lower levels of the Reconfiguration Logic.

An input interface routine processes dynamic inputs (sensor measurements, navigation estimates, guidance commands and other data) into the proper form for the control laws that are subsequently executed. It is assumed that Subsystem Operating Programs (SOPs), external to the FC module and running concurrently with it, perform selection filtering and preliminary data manipulation. It is further assumed that all measurements for a given FC pass are read into the computer at approximately

the same time. Doing so ensures that the measurements are registered with respect to each other and also simplifies the interface between FC and the input/output processor. However, it may prove to be necessary to change this design so as to read some inputs for some control channels separately in order to reduce transport delay.

The design of the switch panel interpretation function assumes the existence of a SOP external to the FC module and running concurrently with it, which reads the cockpit mode switch panel and the rotational and translational hand controllers (RHC and THC). If the RHC or THC is out of detent, the SOP is assumed not to change the switch panel bit words for the interpretation function, which can simply unpack the bit words and set up flags and parameters for the drivers and DAPs.

The state estimation function is implemented in two parts. The motivation for this division is to minimize transport delay by not performing unnecessary calculations between reading of the sensors and issuance of the actuator commands. The first part performs only those computations which require the dynamic input data and are required to obtain the state estimates used in generating the commands. The second part performs those computations which can be postponed until after the actuator commands are issued. Viewed differently, it performs those computations which can be done in advance for the subsequent FC pass, before the next set of measurements is known. It is used to "push down" (precompute) the filters.

1.2.2 Panel Switch Interpretation

Crew control panels enable the crew to select submodes for manual RCS translation and rotation, as well as several parameters and options. The switch panels currently consist of 44 momentary switches, interconnected in such a manner that activation of a switch deactivates all of its complements. Also, when a switch command has been received and accepted by the software, the switch is illuminated. If a command is rejected, the switch does not illuminate, but the complementary command previously in effect remains so, and the switch corresponding to that command remains illuminated.

At any time, 19 switches are activated:

- (1) 3 rotation submodes.
 - (2) 3 translation submodes.
 - (3) 3 attitude deadband wide/narrow options.
 - (4) 3 rotation hi/lo options.
 - (5) 3 translation hi/lo options.
 - (6) Normal/view axes option.
 - (7) Cross-coupled/pure moment option.
 - (8) Normal/vernier RCS option.
 - (9) Inertial/local vertical option.
- } by axis

The PANEL_SWITCH_INTERP procedure will not accept rotational submode changes with the RHC out of detent, nor translational submode changes with the THC out of detent. When a submode switch is activated with the related Hand Controller in detent, the switch corresponding to the new submode is illuminated, confirming the selection. If the related Hand Controller is out of detent, the new submode selection is rejected and the switch previously illuminated will remain so, indicating the previous submode is still in effect. None of the other options can be changed with the RHC or THC out of detent, as the SOP will not send new switch data with either controller deflected.

The rotation submode switches for each axis include a disc rate switch for the discrete rate command submode, an accel switch for the direct rotation acceleration command submode, and a pulse switch for the direct rotation pulse command submode. These switches allow selection of one of the 3 submodes independently in each of the 3 rotational axes.

The rotation hi/lo switches determine certain parameters by axis for the submode in effect in that axis. These parameters include:

- (1) High or low discrete angular rate for the discrete rate command submode.
- (2) High or low angular acceleration level for the direct rotation acceleration command submode.
- (3) High or low angular rate change for the direct rotation pulse command submode.

The translation option switches allow the pilot to select translation submodes by axis.

The translation hi/lo switches determine certain parameters by axis for the submode in effect in that axis. These parameters include:

- (1) High or low acceleration level for the direct translation acceleration command submode.
- (2) High or low velocity increment for the direct translation pulse command submode.

The attitude deadband wide/narrow switches allow the crew to select attitude deadband by axis for the Phase Plane Switching Logic.

The normal/view axes option allows the crew to select whether RHC and THC commands from the aft station are to be referenced to docking (-z facing) or payload view (-x facing) axes.

The cross-coupled/pure moment options allow the crew to determine threshold levels for off-axis compensation firings by the Jet Selection Logic.

Normal RCS or vernier RCS options allow the crew to determine whether the main or vernier RCS jets are used to perform maneuvers.

The inertial/local vertical option determines whether automatic barbecue maneuvers are to be referenced to inertial or local vertical axes.

A switch panel will exist at the aft docking/payload station as well as at the forward Commander's station. Both panels will be configured so that a change in options at either panel will be acknowledged by illumination of the appropriate lamps on both panels. The panel description is only tentative, and subject to change as requirements dictate.

Table 1.2.2-1 gives the input-output requirements of the procedure PANEL_SWITCH_INTERP.

1.3 Control Laws

The control laws are implemented in an RCS DAP, a TVC DAP, and a group of drivers. The interface between the two DAPs is described in Subsection 1.3.1. Subsection 1.3.2 presents the control algorithms for the RCS DAP. Subsection 1.3.3 describes the TVC DAP control laws. Finally, Subsection 1.3.4 gives descriptions of the driver routines which determine the inputs to the RCS and TVC DAPs based upon automatic and manual commands.

Table 1.2.2-1. Input-output requirements for PANEL_SWITCH_INTERP.

Category	Name of Variable or Constant		Description of Variable or Constant	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to PANEL_SWITCH_INTERP	NEWORD1 NEWORD2 NEWORD3	NEWORD1 NEWORD2 NEWORD3	Panel switch discrettes	(None)	ON/OFF	25
Outputs of PANEL_SWITCH_INTERP	NORMAL_VIEW_SWITCH	NORMAL_VIEW_SWITCH	Flag for normal/view axes	(None)	ON/OFF	25
	CFLAG	CFLAG	Flag for hi/low acceleration selections	(None)	ON/OFF	25
	TRANSLATION_OPTION	TRANSLATION_OPTION	Flag for translation submode by axis	(None)	ON/OFF	25
	ROTATION_OPTIONS	ROTATION_OPTIONS	Flag for rotation submode by axis	(None)	1,2,3	25
	TRANSLATION_PULSE_SIZE	$[\Delta v_{\text{pulse}}]$	Pulse Δv by axis	ft/s	0.03 to 0.8	25
	ROTATION_PULSE_SIZE	$[\Delta \omega_{\text{pulse}}]$	Pulse $\Delta \omega$ by axis	rad/s	0.000873 to 0.00873	25
	DISCRETE_OMEGA	$[\omega_{\text{disc}}]$	Discrete ω_D by axis	rad/s	0.00105 to 0.0349	25
	NOM_VERNIER_SW	NOM_VERNIER_SW	Switch for nominal/vernier RCS jets	(None)	ON/OFF	25
	TL	TL	Threshold levels for off-axis compensation firings	ft/s rad/s	TBD	25
	ATT_DB	x_{DB}	Attitude deadbands for phase plane	rad	0.0087 to 0.087	25
INERTIAL_LOCAL_SW	INERTIAL_LOCAL_SW	Auto barbecue maneuver inertial/local vertical axis system selection	(None)	ON/OFF	25	
	LIGHT1 LIGHT2 LIGHT3	LIGHT1 LIGHT2 LIGHT3	Lamp commands for panel switches	(None)	ON/OFF	25

1.3.1 RCS/OMS Interface

A flag, OMS_ON_REQ, is set external to FC to initiate OMS thrusting. When this flag is not set, FC controls the vehicle by means of the RCS exclusively. When the flag is set, control is normally by means of TVC exclusively. However, if only one OMS engine is thrusting, RCS control is also required about the roll axis. Furthermore, if an engine failure occurs during a normal two-engine burn, RCS control may also be needed in pitch and yaw until the vehicle is stably realigned as required by the changed orientation of the vector representing net thrust through the vehicle center of gravity.

1.3.2 RCS DAP

Figure 1.3.2-1 is a block diagram of the RCS DAP. The RCS rotation driver routines supply the following to Error Computation:

- (1) A set of desired IMU gimbal angles $[\phi_D]$.
- (2) A set of desired IMU gimbal angle increments $[\Delta\phi_D]$.
- (3) Desired angular velocity ω_D .
- (4) Desired attitude bias β_{BIAS} .

Items 3 and 4 are vectors in vehicle body coordinates. Every RCS DAP cycle (0.04 s), Error Computation combines these inputs with IMU attitude data $[\phi]$ and with the angular rate estimate $\hat{\omega}$ from the State Estimator. Error Computation also sums the State Estimator outputs of estimated disturbance angular acceleration $\hat{\alpha}_d$, and $\hat{\alpha}_m$, the computed angular acceleration due to inertia cross products and other modelled "bias" effects.

The resulting attitude and rate errors θ_e and ω_e , and the total "undesired" angular acceleration α_{dm} are applied to the Phase Plane Switching Logic along with the magnitudes of the available RCS control accelerations $[\alpha_c]$ and a crew input selecting either a wide or a narrow attitude deadband. The Phase Plane Switching Logic then determines the desired angular rate change $\Delta\omega_D$.

A discrete, HELP_TVC, is set if the TVC DAP needs RCS assistance in controlling the vehicle. This discrete reconfigures the RCS DAP such that the outputs of Error Computation are ignored, and the Phase Plane Switching Logic instead uses the $\Delta\omega_D$ supplied by the TVC DAP.

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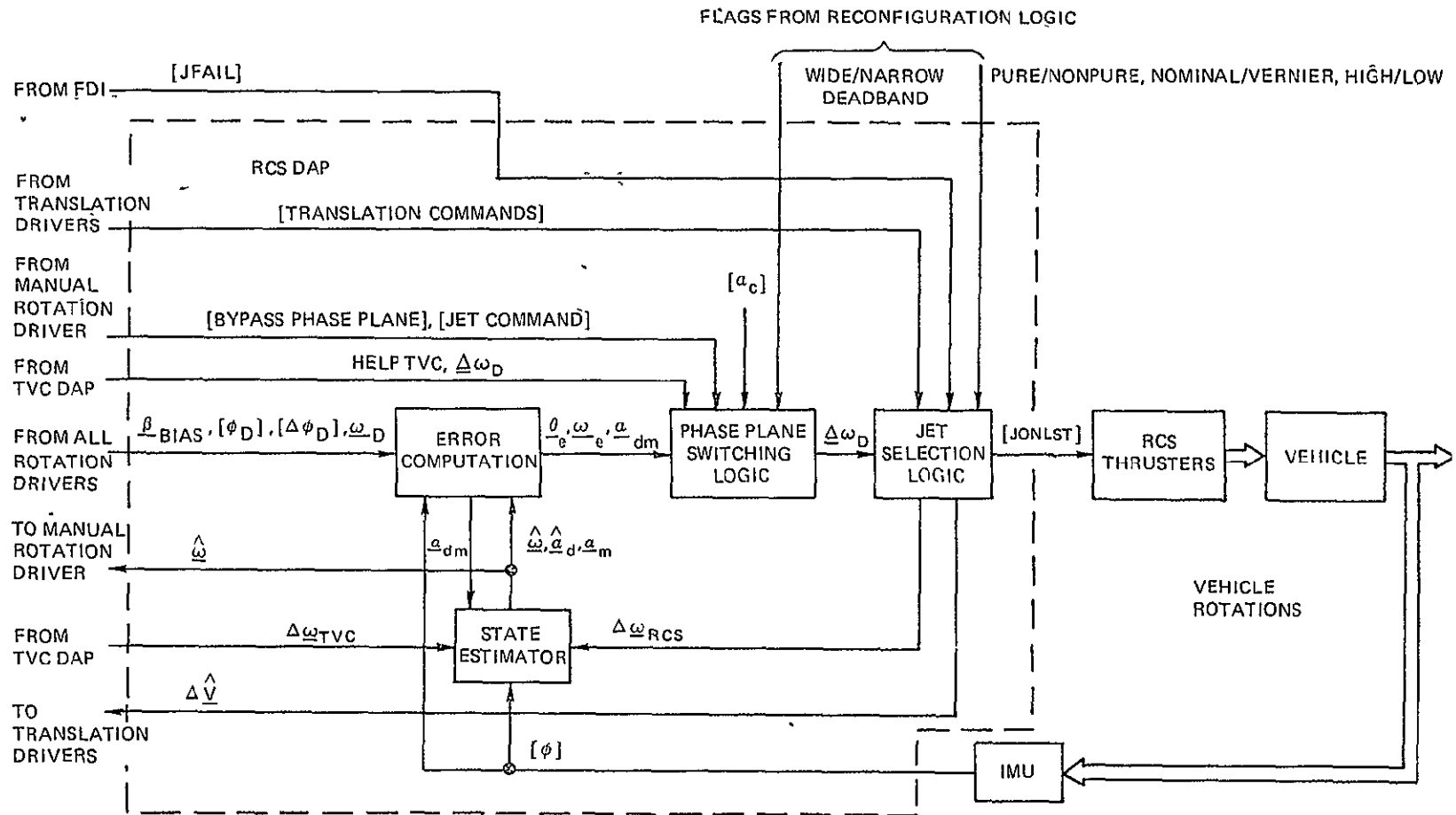


Figure 1.3.2-1. RCS DAP functional block diagram and relationship to vehicle control loop.

The Phase Plane Switching Logic also receives a set of reconfiguration discrettes, [BYPASS_PHASE_PLANE], from the manual rotation driver routine. When BYPASS_PHASE_PLANE for a given axis is set, it turns off the Phase Plane Switching Logic and passes on the integer JET_COMMAND (from the manual rotation driver) as the output $\Delta\omega_D$.

From $\Delta\omega$ and the set of integer-valued translation commands from the translation drivers, the Jet Selection Logic determines [JONLST], those jets which should be fired during the forthcoming cycle. The crew can specify whether to use nominal or vernier jets, and if nominal jets are selected, can choose a high or a low acceleration level (applying to both rotation and translation), and a "pure moment" option that fires additional jets as required to suppress undesired translational velocity changes. If vernier jets are selected, the high/low and pure moment options are not available, and translation commands are not implemented.

The RCS DAP returns two computed quantities to certain drive routines. The estimated angular rate $\hat{\omega}$ is used by the manual rotation driver, and the computed change in translation rate $\Delta\hat{V}$ is used by the automatic and manual translation drivers.

1.3.2.1 Error Computation

The error computation module provides the attitude, angular velocity, and angular acceleration values required by the Phase Plane Switching Logic. A block diagram is shown in Figure 1.3.2.1-1.

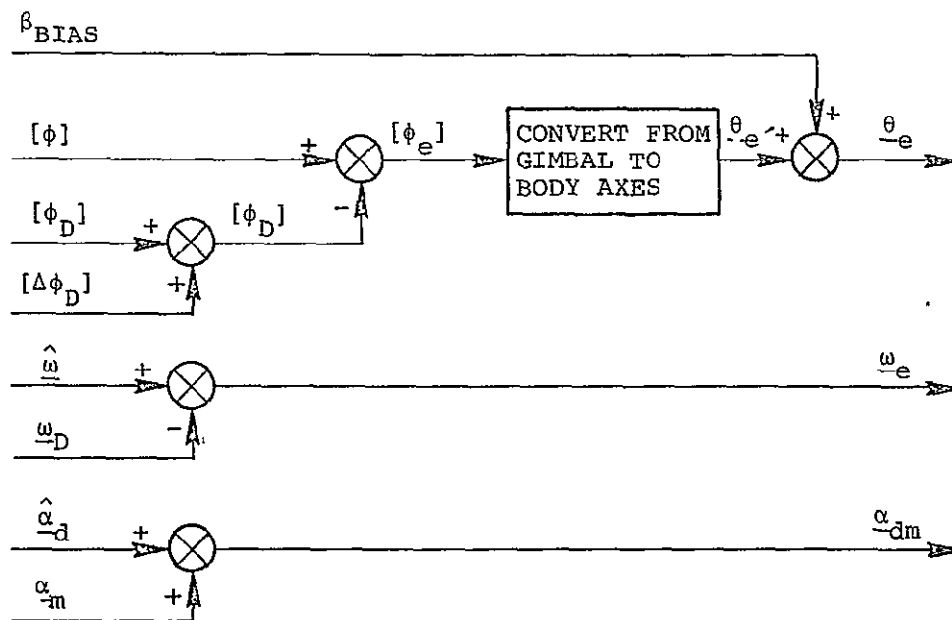


Figure 1.3.2.1-1. Block diagram of the error computation routine.

Table 1.3.2.1-1. Input-output requirements for error computation.

Category	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to RCS_ERRORS	BIAS_BETA	β BIAS	Bias body angles to prevent excessive fuel use when starting and stopping a maneuver	rad	TBD	TBD
	[DFCS_GA]	$[\phi]$	Measured IMU gimbal angles	rad	$-\pi < x \leq \pi$	TBD
	[GA_DESIRED]	$[\phi_D]$	Desired IMU gimbal angles	rad	$-\pi < x \leq \pi$	TBD
	[DELTA_GA]	$[\Delta\phi_D]$	Desired IMU gimbal angle increments per RCS DAP cycle	rad	TBD	TBD
	-					
	OMEGAHAT	$\hat{\omega}$	Updated estimate of body angular rate	rad/s	TBD	TBD
	DESIRED_BODY_RATE	ω_D	Desired body rate	rad/s	TBD	TBD
	ALPHA_DHAT	$\hat{\alpha}_d$	Updated estimate of body angular disturbance acceleration	rad/s ²	TBD	TBD
Outputs of RCS_ERRORS	BIAS_ANGULAR_ACCELERATION	α_m	Modelled bias angular acceleration	rad/s ²	TBD	TBD
	ANGULAR_ERROR	θ_e	Angular position error	rad	TBD	TBD
	RATE_ERROR	ω_e	Angular rate error	rad/s	TBD	TBD
	ALPHA_DM	α_{dm}	Sum of estimated disturbance and modelled bias angular accelerations	rad/s ²	TBD	TBD

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The attitude and angular velocity errors are the differences between the actual and the desired values expressed in body axis coordinates. The input ϕ_D is the incremented value from the previous RCS DAP iteration, unless a driver was called in the present FC cycle, in which case ϕ_D is the driver output. The increment $\Delta\phi_D$ serves to interface drivers with long cycle times to the shorter cycle time of the RCS DAP. The acceleration figure is the sum of the estimated disturbance and modelled bias accelerations. Input-output requirements are listed in Table 1.3.2.1-1.

1.3.2.2 State Estimator

Control of the shuttle vehicle requires estimates of body angular rate, ω , and body angular disturbance acceleration α_d . The procedure used is based on Kalman filter theory in which measurements from the IMU gimbals angles are mixed with extrapolated state estimates to form a filtered estimate of the vehicle state. A block diagram of the State Estimator is illustrated in Figure 1.3.2.2-1.

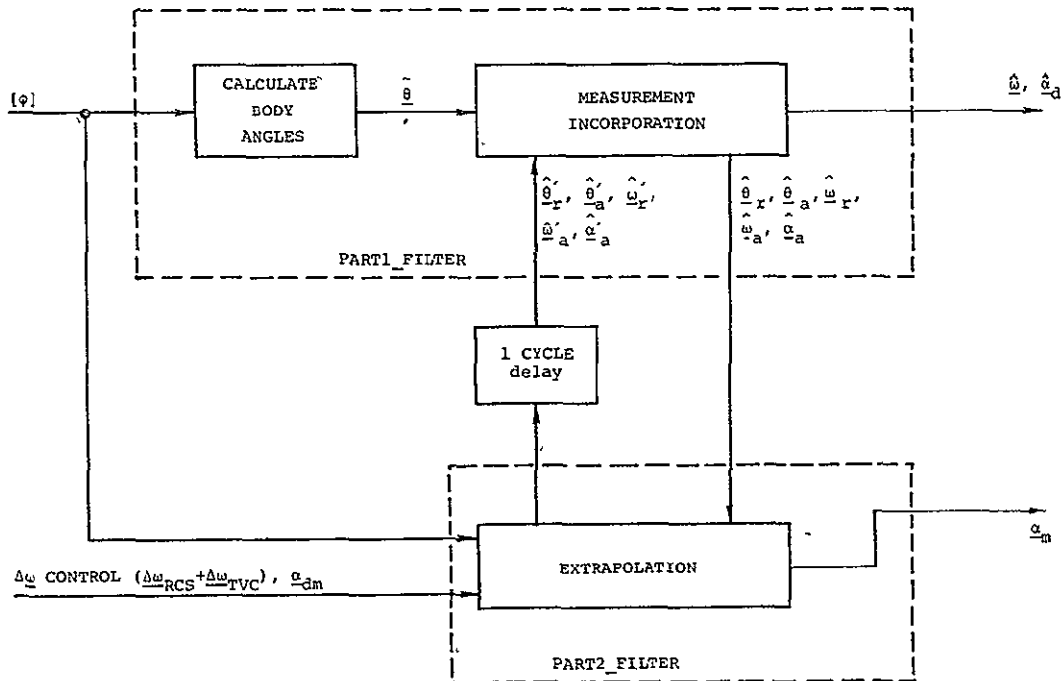


Figure 1.3.2.2-1. Block diagram of the State Estimator.

The discrete filtering process is divided into two parts: extrapolation and measurement incorporation. The extrapolation process requires that the estimate of vehicle state at some time, t_{n-1} , is integrated forward to the next measurement incorporation time, t_n . This

results in a predicted state estimate which includes the effects of any known biases or control inputs occurring in the interval t_{n-1} to t_n . The new estimate of vehicle state is calculated by combining the predicted state estimate with the measured value of state in accordance with the equations given in Subsection 2.3.2.2.

The State Estimator is processed in two stages in order to minimize the time lag between data input and filtered output. The first stage, which occurs in PART1_FILTER, takes the digitized gimbal angles from the IMU and converts them to body angles. These body angles are then combined with the previously calculated extrapolated state to obtain the filtered state. After the appropriate jet control is exercised, PART2_FILTER takes the current state information and extrapolates it to the next measurement incorporation time, when it will be used by PART1_FILTER in the next cycle.

The input-output requirements of the State Estimator are summarized in Tables 1.3.2.2-1 and 1.3.2.2-2.

1.3.2.3 Phase Plane Switching Logic

The object of the Phase Plane Switching Logic is to compute desired changes in angular velocity, so that by turning on or off the appropriate jets to achieve this velocity change, the vehicle limit cycles about a desired attitude and attitude rate. The two-dimensional phase plane is applied to each of the three axes. Limit cycling is desirable since it would be extremely costly to attempt to maintain the desired attitude and rate exactly. By designing appropriate switching lines into the phase plane, the vehicle can be driven into the desired limit cycle. Two separate logics are used depending on the size of the position and rate errors. For large errors, a switching logic has been designed to drive the state into the small error control region. The small error switching logic then drives the state into a limit cycle about the desired attitude and attitude rate.

The input-output requirements for the Phase Plane Switching Logic are given in Table 1.3.2.3-1.

1.3.2.3.1 Small Error Control Law. - The small error switching logic has the following features:

- (1) The design is based upon the optimal switch curves for minimizing a weighted combination of fuel and response time. The optimal curves are separated by a deadband in order to allow for limit cycling.

Table 1.3.2.2-1. Input-output requirements for PART1_FILTER.

Category	Name of Variable or Constant		Description of Variable or Constant	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to PART1_FILTER	[DFCS_GA]	$[\phi]$	Present set of measured gimbal angles	rad	$-\pi < x < \pi$	TBD
	[GA_OLD]	$[\phi_{old}]$	Previous set of measured gimbal angles	rad	$-\pi < x < \pi$	TBD
	ALPHABAR_ACCEL	$\hat{\alpha}'_a$	Extrapolated estimate of body angular acceleration, for acceleration filter	rad/s ²	TBD	TBD
	OMEGABAR_ACCEL	$\hat{\omega}'_a$	Extrapolated estimate of body angular rate, for acceleration filter	rad/s	TBD	TBD
	OMEGABAR_RATE	$\hat{\omega}'_r$	Extrapolated estimate of body angular rate, for rate filter	rad/s	TBD	TBD
	THETABAR_ACCEL	$\hat{\theta}'_a$	Extrapolated estimate of body angles, for acceleration filter	rad	TBD	TBD
	THETABAR_RATE	$\hat{\theta}'_r$	Extrapolated estimate of body angles, for rate filter	rad	TBD	TBD
	KALPHA_ACCEL	$K_{\alpha a}$	Angular acceleration gain for acceleration filter	(None)	TBD	TBD
	KOMEGA_ACCEL	$K_{\omega a}$	Angular rate gain for acceleration filter	(None)	TBD	TBD
	KOMEGA_RATE	$K_{\omega r}$	Angular rate gain for rate filter	(None)	TBD	TBD
	KTHETA_ACCEL	$K_{\theta a}$	Angular position gain for acceleration filter	(None)	TBD	TBD
	KTHETA_RATE	$K_{\theta r}$	Angular position gain for rate filter	(None)	TBD	TBD

Table 1.3.2.2-1. Input-output requirements for PART1_FILTER (Cont.)

Category	Name of Variable or Constant		Description of Variable or Constant	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Outputs of PART1_FILTER	ALPHADHAT	$\hat{\alpha}_d$	Updated estimate of body angular disturbance acceleration	rad/s ²	TBD	TBD
	OMEGAHAT	$\hat{\omega}$	Updated estimate of body angular rate	rad/s	TBD	TBD
	ALPHAHAT_ACCEL	$\hat{\alpha}_a$	Updated estimate of body angular acceleration, for acceleration filter	rad/s ²	TBD	TBD
	OMEGAHAT_ACCEL	$\hat{\omega}_a$	Updated estimate of body angular rate, for acceleration filter	rad/s	TBD	TBD
	OMEGAHAT_RATE	$\hat{\omega}_r$	Updated estimate of body angular rate, for rate filter	rad/s	TBD	TBD
	THETAHAT_ACCEL	$\hat{\theta}_a$	Updated estimate of body angles, for acceleration filter	rad	TBD	TBD
	THETAHAT_RATE	$\hat{\theta}_r$	Updated estimate of body angles, for rate filter	rad	TBD	TBD

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Table 1.3.2.2-2. Input-output requirements for PART2_FILTER.

Category	Name of Variable or Constant		Description of Variable or Constant	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to PART2_FILTER	ALPHADM	α_{dm}	Sum of estimated disturbance and modelled bias angular accelerations	rad/s ²	TBD	TBD
	[DFCS_GA]	$[\phi]$	Present set of measured gimbals angles	rad	TBD	TBD
	[DELTAOMEGA CONTROL]	$[\Delta\omega_{CONTROL}]$	Expected body angular rate change due to RCS jet firings and OMS TVC.	rad/s	TBD	TBD
	DELTAT	Δt	Period of the DAP cycle	s	0.040	TBD
	ALPHAHAT_ACCEL	$\hat{\alpha}_a$	Updated estimate of body angular acceleration, for acceleration filter	rad/s ²	TBD	TBD
	OMEGAHAT_ACCEL	$\hat{\omega}_a$	Updated estimate of body angular rate, for acceleration filter	rad/s	TBD	TBD
	OMEGAHAT_RATE	$\hat{\omega}_r$	Updated estimate of body angular rate, for rate filter	rad/s	TBD	TBD
	THEAHAT_ACCEL	$\hat{\theta}_a$	Updated estimate of body angles, for acceleration filter	rad	TBD	TBD
THEAHAT_RATE	$\hat{\theta}_r$	Updated estimate of body angles, for rate filter	rad	TBD	TBD	
Outputs of PART2_FILTER	[GA_OLD]	$[\phi_{old}]$	Set of measured gimbals angles on the FC pass presently being concluded	rad	TBD	TBD
	BIAS_ANGULAR_ACCELERATION	α_m	Modelled bias angular acceleration	rad/s ²	TBD	TBD
	ALPHABAR_ACCEL	$\hat{\alpha}'_a$	Extrapolated estimate of body angular acceleration, for acceleration filter	rad/s ²	TBD	TBD
	OMEGABAR_ACCEL	$\hat{\omega}'_a$	Extrapolated estimate of body angular rate, for acceleration filter	rad/s	TBD	TBD
	OMEGABAR_RATE	$\hat{\omega}'_r$	Extrapolated estimate of body angular rate, for rate filter	rad/s	TBD	TBD
	THETABAR_ACCEL	$\hat{\theta}'_a$	Extrapolated estimate of body angles, for acceleration filter	rad	TBD	TBD
	THETABAR_RATE	$\hat{\theta}'_r$	Extrapolated estimate of body angles, for rate filter	rad	TBD	TBD

Table 1.3.2.3-1. Input-output requirements for Phase Plane Switching Logic.

Category	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to PHASE_PLANE	B_P_P	B_P_P	Bypass phase plane command	(None)	1, 0	
	JET_CONTROL	JET_CONTROL	Jet rotation command	(None)	1, 0, -1	
	P_D_R	P_D_R	Desired rate change per command	rad/s	TBD	
	DELTA_POSITION	θ'_e	Angular position error	rad	TBD	TBD
	DELTA_RATE	ω'_e	Angular rate error	rad/s	TBD	TBD
	MAG_U_C	$ U_C $	Magnitude of control acceleration	rad/s ²	TBD	TBD
	NO_CHANGE	$\Delta\omega_{D_{old}}$	Residual desired changes in angular rate; indication of jets still on	rad/s	TBD	TBD
	U_D	α_{dm}	Sum of estimated disturbance and modelled bias angular accelerations	rad/s ²	TBD	TBD
Outputs of PHASE_PLANE	X_DB	X_DB	Deadband of DAP limit cycles	rad	0.2° to 20°	TBD
	X_D	$\Delta\omega_D$	Rate change command to Jet Selection Logic	rad/s	TBD	TBD

- (2) The deadband has been chosen to fix the maximum attitude excursion while limit cycling.
- (3) The average attitude error is minimized by biasing the placement of the switch curves.
- (4) Parabolic switch curves approximate the trajectories which the state follows. However, hysteresis logic prevents performance degradation due to errors in these approximations.

Control regions for relatively small errors are illustrated in Figure 1.3.2.3.1-1 and corresponding control actions are given in Table 1.3.2.3.1-1. All logic in this subsection is formulated in terms of positive disturbing accelerations. In the actual implementation, negative disturbances are treated by inverting the signs of the state variables θ_e and ω_e . Biasing the right and left deadbands, DR and DL, to null the average attitude error in accordance with the equations derived in the appendix (see Subsection 4.3.2.3), defines the placement of the switching curves BOUNDARY_II_TO_COAST and BOUNDARY_III_TO_COAST. These curves approximate the trajectory of the state during a firing. When the state lies in Region II, control is applied to drive the state to the curve TARGET_DISTURB. The vehicle is then allowed to coast.

Table 1.3.2.3.1-1. Control actions in small error control regions.

REGION	CONTROL ACTION
I	Drive state to BOUNDARY_I_TO_COAST
II	Drive state to TARGET_DISTURB
III	Drive state to zero rate
IV	Drive state to BOUNDARY_IV_TO_COAST
HS_I	If coming from LARGE_ERROR_CONTROL_LOGIC or REGION_III then drive state to zero rate, else coast
HS_II	If coming from LARGE_ERROR_CONTROL_LOGIC or REGION_II then drive state to TARGET_DISTURB, else coast
CS_I	Coast
CS_II	Coast

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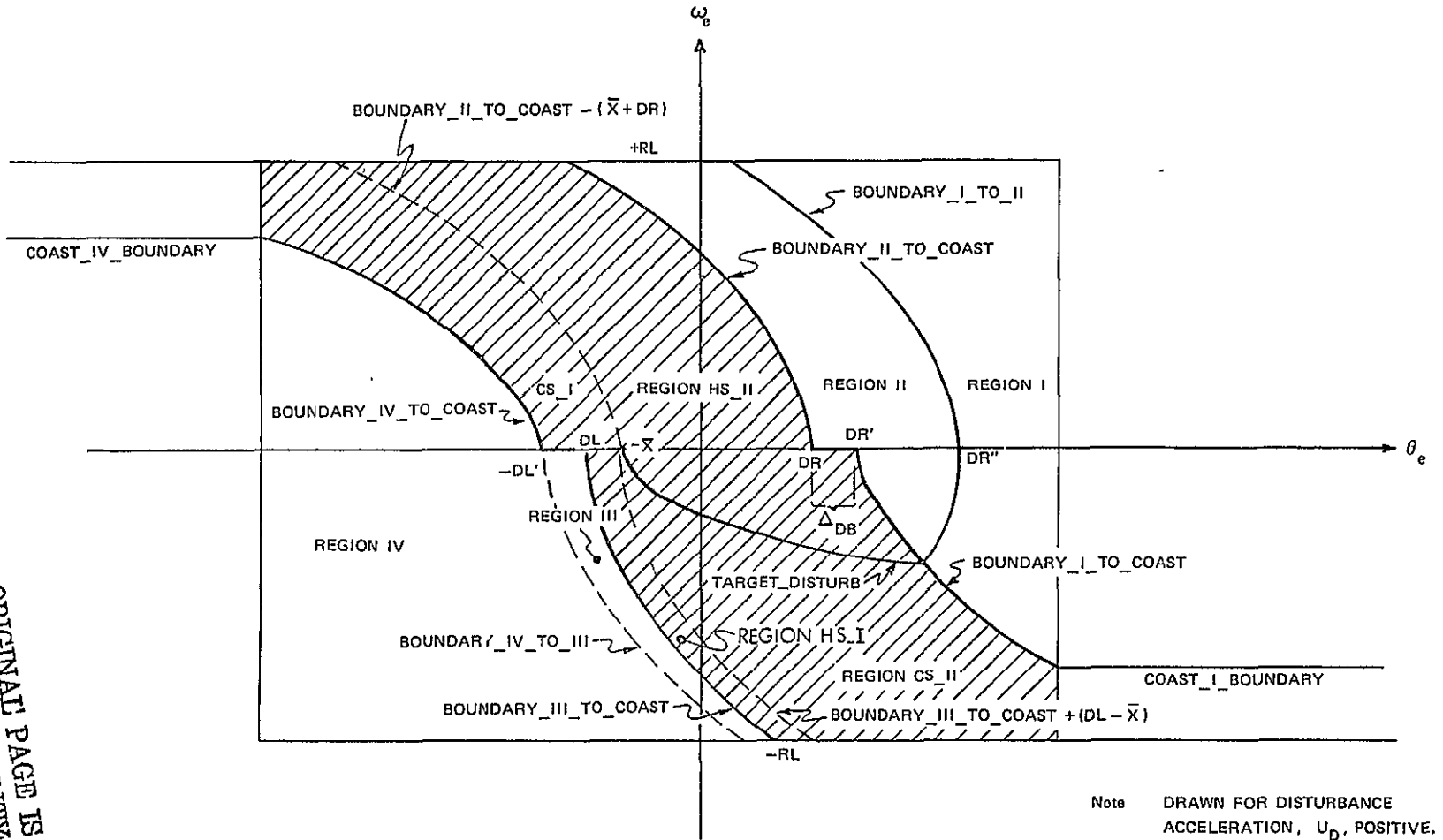


Figure 1.3.2.3.1-1. Small error control logic.

The deadband increment Δ_{DB} is added to prevent fuel-consuming overshoot when the disturbance acceleration is zero or very small. The points

$$DR' = DR + \Delta_{DB}$$

$$DL' = DL - \Delta_{DB}$$

define the placement of the curves BOUNDARY_I_TO_COAST and BOUNDARY_IV_TO_COAST.

A factor, CD, determines the weight given to response time as opposed to fuel consumption, by adjusting the steepness of the switch curves that are normally crossed when entering the coast region (BOUNDARY_IV_TO_COAST and BOUNDARY_I_TO_COAST).

Hysteresis has been incorporated to make the most efficient use of disturbance accelerations, to prevent switching line chatter, and to prevent tight limit-cycling about the point DR. The dashed curves within the shaded area and parallel to BOUNDARY_II_TO_COAST provide hysteresis in the Regions HS_I and HS_II. If the state lies inside either Region HS_I or HS_II, the last computed change in rate was non-zero, and the sign of the newly computed change in rate is not the same as the sign of the last computed change in rate, then no control is applied and the vehicle is allowed to coast. Otherwise, in Region HS_I the state is driven to zero and in Region HS_II the state is driven to TARGET_DISTURB. Whenever the state lies inside either Region CS_I or CS_II the vehicle is simply allowed to coast.

When the state lies to the right of BOUNDARY_I_TO_II, position error is reduced more quickly by driving the state to BOUNDARY_I_TO_COAST and then coasting, instead of driving the state to TARGET_DISTURB and then coasting. This is particularly important as the disturbance acceleration approaches zero. The curve BOUNDARY_I_TO_II is defined by the intersection of TARGET_DISTURB and BOUNDARY_I_TO_COAST.

In Region III the rate error is driven to zero, but in Region IV the state is driven to BOUNDARY_IV_TO_COAST to more quickly reduce position and rate errors.

The input-output requirements for SMALL_ERROR_CONTROL_LOGIC are listed in Table 1.3.2.3.1-2. Input-output requirements for the procedure REGION_II_TARGETTING and the function BOUNDARY are found in Tables 1.3.2.3.1-3 and 1.3.2.3.1-4.

Table 1.3.2.3.1-2. Input-output requirements for SMALL_ERROR_CONTROL_LOGIC..

Category	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to SMALL_ERROR_CONTROL_LOGIC	CD	CD	Phase plane switch curve design parameter	(none)	0.8	TBD
	DL	DL	θ_e intercept for BOUNDARY_III_TO_COAST	rad	TBD	TBD
	DL_PRIME1	DL'	θ_e intercept for BOUNDARY_IV_TO_COAST	rad	TBD	TBD
	DR	DR	θ_e intercept for BOUNDARY_II_TO_COAST	rad	TBD	TBD
	DR_PRIME1	DR'	θ_e intercept for BOUNDARY_I_TO_COAST	rad	TBD	TBD
	DR_PRIME2	DR''	θ_e intercept for BOUNDARY_I_TO_II	rad	TBD	TBD
	K	K	Sign of estimated disturbance acceleration	none	+1.0 or -1.0	TBD
	MAG_U_C	$ U_C $	Magnitude of control acceleration	rad/s ²	TBD	TBD
	MAG_U_D	$ U_D $	Magnitude of disturbance acceleration	rad/s ²	TBD	TBD

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Table 1.3.2.3.1-2. Input-output requirements for SMALL_ERROR_CONTROL_LOGIC (Cont.)

Category	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Outputs of SMALL_ERROR_ CONTROL_LOGIC	NO_CHANGE	$X_{D_{old}}$	Angular rate change computed on last DFCS pass	rad/s	TBD	TBD
	POSITION_ERROR	θ_e	Angular position error	rad	TBD	TBD
	RATE_ERROR	ω_e	Angular rate error	rad/s	TBD	TBD
	U_D	U_D	Disturbance acceleration	rad/s ²	TBD	TBD
	X_BAR	\bar{X}	Displacement of the centroid of a limit cycle	rad	TBD	TBD
	X_D	X_D	Desired change in angular rate	rad/s	TBD	TBD
	X_D	X_D	Desired change in angular rate	rad/s	TBD	TBD

Table 1.3.2.3.1-3. Input-output requirements for REGION_II_TARGETTING.

Category	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to REGION_II_TARGETTING	COAST_I_BOUNDARY	COAST_I_BOUNDARY	Switch curve in large error control region of the phase plane	rad/s	TBD	TBD
	MAG_U_C	$ U_C $	Magnitude of control acceleration	rad/s ²	TBD	TBD
	MAG_U_D	$ U_D $	Magnitude of disturbance acceleration	rad/s ²	TBD	TBD
	P_CEPT	P_CEPT	θ_e axis intercept	rad	TBD	TBD
	POSITION_ERROR	θ_e	Angular position error	rad	TBD	TBD
	RATE_ERROR	ω_e	Angular rate error	rad/s	TBD	TBD
	RL	RL	Rate limits of large error control region of the phase plane	rad/s	$4\pi/180$	TBD
	TARGET_ARL	TARGET_ARL	Possible target curve for Region II	rad/s	TBD	TBD
	X_BAR	\bar{X}	Displacement of the centroid of a limit cycle	rad	TBD	TBD
	X_D	X_D	Desired change in angular rate	rad/s	TBD	TBD
Outputs of REGION_II_TARGETTING	P_CEPT	P_CEPT	θ_e axis intercept	rad	TBD	TBD
	TARGET_ARL	TARGET_ARL	Possible target curve for Region II	rad/s	TBD	TBD
	X_D	X_D	Desired change in angular rate	rad/s	TBD	TBD

Table 1.3.2,3.1-4. Input-output requirements for BOUNDARY.

	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to BOUNDARY	B_SIGN	B_SIGN	θ direction to which the switch curve proceeds from its origin on the θ axis	(none)	(-1.0 or +1.0)	TBD
	CD	CD	Phase plane switch curve design parameter	(none)	(0,0 to 1,0)	TBD
	DR	DR	θ axis intercept	rad	TBD	TBD
	RATE	ω	Angular rate	rad/s	TBD	TBD
	UC	UC	Magnitude of control acceleration	rad/s ²	TBD	TBD
	UD	UD	Magnitude of disturbance acceleration	rad/s ²	TBD	TBD
Outputs of BOUNDARY	POSITION	θ	Angular position on a phase plane switch curve	rad	TBD	TBD

1.3.2.3.2 Large Error Control Law. - Control regions for relatively large errors are illustrated in Figure 1.3.2.3.2-1, and corresponding control actions are given in Table 1.3.2.3.2-1. As in the preceding subsection, all logic is formulated in terms of positive disturbing accelerations. In the actual implementation, negative disturbances are treated by inverting the signs of the state variables, θ_e and ω_e .

Table 1.3.2.3.2-1. Control actions in large error control regions.

REGION	CONTROL ACTION
I	Drive state to $-(\text{TARGET_ARL})$
II	Drive state to TARGET_ARL
III	Drive state to COAST_IV_BOUNDARY
IV	Drive state to $-\text{RL}$
HL_I	If coming from Region II, then drive state to TARGET_ARL , else coast
HL_II	If coming from Region I, then drive state to $-(\text{TARGET_ARL})$, else coast
CL_I	Coast
CL_II	Coast

The purpose of the large error control logic essentially is to drive the state into the small error control region. Bounds between the small error and large error regions are set by the values of the parameters RL and RL' (currently 4.0 and 3.0°/s respectively). The rate-error bounds are equal to $\pm\text{RL}$. The left position error limit, -PLL, is defined by the intersection of BOUNDARY_IV_TO_COAST and COAST_IV_BOUNDARY. Similarly, the right position error limit, +PLR is defined by the intersection of BOUNDARY_I_TO_COAST and COAST_I_TO_BOUNDARY. The boundaries COAST_IV_BOUNDARY AND COAST_I_BOUNDARY are rate errors equal to $\pm\text{RL}'$.

TARGET_ARL is the average of RL and RL'. TARGET_ARL is taken to be the target rate when the state is in Region II or Region III. When the state lies in either Region I or Region IV then $-(\text{TARGET_ARL})$ is taken to be the target rate.

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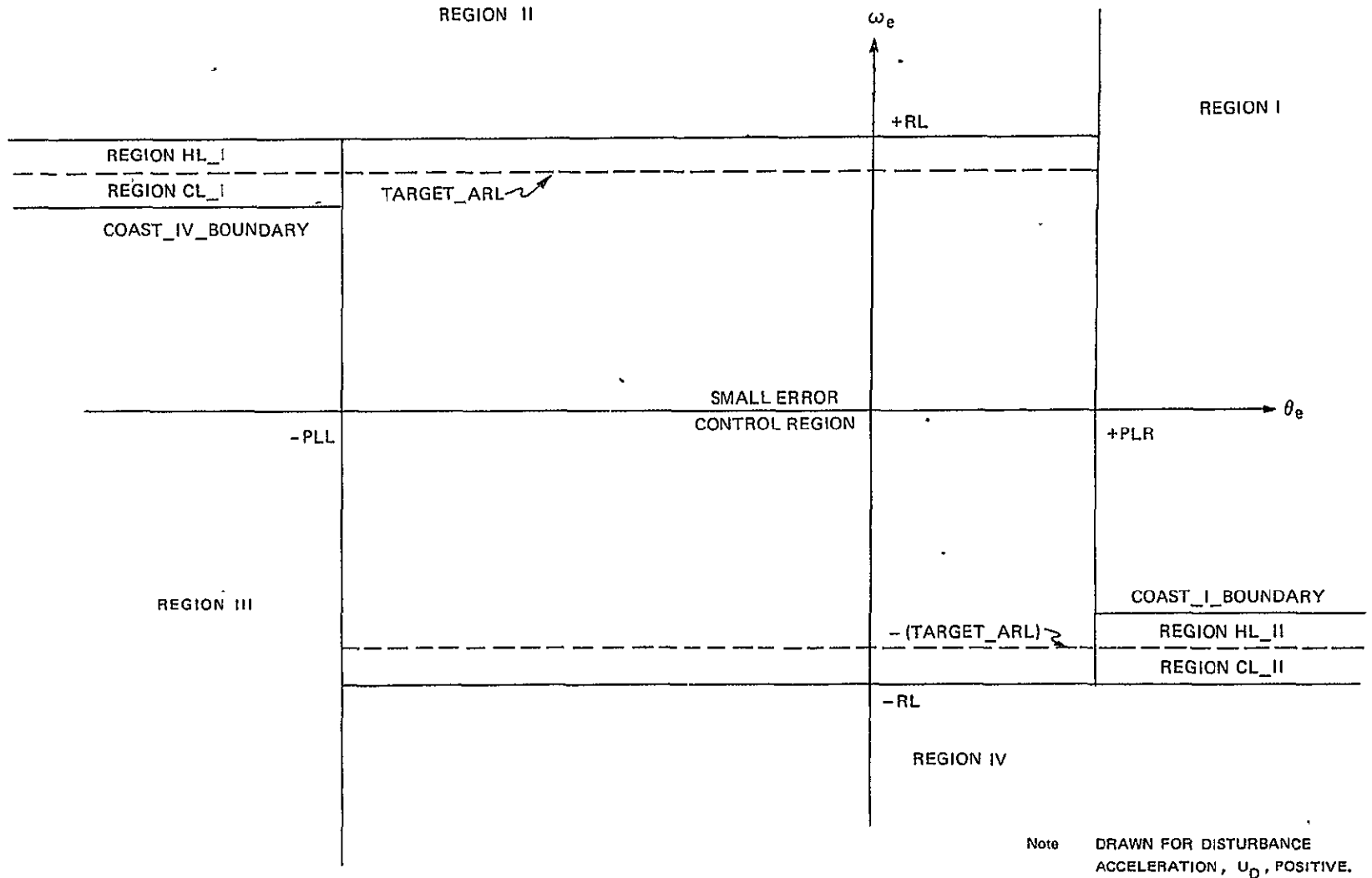


Figure 1.3.2.3.2-1. Large error control logic.

Hysteresis is incorporated into the large error coast regions to prevent switching line chatter. If the state is driven into Region HL_I from Region II, then it is further driven to TARGET_ARL. If the state is driven into Region CL_I from Region III then it is further driven to TARGET_ARL. If the state otherwise appears in Region HL_I or Region CL_I, the vehicle is allowed to coast. A similar situation occurs in Regions HL_II and CL_II. If the state is driven into Region HL_II from Region I, or if the state is driven into Region CL_II from Region IV, then it is further driven to $-(TARGET_ARL)$. Should the state otherwise appear in either Region HL_II or Region CL_II, then the vehicle is allowed to coast.

A final feature of the small error control logic can be described, now that TARGET_ARL has been introduced. If the disturbance acceleration is very large, part of the curve TARGET_DISTURB may lie below $-(TARGET_ARL)$. In this situation, a check is made to see if a rate change to drive the state to TARGET_DISTURB is greater than a rate change to drive the state to $-(TARGET_ARL)$. If it is, the state is driven to $-(TARGET_ARL)$, which means less fuel consumption with the result of finishing in a limit cycle about the origin.

The input-output requirements for LARGE_ERROR_CONTROL_LOGIC are listed in Table 1.3.2.3.2-2.

1.3.2.4 Jet Selection

There are two independent jet selection routines: one to control the main RCS jets, and the other to control the vernier jets. A flag set outside the FC (either manually or automatically) is interrogated in order to make the appropriate decision (see Table 1.3.2.4-1).

1.3.2.4.1 Jet Selection for Main RCS Jets. - The Jet Selection Logic determines which jets should be turned on or off each FC cycle based upon the action desired. No firing times are calculated for the jets, rather they are constrained to be either on or off for the duration of each FC cycle. The jet numbers referenced herein apply to the FD-2 RCS configuration. The "new" jet numbering system is described in Sub-section 4.3.2.4.

This design includes jet-failure logic which allows the Jet Selection Logic to retain all 6 degrees of control with any two jet failures or manifold shutdowns. Logical variables are used to indicate whether a jet is failed or normal and, also, whether a jet should be turned on

Table 1.3.2.3.2-2. Input-output requirements for LARGE_ERROR_CONTROL_LOGIC.

Category	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to LARGE_ERROR_ CONTROL_LOGIC	COAST_I_ BOUNDARY	COAST_I_ BOUNDARY	Switch curve in large error control region of the phase plane	rad/s	$-3\pi/180$	TBD
	COAST_IV_ BOUNDARY	COAST_IV_ BOUNDARY	Switch curve in large error control region of the phase plane	rad/s	$3\pi/180$	TBD
	K	K	Sign of estimated disturbance acceleration	(none)	+1.0 or -1.0	TBD
	NO_CHANGE	$X_{D_{old}}$	Angular rate change computed on last DFCS pass	rad/s	TBD	TBD
	PLL	PLL	Left position limit of large error control region	rad	TBD	TBD
	PLR	PLR	Right position limit of large error control region	rad	TBD	TBD

Table 1.3.2.3.2-2. Input-output requirements for LARGE_ERROR_CONTROL_LOGIC (Cont.).

Category	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Outputs of LARGE_ERROR_ CONTROL_LOGIC	POSITION_ ERROR	θ_e	Angular position error	rad	TBD	TBD
	RATE_ ERROR	ω_e	Angular rate error	rad/s	TBD	TBD
	RL	RL	Rate limits of large error control region of the phase plane	rad/s	TBD	TBD
	X_D	X_D	Desired change in angular rate	rad/s	TBD	TBD
	X_D	X_D	Desired change in angular rate	rad/s	TBD	TBD

Table 1.3.2.4-1. Input-output requirements for Jet Selection.

Category	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Input	VERNIER_JETS	N/A	Flag for Vernier Jet Logic	(none)	0,1	TBD

or off. Then Boolean algebra equations are written relating jet-failure information to the on/off state of each jet. In this way proper control can still be maintained in the presence of jet failures. The only exception is that $\pm Y$ control may be lost if both nose thrusters on the same side fail..

The logic provides either low- or high-level accelerations for both translations and rotations. For translations both low- and high-level accelerations provide at least 0.3 ft/s^2 acceleration, with up to one jet failure or one manifold shutdown. The acceleration may be less with two jet failures or two manifold shutdowns. High-level translation commands result in the maximum available thrust in the commanded axis. However, the logic permits high-level translational acceleration in only one axis at a time. Tables 1.3.2.4.1-1, 1.3.2.4.1-3, and 1.3.2.4.1-5 give the jets selected for translations. These tables do not include jet-failure cases. As a general rule, if a normally selected jet is failed, and an adjacent jet is neither selected nor failed, it will be chosen in lieu of the original jet. Modifications to the jet selection for other failure conditions are peculiar to the particular commands and failures, and are too numerous to tabulate.

For both pitch and yaw control, the high-level option corresponds to the coupled thruster option. For pitch, two nose and two tail thrusters are selected; for yaw, one nose and one tail thruster are selected. These selections minimize translational and rotational coupling. The low-level pitch and yaw options are designed to provide minimum control accelerations (which can provide more efficient attitude-hold limit cycling). The low-level pitch and yaw options have sub-options of preferences for using either nose or tail jets. These preferences permit a degree of propellant usage balancing between the forward and aft tanks.

For roll control, both the high- and low-level options minimize translational coupling and use tail thrusters only.. The high-level roll option corresponds to a two-couple selection, and the low-level roll option to a one-couple selection (however, the "couples" are not true couples due to thruster canting). The low-level roll option provides more than adequate control acceleration and it is used for nominal operation. The high-level roll option was designed to be used only when tail $\pm Y$ thrusters are firing and their coupling into roll would reduce the nominal low-level roll acceleration. The high-level roll option

can not be selected manually. However, the Jet Selection Logic automatically uses high-level roll control when tail $\pm Y$ thrusters couple unfavorably into roll. The jets selected with no jet failures for rotational commands alone, and for rotations combined with translations, are listed in Tables 1.3.2.4.1-2 through 1.3.2.4.1-5.

Each cycle the Jet Selection Logic computes the translational and rotational rate changes resulting from a 1-cycle firing of the jets selected by the logic. This information is used by the State Estimator to immediately account for rate changes due to jet firings. In addition, this information is used by the Jet Selection Logic itself to open-loop compensate any off-axis rate changes produced by jet firings. A record is kept of the total off-axis rate changes produced in each axis since the last time a command was issued in that axis. When the resultant velocity reaches a preset threshold level, a compensation command will be issued by the Jet Selection Logic to compensate for the off-axis rate changes. It should be noted that the receipt of a closed-loop command will cause the record of off-axis velocity produced on that axis to be zeroed. Thus open-loop compensation commands are issued only in the absence of a closed-loop command. The length of the compensation firings may be specified to be any integral number of FC cycles in duration. In this way the fuel loss due to jet-on delays and dribble penalties may be reduced. If open-loop compensation of off-axis rate changes is not desired, the threshold levels may be set to very large numbers. This will prevent compensation commands from being issued.

A block diagram of the jet selection routine is shown in Figure 1.3.2.4.1-1. The input-output requirements are presented in Table 1.3.2.4.1-6.

1.3.2.4.2 Jet Selection for Vernier Jets. - The vernier jet selection is provided with unit vectors giving the direction of rotational acceleration for each of the six vernier jets and for jets 1 and 2 combined and jets 5 and 6 combined. The logic will then select the jet(s) corresponding to the acceleration unit vector which provides the maximum dot product with the command vector.

The input-output requirements are given in Table 1.3.2.4.2-1.

1.3.3 TVC DAP

The TVC DAP must be capable of controlling the attitude of the vehicle during normal two-engine burns and also in the event of a single

Table 1.3.2.4.1-1. X-translation Jet Selection Logic.

COMMAND	ACCELERATION LEVEL	JETS SELECTED
+X	High	15, 16, 27, 28
+X	Low	15, 27
-X	High	1, 2, 3
-X	Low	1, 3

Table 1.3.2.4.1-2. Yaw rotational Jet Selection Logic when there is no y-translation command.

COMMAND	ACCELERATION LEVEL	JETS SELECTED
+ Yaw	High	4, 29
+ Yaw	Low (nose)*	4
+ Yaw	Low (tail)*	29
- Yaw	High	11, 17
- Yaw	Low (nose)*	11
- Yaw	Low (tail)*	17

* for the low acceleration level, either nose-only or tail-only jets can be selected.

Table 1.3.2.4.1-3. Y-translation and yaw rotation combined Jet Selection Logic.

ROTATIONAL COMMAND*	JETS SELECTED FOR Y-TRANSLATION COMMAND			
	+Y		-Y	
	HIGH	LOW	HIGH	LOW
+Yaw	4, 5	4	29, 30, 31	29, 30
-Yaw	17, 18, 19	17, 18	11, 12	11
NONE	4, 5, 17, 18, 19	4, 17, 18	11, 12, 29, 30, 31	11, 29, 30

*When a Y-translational command is present, the high level is assumed for all yaw commands

Table 1.3.2.4.1-4. Pitch and roll Jet Selection Logic when there is no z-translation command.

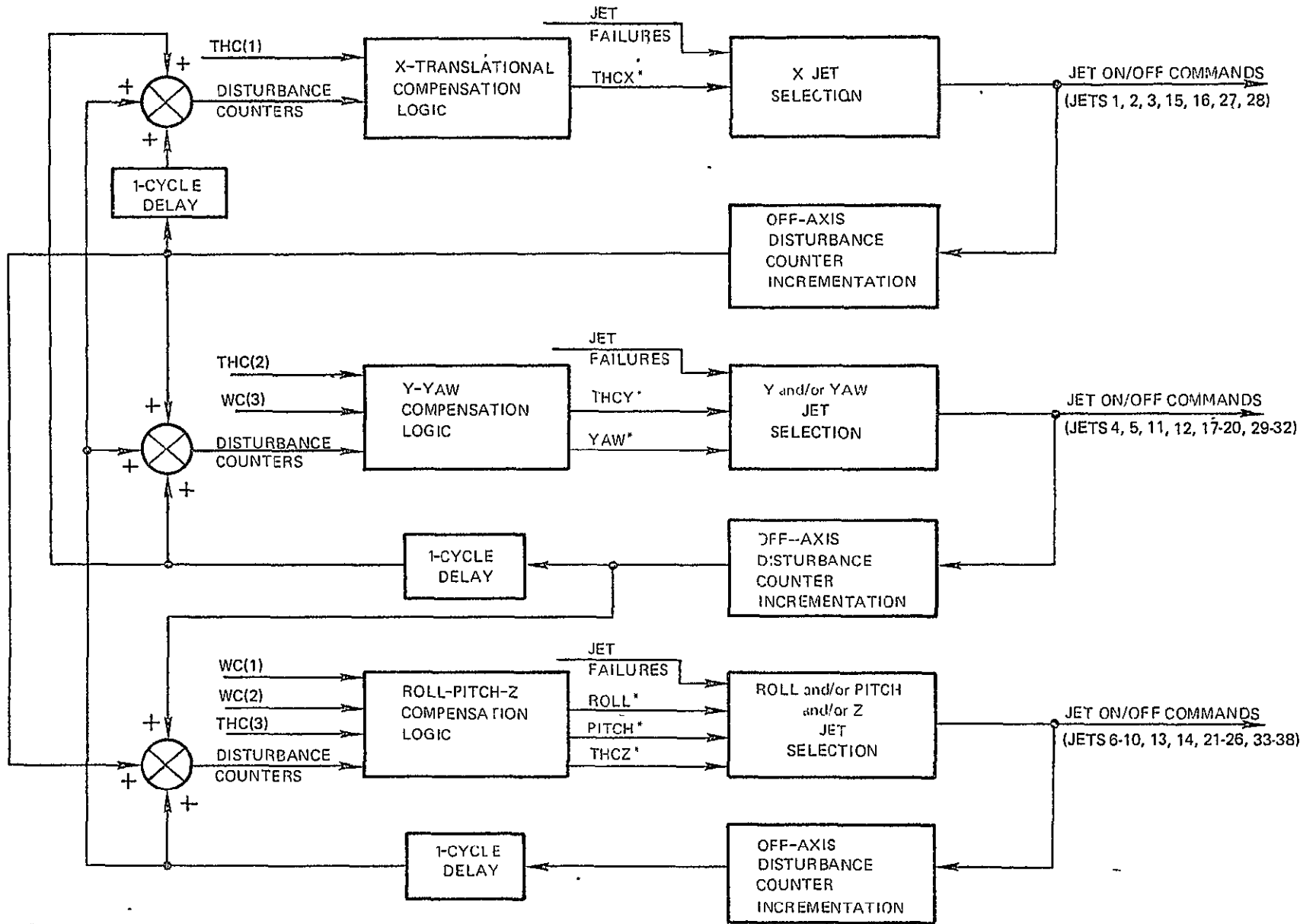
Pitch Command	Pitch Acceleration Level	Jets Selected for Roll/Pitch Commands				
		+Roll		-Roll		No Roll Command
		Low	High	Low	High	
+Pitch	High	9, 13, 33	9, 13, 33, 34, 35	9, 13, 21,	9, 13, 21, 22, 36	9, 13, 21, 33
	Low(Nose)	33	24, 33, 34	21	21, 22, 36	9, 13
	Low(Tail)	33	24, 33, 34	21	21, 22, 36	21, 33
-Pitch	High	8, 24	8, 24, 25, 33	6, 36	6, 21, 36, 37	6, 8, 24, 36
	Low(Nose)	24	24, 25, 33	36	21, 36, 37	6, 8
	Low(Tail)	24	24, 25, 33	36	21, 36, 37	24, 26
None	None	24, 33	24, 25, 33, 34	21, 36	21, 22, 36, 37	- - - -

Table 1.3.2.4.1-5. Z-translation and pitch and roll rotation combined Jet Selection Logic.

Rotational Commands*		Jets Selected for Z-Translation Logic			
		+Z		-Z	
		High	Low	High	Low
+Pitch	Low	7, 21, 33, 34, 35	33	9, 10, 13, 14, 24, 25, 26, 36	9, 13, 24
	High	7, 33, 34, 35	33, 34, 35	9, 10, 13, 14, 24, 25, 26	9, 10, 13, 14, 24, 25, 26
	Low	7, 21, 22, 23, 33	21	9, 10, 13, 14, 24, 36, 37, 38	9, 13, 36
	High	7, 21, 22, 23	21, 22, 23	9, 10, 13, 14, 36, 37, 38	9, 10, 13, 14, 36, 37, 38
	No Roll	6, 8, 21, 22, 23, 33, 34, 35	21, 33	9, 10, 13, 14, 24, 36	9, 13
	High	6, 7, 8, 33, 34, 35	6, 7, 8, 33, 34, 35	24, 25, 26	24, 25, 26
-Pitch	Low	6, 7, 8, 33, 34	7, 33	24, 25, 26, 36	24, 25
	High	6, 7, 8, 33, 34, 35	6, 7, 8, 33, 34, 35	24, 25, 26	24, 25, 26
	Low	6, 7, 8, 21, 22	7, 21	24, 36, 37, 38	36, 37
	High	6, 7, 8, 21, 22, 23	6, 7, 8, 21, 22, 23	36, 37, 38	36, 37, 38
	No Roll	6, 7, 8, 21, 33	7	9, 13, 24, 25, 26, 36, 37, 38	24, 25, 36, 37
	High	6, 7, 8, 21, 33, 34, 35	7, 33	9, 10, 13, 14, 24, 25, 26, 36	9, 13, 24, 25
No Pitch	Low	6, 7, 8, 33, 34, 35	6, 7, 8, 33, 34, 35	9, 10, 13, 14, 24, 25, 26	9, 13, 24, 25, 26
	High	6, 7, 8, 33, 34, 35	6, 7, 8, 33, 34, 35	9, 10, 13, 14, 24, 25, 26	9, 13, 24, 25, 26
	Low	6, 7, 8, 21, 22, 23, 33	7, 21	9, 10, 13, 14, 36, 37, 38	9, 13, 36, 37
	High	6, 7, 8, 21, 22, 23	6, 7, 8, 21, 22, 23	9, 10, 13, 14, 36, 37, 38	9, 13, 36, 37, 38
	No Roll	6, 7, 8, 21, 22, 23, 33, 34, 35	7, 21, 33	9, 10, 13, 14, 24, 25, 26, 36, 37, 38	9, 13, 24, 25, 36, 37
	High	6, 7, 8, 21, 22, 23	6, 7, 8, 21, 22, 23	9, 10, 13, 14, 36, 37, 38	9, 13, 36, 37, 38

* All pitch commands are high level. High level roll is used only when tail y jets are selected and their roll disturbance is in the opposite direction of the roll command.

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* JET SELECTION COMMAND AFTER MODIFICATION BY COMPENSATION LOGIC

Figure 1.3.2.4.1-1. Block diagram of Jet Selection for main RCS Jets.

Table 1.3.2.4.1-6. Input-output requirements for main RCS Jet Selection.

Category	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/ś)
	Computer Notation	Mathematical Notation				
Inputs from Manual Translation Driver or Guidance	TBD	THC	Translation commands in the X, Y, and Z axes	(none)	-1, 0, 1	TBD
Inputs from Pilot	TBD	TJP	A logical variable commanding the use of tail jets only (TJP=true) or nose jets only (TJP=false) for low-level pitch	(none)	TRUE/FALSE	TBD
	TBD	TJY	Similar to TJP only pertaining to yaw	(none)	TRUE/FALSE	TBD
Inputs from Manual Rotation Driver or Phase Plane	TBD	WC	Rotation rate change commands in the roll, pitch, yaw (X, Y, Z) axes	rad/s	TBD	TBD
Inputs from TBD Input Data Routine(s)	TBD	A	1 x 84 array containing translational and rotational accelerations for 1 representative jet in each of the 14 jet Groups	m/s and rad/s	TBD	*
	TBD	FL	1 x 38 array indicating whether each jet normal (FL=false) or failed (FL=true)	(none)	TRUE/FALSE	*
	TBD	LEV	Commanded acceleration levels for X, Y, Z, roll, pitch, and yaw, selectable per axis	(none)	1, 2	*

* Function of Input Routine(s).

Table 1.3.2.4.1-6. Input-output requirements for main RCS Jet Selection (Cont.).

Category	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
	TBD	MODCYC	Number of cycles a compensation firing is to be held	(none)	TBD Integer	*
	TBD	OFFDLY	Delay in turning off a jet	s	TBD	* 1
	TBD	ONDLY	Delay in jet ignition	s	TBD	*
	TBD	TL	Threshold levels in translational and rotational compensation logic	m/s and rad/s	TBD	*
Output to State Estimator	TBD	DV	The expected rate changes each cycle in X, Y, Z, roll, pitch, and yaw resulting from jet firings	m/s and rad/s	TBD	TBD
Output to Thrust Effectors	TBD	JTLST .	On or off command for each of the 38 main RCS jets	(none)	0, 1	TBD

* Function of Input Routine(s).

Table 1.3.2.4.2-1. Input-output requirements for Vernier Jet Selection.

Category	Name of Variable or Constant		Description of Variable or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to Vernier	TBD	AM	Magnitudes of the acceleration vectors from which α_1 through α_8 are formed.	rad/s ²	TBD	TBD
	TBD	α_1	Unit vectors in the direction of the roll, pitch, and yaw accelerations for each of the 6 vernier jets	(none)	±1.0	TBD
	TBD	α_7	Unit vector in direction of combined acceleration of jets 1 and 2	(none)	±1.0	TBD
	TBD	α_8	Unit vector in direction of combined acceleration of jets 5 and 6	(none)	±1.0	TBD
	TBD	[CMD]	Commands for roll, pitch, yaw	(none)	±1.0	TBD
	TBD	DT	DAP minor cycle time	s	TBD	TBD
Outputs of Vernier	TBD	[DWJ]	Roll, pitch, and yaw rate changes resulting from 1-cycle firing of jets selected by vernier logic	rad/s	TBD	TBD
	TBD	[J]	On/Off commands; one for each of the 6 vernier jets	(none)	0,1	TBD

engine failure. Control of the vehicle attitude in pitch and yaw is accomplished with the gimballed OMS engines while roll control may be provided either by the gimballed OMS engines or by the RCS jets.

There are two modes of operation during OMS burns, automatic and manual. In the automatic mode the following functions are performed by the TVC DAP:

- (1) Provide OMS gimbal actuator positioning commands and RCS jet control commands for attitude control.
- (2) Provide orbiter three-axis automatic attitude stabilization and control using three-axis attitude command signals from the Guidance and Navigation modules (i.e., steering loop).
- (3) Provide OMS gimbal actuator trim signals prior to thrust initiation.
- (4) Transmit thrust-on and thrust-off commands to the OMS engines as provided by the guidance loop.
- (5) Transmit a thrust-off command to the OMS engines as provided by manual input.
- (6) In the event of an engine failure during a two-engine burn, continue thrusting with the remaining engine but retrim the engine actuator to line up the engine thrust direction with the center of gravity (cg) of the vehicle. Also, disable the TVC DAP and transfer to RCS jet control by routing guidance to the RCS DAP. Roll attitude control stays with the RCS DAP, but the pitch and yaw control is returned to the TVC DAP once the body rates drop below a preset value. The burn is then completed with the good engine.

Subsection 1.3.3.1 describes the pitch and yaw control, and Subsection 1.3.3.2 the roll control, for the automatic TVC mode.

In the manual mode, the vehicle follows angular rate commands proportional to rotation hand controller deflections. This mode is initiated and terminated by manual control. In the event of an engine failure, the burn is completed with the remaining engine. In the manual mode the TVC DAP must do the following:

- (1) Provide OMS gimbal actuator positioning signals and RCS jet control signals to follow rate commands.
- (2) Provide orbiter three-axis angular rate control using three-axis rate commands from the manual controller.

- (3) Initiate and terminate the mode in response to manual commands.
- (4) Provide OMS gimbal actuator trim signals derived from manual inputs prior to thrust initiation.
- (5) Transmit thrust-on and thrust-off commands to the OMS engines as provided by manual inputs.

Subsection 1.3.3.3 describes the manual TVC mode control law.

1.3.3.1 Automatic Pitch/Yaw TVC Law

In this subsection the control law which provides automatic pitch or yaw attitude control for a one-engine or two-engine burn is described. The method for providing OMS gimbal actuator trim signals is to be determined. The TVC DAP must compute engine gimbal servo commands in response to computed errors between the commanded and measured vehicle attitudes such that these errors are kept small.

A block diagram of the TVC DAP and its relationship to the vehicle control loop is shown in Figure 1.3.3.1-1. The external rate commands come from the Guidance module via a driver. These are integrated to form attitude increments and further passed through the guidance loop compensation filter which serves the purpose of stabilizing the otherwise unstable guidance loop. The output of this filter is the vehicle attitude command. The difference between the commanded vehicle attitude and the actual (measured) vehicle attitude is the attitude error which is the input to the digital compensation filter. The output of the filter passes through a thrust misalignment correction (TMC) filter (explained below), is differenced with the engine position signal, and finally is sent through a zero-order hold to obtain the engine gimbal servo error as a continuous signal. The OMS engine dynamics include the bang-bang amplifier, motor drive, engine inertia, etc. The vehicle dynamics relate the actual vehicle attitude to the actual engine deflection. The engine dynamics and vehicle dynamics are continuous components of the control loop. The sampling rate of the digital components in the loop is 25 Hz, corresponding to a sampling period of 0.04 second.

The purpose of the TMC filter is to cancel out the effects of any thrust misalignment relative to the vehicle cg while also eliminating any steady-state attitude error. The TMC filter removes the bias effect of thrust misalignment. Without the TMC filter, the steady-state attitude is nonzero, and its magnitude depends on the dc gain of the

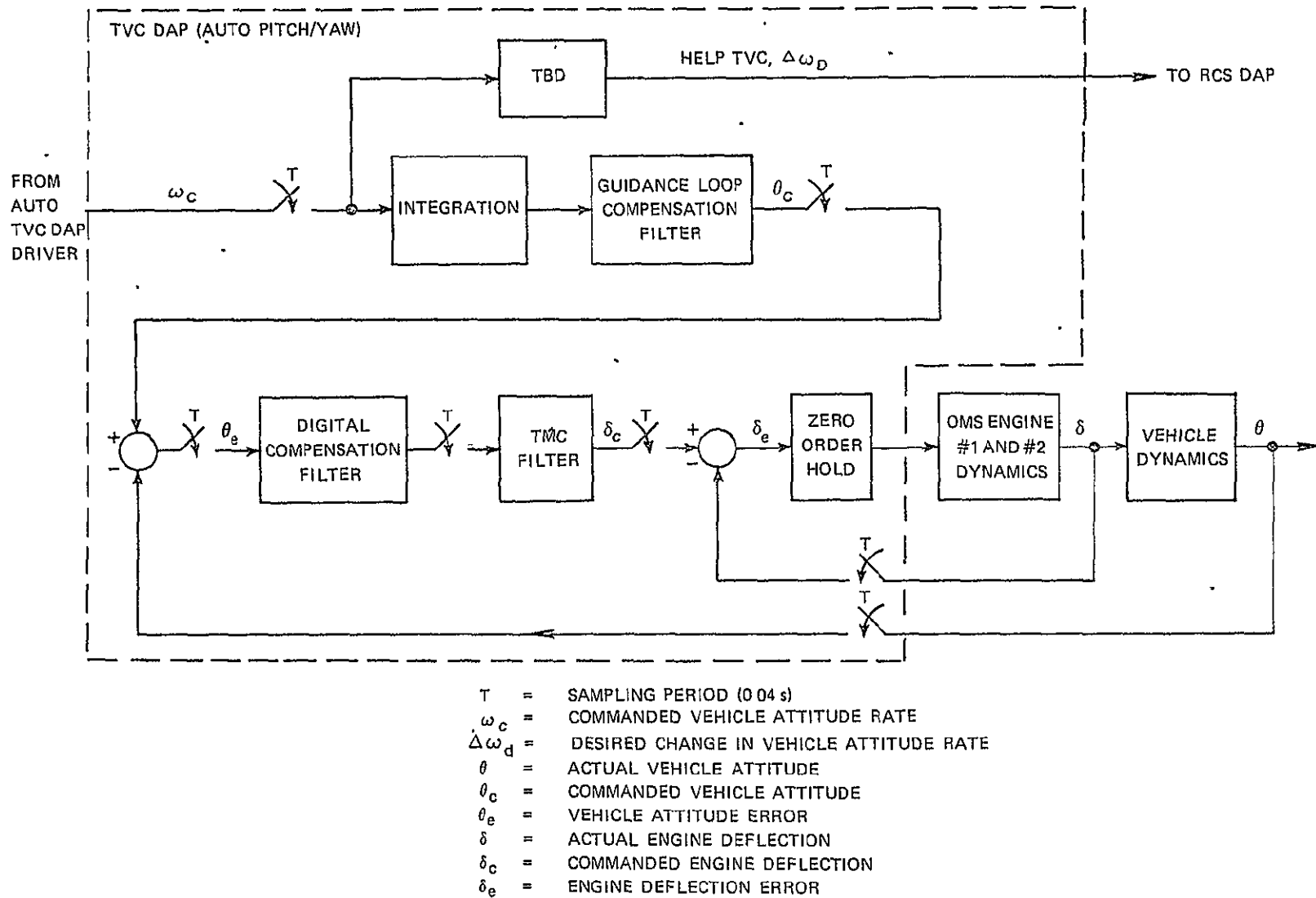


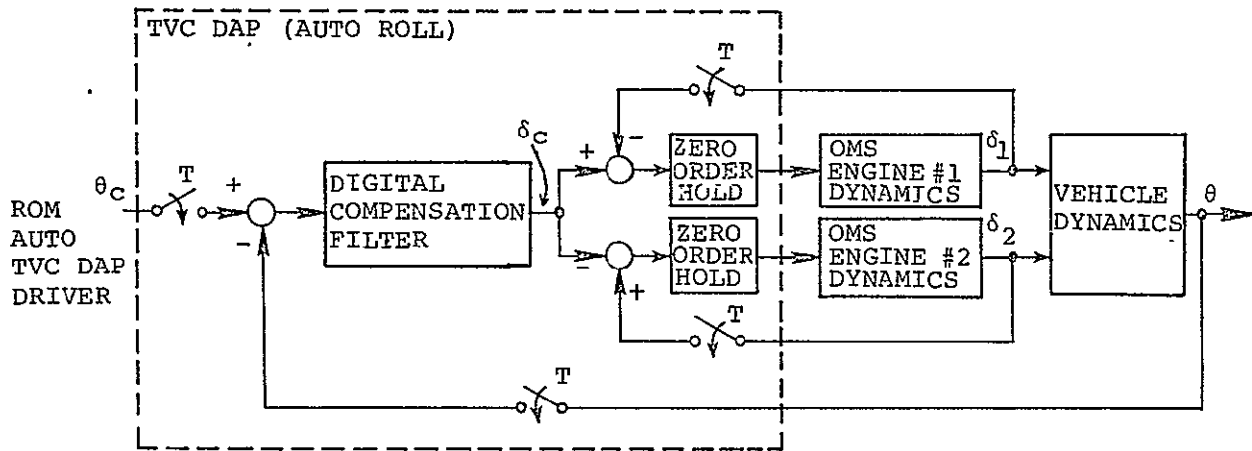
Figure 1.3.3.1-1. TVC DAP auto pitch/yaw channel and relationship to vehicle control loop.

digital compensation filter. Since the TMC filter acts like a proportional plus integral transfer function, its inclusion causes the dc gain of the forward loop to become infinite, thus eliminating any steady-state attitude error as the result of a constant bias in the thrust position relative to the engine servo command. The digital compensation filter in series with the TMC filter generates the engine gimbal servo commands from the attitude error.

The inputs and outputs of the TVC DAP pitch/yaw channel are described in Table 1.3.3.1-1.

1.3.3.2 Automatic Roll TVC Law

During TVC burns, roll attitude control is achieved by applying differential commands in the pitch plane to the two OMS engines. A block diagram of this loop is shown in Figure 1.3.3.2-1.



T = sampling period (0.04s)

θ_c = commanded vehicle roll angle

θ = actual vehicle roll angle

δ_c = commanded engine deflection

δ_1, δ_2 = actual engines 1 and 2 deflections in pitch plane

Figure 1.3.3.2-1. TVC DAP auto roll channel and relationship to vehicle control loop.

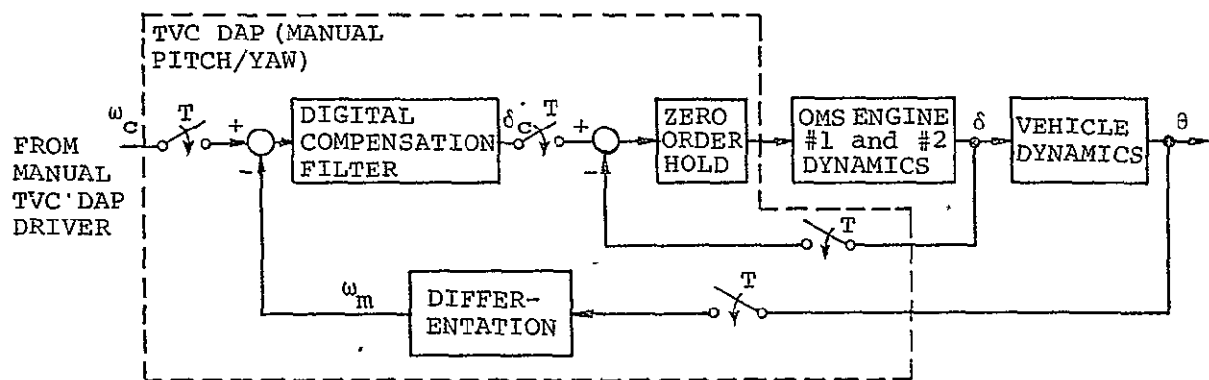
Table 1.3.3.1-1. Input-output requirements for TVC DAP pitch/yaw channel.

	Name of Variable or Constant		Description of Variable or Constant	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Input	TBD	ω_c	Pitch or yaw rate command	rad/s	TBD	TBD
	TBD	θ	IMU-derived body attitude data	rad	TBD	TBD
Output	TBD	δ_e	Engine deflection error	rad	TBD	TBD
	BYPASS_PHASE_PLANE	(none)	Phase plane switching logic bypass command	(none)	0, 1	TBD
	TBD	$\Delta\omega_d$	Desired pitch or yaw rate change	rad/s	TBD	TBD

The roll attitude command coming from the guidance module via the driver will predominantly stay constant; thus the loop operates in an attitude-hold mode. This command is compared with the roll attitude and the error passed through a digital compensation filter. The output is the engine command. It is applied with opposite polarities to the two OMS engine servos after comparison with the corresponding engine position signals.

1.3.3.3 Manual TVC Law

Manual pitch or yaw TVC is performed by gimbaling the OMS engines. A block diagram of the manual TVC loop is shown in Figure 1.3.3.3-1.



T = sampling period (0.04s)

ω_c = manually commanded vehicle attitude rate

θ = actual vehicle attitude

ω_m = derived vehicle attitude rate

δ = actual engine deflection

δ_c = commanded engine deflection.

Figure 1.3.3.3-1. TVC DAP manual pitch/yaw channel and relationship to vehicle control loop.

The difference between the manual rate command and the derived rate forms the rate error. The rate is derived by simple back-differencing of measured vehicle attitude increments. The error is passed through the digital compensation filter whose main function is to attenuate the high bending frequencies and to filter the noise

resulting from differentiation of attitude. This signal represents the engine position command. It is differenced with the measured engine position and the error thus formed is sent to the engine servo.

Manual roll control design is TBD.

1.3.4 RCS DAP and TVC DAP Drivers

1.3.4.1 RCS DAP Drivers

1.3.4.1.1 Manually Commanded RCS DAP Drivers. - Manual control of the vehicle using the RCS jets is accomplished by the procedures MAN_RCS_ROT and MAN_RCS_TRANS driving the RCS DAP and the Jet Selection Logic. Each procedure accepts commands from a Rotational Hand Controller (RHC) or a Translational Hand Controller (THC), as well as option and parameter selections from the switch panel via the procedure PANEL_SWITCH_INTERP.

Hand controllers and switch panels are placed at two stations: the Commander's station (+x facing) and the aft station. Hand controller commands from the aft station may be referenced to docking axes (-z facing) or payload viewing axes (-x facing). Selection between commands from the two stations is performed by the external SOP.

1.3.4.1.1.1 Rotation. - Manual control of the orbiter attitude and attitude rate is accomplished by the routine MAN_RCS_ROT containing three submodes selectable by axis:

- (1) Discrete rate command submode.
- (2) Direct rotation acceleration command submode.
- (3) Direct rotation pulse command submode.

The procedure MAN_RCS_ROT accepts proportional inputs from an RHC and selectable parameters chosen through PANEL_SWITCH_INTERP, and it produces rotation commands for the RCS DAP.

MAN_RCS_ROT is not available when the TVC DAP is in operation. Should RCS jets be required for attitude control during an OMS burn, RHC inputs will be interpreted by a manual TVC DAP driver, and the TVC DAP will generate attitude and angular rate commands for the RCS DAP.

Hysteresis is incorporated in the procedure RHC_READ to prevent ON/OFF "chatter" in RHC commands.

Should the RHC be out of detent, new rotation submode selections are rejected, and commands are sent to the switch panel lights to indicate that the previous rotation submodes are still in effect.

Table 1.3.4.1.1.1-1 gives the input-output requirements of MAN_RCS_ROT.

Table 1.3.4.1.1.1-1. Input-output requirements for MAN_RCS_ROT.

Category	Name of Variable or Constant		Description of Variable or Constant	Units	Value	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to MAN_RCS_ROT	RHC	δ_{RHC}	Values of RHC deflection	TBD	TBD	25
	INIT_MAN_ROT_FLAG	INIT_MAN_ROT_FLAG	Flag for initialization of MAN_RCS_ROT	(None)	ON/OFF	25
	ROTATION_OPTIONS	ROTATION_OPTIONS	Rotation submode selection by axis	(None)	1,2,3	25
	CFLAG	CFLAG	Flag for hi/lo accel selection	(None)	ON/OFF	25
	OMEGA_HAT	$\hat{\omega}$	Current angular rate estimate	rad/s	TBD	25
	ROTATION_PULSE_SIZE	$[\Delta\omega_{pulse}]$	Selected pulse $\Delta\omega$	rad/s	0.000873 to 0.00873	25
	DISCRETE_OMEGA	$[\omega_{disc}]$	Discrete ω by axis	rad/s	0.00105 to 0.0349	25
Outputs of MAN_RCS_ROT	DESIRED_OMEGA	ω_D	Desired rotational velocities	rad/s	TBD	25
	LIGHT1	LIGHT1	Commands for panel switch lamps	(None)	ON/OFF	25
	BYPASS_PHASE_PLANE	BYPASS_PHASE_PLANE	Flag for direct control of jet select	(None)	ON/OFF	25
	CLSTRF	CLSTRF	Flags for hi/lo accel option by axis	(None)	ON/OFF	25
	JET_COMMAND	JET_COMMAND	Jet firing commands by axis	(None)	-1,0,1	25

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1.3.4.1.1.1.1 Discrete Rate Command Submode. - When this submode is selected for a given axis, the response to a deflection of the RHC is a vehicle rate equal to a preset value. This preset value can be one of two in the range 0.06 to 2.0 deg/s, and is selectable by axis via the switch panel. This rate is maintained as long as the RHC is out of detent in the given axis. When the RHC is returned to detent, the existing vehicle attitude in the given axis is held.

1.3.4.1.1.1.2 Direct Rotation Acceleration Command Submode. - When this submode is selected for a given axis, the response to a deflection of the RHC consists of firing commands to RCS jets appropriate for producing a moment with the same sense as the RHC deflection. The jets remain on as long as the RHC is out of detent in the given axis. The jets are off as long as the RHC is in detent, allowing the attitude to drift freely.

Two levels of angular acceleration, differing by a factor of 1.8 to 2.7, are selectable via the switch panel.

1.3.4.1.1.1.3 Direct Rotation Pulse Command Submode. - When this submode is selected for a given axis, the response to a deflection of the RHC consists of a single continuous command to the jets until the angular velocity of the vehicle is changed by a preset increment. No further rate increment is commanded until the RHC is returned to detent and again deflected. Two values of increment are available over the range 0.05 to 0.50 deg/s, and are selectable by axis via the switch panel.

1.3.4.1.1.2 Translation. - Manual control of vehicle translation with the RCS jets is accomplished by the routine MAN_RCS_TRANS containing two submodes, selectable by axis:

- (1) Direct translation acceleration command submode.
- (2) Direct translation pulse command submode.

MAN_RCS_TRANS accepts integer commands from a THC as well as selectable parameters chosen through PANEL_SWITCH_INTERP, and it produces translation rate change commands for the Jet Selection Logic. If the THC is out of detent, new translation submode selections are rejected, and commands are sent to the switch panel lights to indicate that the previous translation submodes are still in effect. MAN_RCS_TRANS is not available when the TVC DAP is operating.

THC hysteresis is incorporated in the hardware.

Table 1.3.4.1.1.2-1 gives the input-output requirements of MAN_RCS_TRANS.

Table 1.3.4.1.1.2-1. Input-output requirements for MAN_RCS_TRANS.

Category	Name of Variable or Constant		Description of Variable or Constant	Units	Value	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to MAN_RCS_TRANS	THC	THC	Flag for THC deflection containing sense	(None)	-1,0,1	25
	TRANSLATION_OPTION	TRANSLATION_OPTION	Flag for translation submode selections by axis	(None)	ON/OFF	25
	DELTA_V	ΔV	Estimated translational rate changes	ft/s	TBD	25
	TRANSLATION_PULSE_SIZE	$[\Delta V_{pulse}]$	Selected rate change per pulse	ft/s	0.03 to 0.8	25
	CFLAG	CFLAG	Flag for hi/lo accel selection	(None)	ON/OFF	25
Outputs of MAN_RCS_TRANS	LIGHT2	LIGHT2	Commands for panel switch lamps	(None)	ON/OFF	25
	W	W	Rate change commands to jet select	rad/s ft/s	TBD	25
	CLSTRF	CLSTRF	Flag for hi/lo acceleration by axis	(None)	ON/OFF	25

1.3.4.1.1.2.1 Direct Translation Acceleration Command Submode. - When this submode is selected for a given axis, the response to a THC deflection consists of firing commands to the RCS jets appropriate for producing translation with the same sense as the THC deflection. Two levels of translational acceleration are available through the switch panel. The jets remain on as long as the THC is out of detent in the given axis. The jets are off as long as the THC is in detent, allowing the vehicle to drift freely.

1.3.4.1.1.2.2 Direct Translation Pulse Command Submode. - When this submode is selected for a given axis, the response to a deflection of the THC consists of a single continuous command to the jets until the translational velocity of the vehicle is changed by a preset increment. No further rate increment is commanded in this axis until the THC is returned to detent and again deflected. Two values of increment, over the range 0.03 ft/s to 0.8 ft/s, are selectable by axis via the switch panel.

1.3.4.1.2 Automatically Commanded RCS DAP Drivers

1.3.4.1.2.1 Rotation. - Only automatic steering commands are accepted for the rotational axes while in the automatic mode. There is no response to any deflection of the RHC. The RCS DAP is driven by the automatic attitude maneuver routines described below. When none are in progress, the RCS DAP will perform attitude hold.

1.3.4.1.2.1.1 Three-Axis Automatic Attitude Maneuver. - The purpose of the automatic attitude maneuver routine (ATTITUDE_MANEUVER) is to supply the RCS DAP with parameters necessary to perform a desired reorientation of the spacecraft. There are four RCS DAP parameters. The first of these quantities is a set of desired gimbal angles, $[\phi_D]$, which is updated regularly during the maneuver. To achieve a smooth sequence of commands between successive updates, the routine generates a set of incremental gimbal angles, $[\Delta\phi_D]$, to be added to $[\phi_D]$ by the RCS DAP Error Computation. Also computed are the desired angular velocity vector, ω_D , and a set of bias angles, β_{BIAS} , all in vehicle coordinates. The bias angles β_{BIAS} are used by the RCS DAP to prevent fuel-consuming overshoot when starting and stopping an automatic maneuver.

The block diagram of ATTITUDE_MANEUVER is illustrated in Figure 1.3.4.1.2.1-1. Maneuvers are performed by rotating the spacecraft about the axis of single equivalent rotation, \underline{u}_r , through the angle A_M . To compute A_M and \underline{u}_r , ATTITUDE_MANEUVER accepts as input the present gimbal angles, $[\phi]$, the desired magnitude of the angular rate, ω_r , and the desired terminal set of gimbal angles, $[\phi_C]$. If A_M is found to be less than or equal to 0.25 degree, then the routine switches to HOLD_ATTITUDE which supplies the RCS DAP with the terminal commanded gimbal angles, $[\phi_C]$, and zeros the remaining inputs to the RCS DAP. If A_M is greater than 0.25 degree, then the steering procedure cycles every

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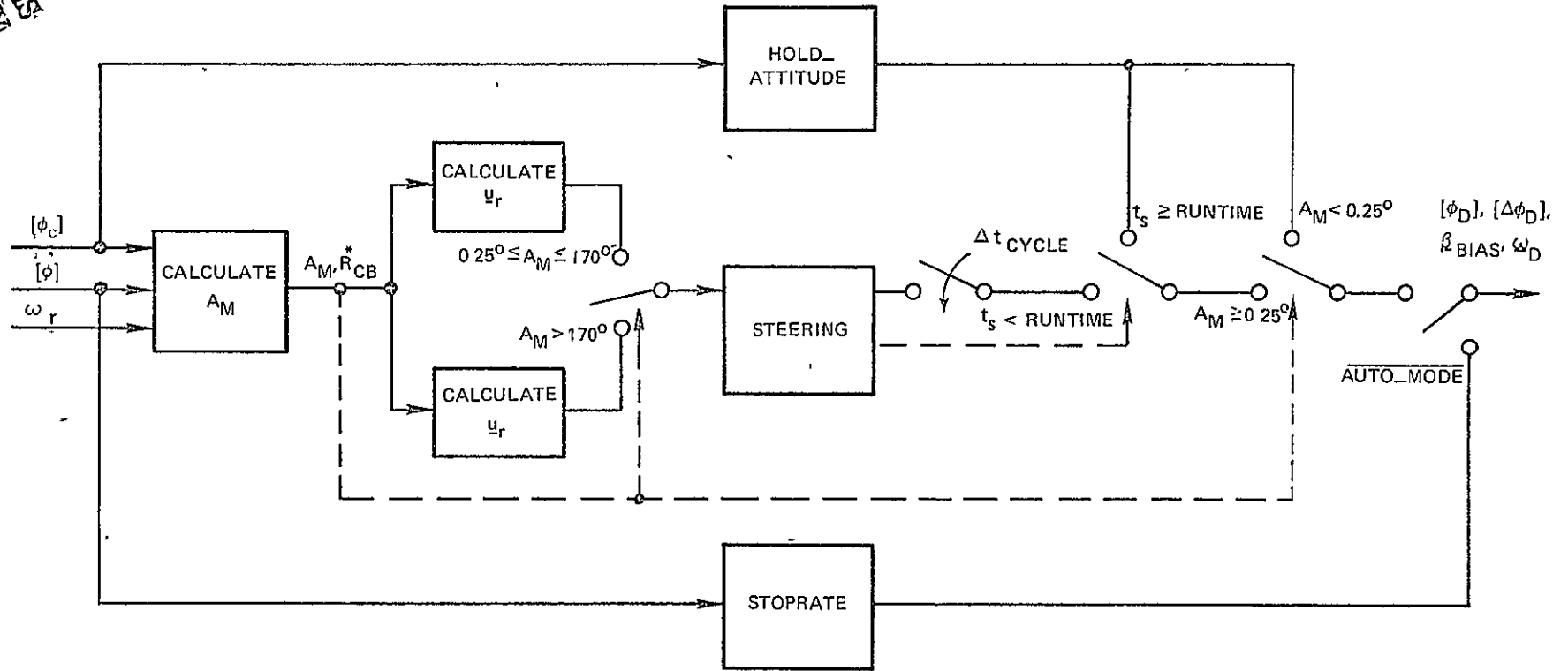


Figure 1.3.4.1.2.1-1. Block diagram of attitude maneuver.

Δt_{cycle} seconds, and computes on each pass the four sets of quantities to be used by the RCS DAP in following the angular path defined by \underline{u}_r and A_M . At the termination of the maneuver ($t_{\text{cycle}} > t_S$) the routine switches to HOLD_ATTITUDE. If the mode selection is changed from auto during the execution of STEERING, the STOPRATE procedure is executed. STOPRATE sets the desired gimbal angles equal to the present gimbal angles and zeroes the remaining inputs to the RCS DAP.

There are two desired capabilities not present in the current design of ATTITUDE_MANEUVER.

- (1) It is desirable to be able to call ATTITUDE_MANEUVER and request that it compute the time required for the maneuver without a maneuver actually being performed.
- (2) It is desirable to be able to pass to ATTITUDE_MANEUVER the desired final body rates. These rates would not be used as additional boundary values with which to compute the maneuver path, but rather, as an alternative to always performing a HOLD_ATTITUDE at the end of the maneuver. This is a fuel saving strategy for those cases when the vehicle rate at the end of the maneuver has components that are desirable for post-maneuver tracking.

The input-output requirements for ATTITUDE_MANEUVER are listed in Table 1.3.4.1.2.1-1.

1.3.4.1.2.1.2 Two-Axis Automatic Attitude Maneuvers. - Two-axis maneuvers are accomplished by first executing the procedure VECPOINT and then the procedure ATTITUDE_MANEUVER. VECPOINT computes the desired set of terminal gimbal angles, $[\phi_C]$, required by ATTITUDE_MANEUVER, from a body-fixed unit vector, \underline{u}_{ANB} , and a desired unit vector in stable member coordinates, \underline{u}_{DSM} , to which \underline{u}_{ANB} is to be aligned. In general, this procedure will reduce the fuel required for the maneuver by not constraining the orientation of the spacecraft about the pointing axis defined by \underline{u}_{DSM} . Additionally, the attitude about \underline{u}_{DSM} will be left unchanged. Consequently, the crew may specify the attitude about the pointing axis to satisfy additional communication, visibility, or thermal constraints, if desired. This is done by manually reorienting the spacecraft about the pointing axis either prior to, or after the maneuver. If this procedure is done after the automatic maneuver, a final trim will

Table 1.3.4.1.2.1-1. Input-output requirements for automatic attitude maneuver.

Category	Name of Variable or Constant		Description of Variables or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to ATTITUDE MANEUVER	DEG_TO_RAD	DEG_TO_RAD	Degrees to radians conversion factor	(None)	$\pi/180$	TBD
	[GA_B]	$[\phi]$	Initial gimbal angles	rad	$-\pi < x \leq \pi$	TBD
	[GA_COMMANDED]	$[\phi_c]$	Terminal commanded gimbal angles	rad	$-\pi < x \leq \pi$	TBD
Inputs to STEERING	AUTO_MODE	AUTO_MODE	Automatic mode switch	(None)	ON/OFF	TBD
	DELTAT_C	Δt_{cycle}	Period of the cycle of STEERING	s	1.2	TBD
	DESIRED_MAGNITUDE_OF_BODY_RATE	ω_r	Desired magnitude of body rate	rad/s	$x < 0.034$	TBD
	FAST_DFCS_FLAG2	t_{fast}	RCS DAP cycle time	s	0.04	TBD
	[GA_B]	$[\phi]$	Initial gimbal angles	rad	$-\pi < x \leq \pi$	TBD
	RUNTIME	RUNTIME	FCOS runtime	s	0 to ∞	TBD
Inputs to HOLD ATTITUDE	[GA_COMMANDED]	$[\phi_c]$	Terminal commanded gimbal angles	rad	$-\pi < x \leq \pi$	TBD
Outputs of ATTITUDE MANEUVER	\underline{u}_R	\underline{u}_r	Single equivalent rotation unit vector; rotation through the angle A_M	(None)	$ \underline{u}_r = 1$	TBD
	A_M	A_M	Angle of rotation about \underline{u}_r	rad	TBD	TBD
Outputs of STEERING, HOLD ATTITUDE, and STOPRATE (same output for all)	BIAS_BETA	β_{BIAS}	Bias body angles to prevent overshoot when starting and stopping a maneuver	rad	TBD	TBD
	[DELTA_GA]	$[\Delta\phi_D]$	Incremental gimbal angles	rad	TBD	TBD
	DESIRED_BODY_RATE	$\underline{\omega}_D$	Desired body rate	rad/s	TBD	TBD
	[GA_DESIRED]	$[\phi_D]$	Desired gimbal angles	rad	$-\pi < x \leq \pi$	TBD

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usually be required to assure that \underline{u}_{ANB} is aligned with \underline{u}_{DSM} . The input-output requirements for VECPOINT are listed in Table 1.3.4.1.2.1-2. Input-output requirements for ATTITUDE_MANEUVER are listed in Table 1.3.4.1.2.1-1.

Table 1.3.4.1.2.1-2. Input-output requirements for two-axis automatic attitude maneuvers.

Category	Name of Variable or Constant		Description of Variables or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to VECPOINT	\underline{u}_{ANB}	\underline{u}_{ANB}	Unit vector in vehicle axes	(None)	$ \underline{u}_{ANB} = 1$	TBD
	\underline{u}_{DSM}	\underline{u}_{DSM}	Unit vector in stable member axes to which \underline{u}_{ANB} is to be aligned	(None)	$ \underline{u}_{DSM} = 1$	TBD
Outputs of VECPOINT	[GA_COMMANDED]	$[\phi_c]$	Terminal commanded gimbals angles	rad	$-\pi < x \leq \pi$	TBD

1.3.4.1.2.1.3 OMS Prethrust Maneuver. - The OMS prethrust maneuver is a special case of the two-axis automatic maneuver in which the body-fixed unit vector, \underline{u}_{ANB} , is the OMS initial net thrust vector. For two-engine OMS burns, this vector lies on the line connecting the vehicle cg to a "virtual" OMS engine midway between the two real OMS engines. The maneuver is accomplished by first executing the procedure OMS_PRETHRUST_DIRECTION, which calculates the two-engine thrust vector, and then the procedures VECPOINT and ATTITUDE_MANEUVER (Subsection 1.3.4.1.2.1.2). The initial OMS gimbals angles required to point the OMS engines parallel to each other and with a net thrust vector through the vehicle cg are calculated by OMS_PRETHRUST_DIRECTION for use by the TVC DAP. Implementation of OMS_PRETHRUST_DIRECTION is TBD.

1.3.4.1.2.1.4 Automatic Attitude Maneuver Service Routines. - ATTITUDE_MANEUVER and VECPOINT use the service routines described below. Their input-output requirements are listed in Table 1.3.4.1.2.1-3.

(1) ANGLES_TO_DCM

This procedure converts three gimbals angles, $[\phi]$, to a direction cosine matrix, \hat{C}^* , that relates the corresponding spacecraft axes orientation to the stable-member frame.

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Table 1.3.4.1.2.1-3. Input-output requirements for automatic maneuver service routines.

Category	Name of Variable or Constant		Description of Variables or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to ANGLS_TO_DCM	[GA]	[ϕ]	Set of gimbal angles	rad	$-\pi < x \leq \pi$	TBD
Outputs of ANGLS_TO_DCM	* C	* C	Direction cosine matrix relating spacecraft axes to stable member axes	(none)	TBD	TBD
Inputs to DCM_TO_ANGLES	* C	* C	Direction cosine matrix relating spacecraft axes to stable member axes	(none)	TBD	TBD
	PI	π	π	(none)	π	TBD
Outputs of DCM_TO_ANGLES	[GA]	[ϕ]	Set of gimbal angles	rad	$-\pi < x \leq \pi$	TBD

Table 1.3.4.1.2.1-3. Input-output requirements for automatic maneuver service routines (Cont.).

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Category	Name of Variable or Constant		Description of Variables or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to ROTATION_MATRIX	A	A	Angle of rotation	rad	$0 \leq x \leq \pi$	TBD
	\vec{U}_R	\vec{u}_r	Unit vector about which rotation occurs	(none)	$ \vec{u}_r = 1$	TBD
	ID_MATRIX [*]	$I_{identity}^*$	(3x3) identity matrix	(none)	0, 1	TBD
Outputs of ROTATION_MATRIX	\vec{R}	\vec{R}	Formal parameter, rotation matrix	(none)	TBD	TBD

(2) DCM_TO_ANGLES

This procedure extracts the gimbal angles from a direction-cosine matrix, $\overset{*}{C}$, that relates the spacecraft coordinates to the stable-member coordinates.

(3) ROTATION_MATRIX

This procedure computes the direction-cosine matrix, $\overset{*}{R}$, that relates one coordinate frame to another which is rotated with respect to the first by an angle A about a unit vector \underline{u}_r .

1.3.4.1.2.1.5 Automatic Rate Drivers. - The automatic rate drivers are initiated by the automatic tracking routines.

(1) SM_RATE_ANGLE_DRIVE

SM_RATE_ANGLE_DRIVE supplies commands to the RCS DAP to rotate the vehicle about a desired angular velocity vector in stable member coordinates. Before initiating SM_RATE_ANGLE_DRIVE the attitude of the vehicle must lie within the deadband of the RCS DAP. The input-output requirements for SM_RATE_ANGLE_DRIVE are listed in Table 1.3.4.1.2.1-4.

(2) BODY_RATE_ANGLE_DRIVE

BODY_RATE_ANGLE_DRIVE supplies commands to the RCS DAP to rotate the vehicle about a desired angular velocity vector in body coordinates. Before initiating BODY_RATE_ANGLE_DRIVE the attitude of the vehicle must lie within the deadband of the RCS DAP. The input-output requirements for BODY_RATE_ANGLE_DRIVE are listed in Table 1.3.4.1.2.1-5.

(3) Transformation Matrix from Gimbal Axes to Vehicle Axes (COMPMPGA)

COMPMPGA is a service routine used by BODY_RATE_ANGLE_DRIVE to compute the transformation matrix from gimbal angle rates to body angle rates.

1.3.4.1.2.1.6 Automatic Tracking

1.3.4.1.2.1.6.1 Tracking a Specified Target with a Specified Body Axis with Variable Attitude Control about the Specified Body Axis. - This mode will be used for tracking targets

of interest such as another vehicle, a celestial body, or an arbitrary inertial vector. The body tracking axis shall be identified as a

Table 1.3.4.1.2.1-4. Input-output requirements for SM_RATE_ANGLE_DRIVE.

Category	Name of Variable or Constant		Description of Variables or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to SM_RATE_ANGLE_DRIVE	[GA_INITIAL]	$[\phi_I]$	Set of initial gimbal angles	rad	$-\pi < x \leq \pi$	TBD
	SM_RATE	$\omega_{D(SM)}$	Desired angular velocity vector in stable member coordinates	rad/s	$x < 0.034$	TBD
Outputs of SM_RATE_ANGLE_DRIVE	BODY_RATE	$\omega_{D(BA)}$	Desired angular velocity vector in body coordinates	rad/s	$x < 0.034$	TBD

Table 1.3.4.1.2.1-5. Input-output requirements for BODY_RATE_ANGLE_DRIVE.

Category	Name of Variable or Constant		Description of Variables or Constants	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to BODY_RATE_ ANGLE_DRIVE	[GA_INITIAL]	$[\phi_I]$	Set of initial gimbal angles	rad	$-\pi < x \leq \pi$	TBD
	BODY_RATE	$\omega_{D(BA)}$	Desired angular velocity vector in body coordinates	rad/s	$x < 0.034$	TBD
	FAST_DFCS_FLAG2	t_{fast}	Period of the RCS DAP cycle	s	0.04	TBD
Outputs of BODY_RATE_ ANGLE_DRIVE	[GA_DESIRED]	$[\phi_D]$	Set of intermediate desired gimbal angles	rad	$-\pi < x \leq \pi$	TBD
	[DELTA_GA]	$[\Delta\phi_D]$	Set of incremental gimbal angles	rad	TBD	TBD
	BIAS_BETA	β_{BIAS}	Set of bias body angles	rad	(0,0,0)	TBD
	BODY_RATE	$\omega_{D(BA)}$	Desired angular velocity vector in body coordinates	rad/s	$x < 0.034$	TBD

principal vehicle axis, a tracking sensor, or as an arbitrary vehicle axis. An arbitrary vehicle axis shall be identified with the angles γ and ρ as shown in Figure 1.3.4.1.2.1-2. Attitude control about the tracking axis shall be:

- (1) Free, in which case no control is exercised.
- (2) Hold, in which case the attitude pertaining at the end of the acquisition maneuver is maintained within the bounds of the deadband.
- (3) Rate Command, in which case the vehicle is rotated at a specified rate, ω , about the tracking axis.

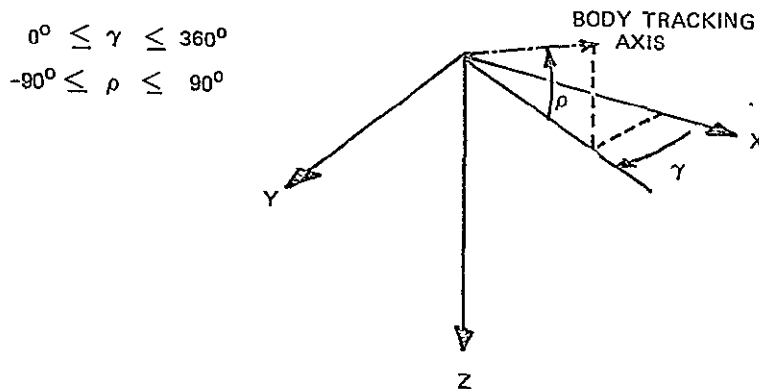


Figure 1.3.4.1.2.1-2. Arbitrary vehicle tracking axis.

If the Hold option has been selected and if the tracking axis is a principal vehicle axis, the manual discrete rate rotational submode is operable about that axis.

The barbecue (solar heat distribution) modes are examples of the Rate Command option. In the local vertical barbecue mode, the X axis of the vehicle is maintained perpendicular to the local vertical and to the sun line; in the inertial barbecue mode, the X axis of the vehicle is held in alignment with an inertial vector. In either mode, the vehicle is rotated in roll at a specified rate.

1.3.4.1.2.1.6.2 Tracking a Specified Target with a Specified Body Axis and Maintain a Specified Attitude about the Specified Body Axis. - This mode will be used for tracking targets of interest such as another vehicle, a star, a planet, or an arbitrary inertial vector. The vehicle tracking axis will be identified by the angles γ , ρ and θ where γ and ρ are defined as in the previous subsection

and θ is defined as the positive sensed angle between planes A and B. Plane A is defined by the negative orbital angular momentum vector, $-H$, and the line of sight. Plane B is defined by the body $+Y$ axis and the line of sight (see Figure 1.3.4.1.2.1-3). This definition of θ precludes the alignment of the line of sight with either the body Y axis or the momentum vector.

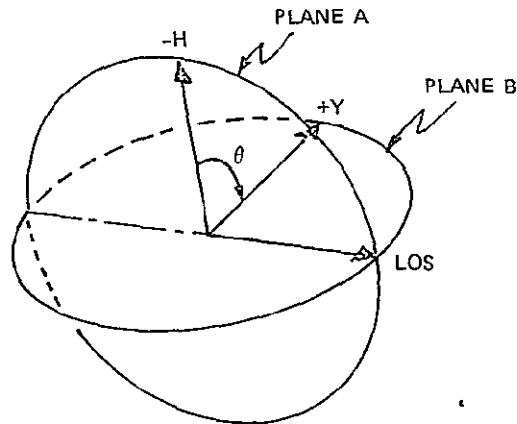


Figure 1.3.4.1.2.1-3. Definition of θ for 3-axis tracking.

1.3.4.1.2.1.7 Pointing. - To be determined.

1.3.4.1.2.1.8 Payload Supplied Commands. - To be determined.

1.3.4.1.2.2 Translation. - Automatic $\pm X$ and $\pm Z$ thrust commands are responded to in the automatic mode. The automatic translation driver produces appropriate translation commands for the Jet Selection Logic, which responds by commanding jets on to produce a thrust in the desired axis or axes. The $\pm Y$ rate change is held below a limiting value. Implementation of this driver is TBD.

1.3.4.2 TVC DAP Drivers

1.3.4.2.1 Manually Commanded TVC DAP Driver. - The manual TVC DAP driver will interface the Rotational Hand Controller (RHC) signal to the TVC DAP. When manual TVC is selected, the response to a deflection of the RHC will be an angular rate proportional to the amount of RHC deflection. Implementation of the manual TVC DAP driver is TBD.

1.3.4.2.2 Automatically Commanded TVC DAP Driver. - The auto TVC DAP driver will interface commands from the Guidance module to the TVC DAP. Implementation of the auto TVC DAP driver is TBD.

1.4 OMS/RCS Failure Detection and Identification

The OMS and RCS failure detection and identification (FDI) function is divided into three subfunctions:

- (1) OMS engine FDI.
- (2) OMS actuator FDI.
- (3) RCS jet FDI.

These are described in Subsections 1.4.1 through 1.4.3 respectively.

1.4.1 OMS Engine FDI

The purpose of the OMS engine FDI procedure, OMS_ENGINE_FDI, is to detect and identify off-nominal thrust performance of the OMS engines. The following qualifications apply:

- (1) OMS_ENGINE_FDI provides the capability for detecting and identifying hard failures only; i.e., full-off or full-on failures.
 - (a) A full-off failure is defined as the case in which an engine is providing essentially zero thrust when commanded on.
 - (b) A full-on failure is defined as the case in which an engine is providing essentially full thrust when commanded off.
- (2) OMS_ENGINE_FDI detects and identifies failures of a single engine or failures of both engines whether simultaneous or not.
- (3) Both engine thrust vectors are assumed to be aligned in the xz plane so as to yield zero net torque on the vehicle whenever OMS_ENGINE_FDI is being called.
- (4) It is further assumed that RCS jet firings are inhibited until the failed engine is identified.

OMS_ENGINE_FDI has as inputs the following quantities:

- (1) The IMU-measured accumulated vehicle velocity change since the beginning of the OMS burn.
- (2) The roll angular disturbance acceleration estimate from the state estimator.

(3) The OMS engine ON/OFF commands.

(4) An initialization flag.

The outputs of OMS_ENGINE_FDI are two failure flags indicating the status of the OMS engines. The FDI executive program displays the status of the OMS engines to the crew and, if either failure flag is on, sends a signal to the FC module for automatic reconfiguration of the TVC DAP control mode and of the state estimator. The inputs and outputs of OMS_ENGINE_FDI are listed in Table 1.4.1-1.

Table 1.4.1-1. Input-output requirements for OMS_ENGINE_FDI.

Category	Name of Variable or Constant		Description of Variable or Constant	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs	ACCUM_DELTA_V	Δv_n	Accumulated vehicle velocity change since the beginning of the OMS burn	ft/s	TBD	25
	ROLL_DISTURB_ACCEL	$\hat{\alpha}_{d_r}$	Roll angular disturbance acceleration estimate	rad/s ²	TBD	25
	OMS1_ON_CMD	OMS1_ON_CMD	OMS engine #1 ON/OFF command	(None)	ON/OFF	25
	OMS2_ON_CMD	OMS2_ON_CMD	OMS engine #2 ON/OFF command	(None)	ON/OFF	25
	OMSE_INIT_FLAG	OMSE_INIT_FLAG	Initialization flag	(None)	ON/OFF	1
Outputs	OMS1_FAIL	OMS1_FAIL	OMS engine #1 failure flag	(None)	ON/OFF	25
	OMS2_FAIL	OMS2_FAIL	OMS engine #2 failure flag	(None)	ON/OFF	25

The logic used in OMS_ENGINE_FDI is fairly simple. The procedure is called once every second, and the increment in the accumulated velocity over the interval since the last call to the procedure is checked to determine whether two, one, or no engines are firing. If it is determined that two or no engines are firing, then the failure flags are set (by separate rules) according to the engine ON/OFF commands. If it is determined that one engine is firing, then the magnitude and sign of the

roll disturbance acceleration is checked. If it is outside a deadband, then the failure flags are set by rules according to the sign of the roll disturbing acceleration and the engine ON/OFF commands. If the disturbing acceleration is within the deadband, the failure flags are left at their present values.

1.4.2 OMS Actuator FDI

The purpose of the OMS actuator FDI procedure, OMS_ACTUATOR_FDI, is to detect and identify off-nominal performance of the pitch and yaw gimbals of the OMS engines. The following qualifications apply:

- (1) OMS_ACTUATOR_FDI provides capability for directly detecting and identifying full-off failures only. Full-on failures are indirectly detected and identified as described below.
 - (a) A full-off failure is defined as the case in which the actuator output screw is not extending or retracting when commanded to do so.
 - (b) A full-on failure is defined as the case in which the actuator output screw continues extending or retracting when commanded to reverse direction or stop.
- (2) Based on results presented in Reference 1.4.2-1 an unfailed OMS gimbal actuator is assumed to respond to a command (i.e., an applied voltage) and attain a steady-state nominal deflection rate within one minor cycle time (40 ms).
- (3) The accuracy of the OMS actuator output position transducer is assumed to be adequate to permit the use of estimates of gimbal deflection rate to detect and identify full-off failures with zero probability of a false alarm.
- (4) OMS_ACTUATOR_FDI is not designed to detect and identify failures downstream of the actuator output; i.e., in the gimbal mounting structure. Depending upon the exact nature of such a failure, indirect detection may be possible.

It should be noted that since inputs for performance monitoring of the four actuators are made available and processed for each actuator separately, the failure detection and identification problem reduces to one of detection only.

OMS_ACTUATOR_FDI has as inputs the following quantities:

- (1) The OMS engine gimbals deflection for each actuator as measured by the actuator output position transducer, a linear voltage differential transformer (LVDT).*
- (2) The OMS engine gimbals deflection error for each actuator as calculated by the TVC DAP.
- (3) A procedure call counter.
- (4) An initialization flag.

The outputs of OMS_ACTUATOR_FDI are:

- (1) A failure flag for each actuator.
- (2) An indicator for each actuator which specifies whether that actuator is being commanded to extend, retract, or remain immobile.

The FDI executive program displays the status of the actuators to the crew which may elect to initiate reconfiguration of a failed actuator via manual command. The inputs and outputs of OMS_ACTUATOR_FDI are listed in Table 1.4.2-1.

A simplified block diagram of an OMS gimbal actuator servo loop is shown in Figure 1.4.2-1. The gimbal deflection command is differenced with the measured gimbal deflection to obtain the gimbal deflection error. The deflection error is then supplied to the servo amplifier, a bang-bang amplifier with deadzone and hysteresis. The output of the servo amplifier is the actuator input voltage which drives the actuator motor. An LVDT position transducer senses the actuator output extension and its gain is adjusted to give 1° of gimbal deflection for 1° of command. If the absolute value of the gimbal deflection error is greater than e_g (0.4°), then the actuator should be either extending or retracting.

The logic of OMS_ACTUATOR_FDI is as follows.

- (1) Once every second the procedure is called with OMSA_CALL_COUNTER=1. On this first pass, the gimbal deflection error of each actuator is checked. The extension indicator for

* The actuator extension length rather than the OMS gimbal angle itself is the sensed quantity.

that actuator is set to -1, 0, or 1 according to whether the actuator is being commanded to retract, remain immobile, or extend.*

Table 1.4.2-1. Input-output requirements for OMS_ACTUATOR_FDI.

Category	Name of Variable or Constant		Description of Variable or Constant	Units	Value or Range	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs	[OMS_GIMBAL]	$[\delta]$	OMS engine gimbal deflections	rad	$-0.123 < x < 0.123$	25
	[OMS_GIMBAL_ERROR]	$[\delta_e]$	OMS engine gimbal deflection errors	rad	TBD	25
	OMSA_CALL_COUNTER	OMSA_CALL_COUNTER	Procedure call counter	(None)	$0 < x < 3$	1
	OMSA_INIT_FLAG	OMSA_INIT_FLAG	Initialization flag	(None)	ON/OFF	1
Outputs	[OMS_ACTUATOR_FAIL]	[OMS_ACTUATOR_FAIL]	OMS actuator failure flags	(None)	ON/OFF	25
	[OMS_ACTUATOR_EXTEND]	[OMS_ACTUATOR_EXTEND]	OMS actuator extension indicators	(None)	-1, 0, 1	1

- (2) If any actuator extension indicator is nonzero, the FDI execution program calls OMS_ACTUATOR_FDI a second time with OMS_CALL_COUNTER=2 one minor cycle (40 ms) after the first call. On this pass, the nonzero actuator extension indicators are recomputed. If the second-pass value is the same as the first-pass value, the gimbal deflection is recorded; otherwise the actuator extension indicator is set to zero.
- (3) If any actuator extension indicator is still nonzero, the FDI executive program calls OMS_ACTUATOR_FDI a third time with OMS_CALL_COUNTER=3 one minor cycle after the second call. On this pass, nonzero actuator extension indicators

The gimbal deflection error supplied to OMS_ACTUATOR_FDI should be equal to the last value sent to the servo amplifier, even if it has changed in the interim.

are recomputed once more and if still unchanged, the gimbal deflection is recorded again. Finally, if the measured gimbal deflection increment is below a certain threshold, a failure counter is incremented.

- (4) The actuator failure flag is set to ON if the counter reaches 2.

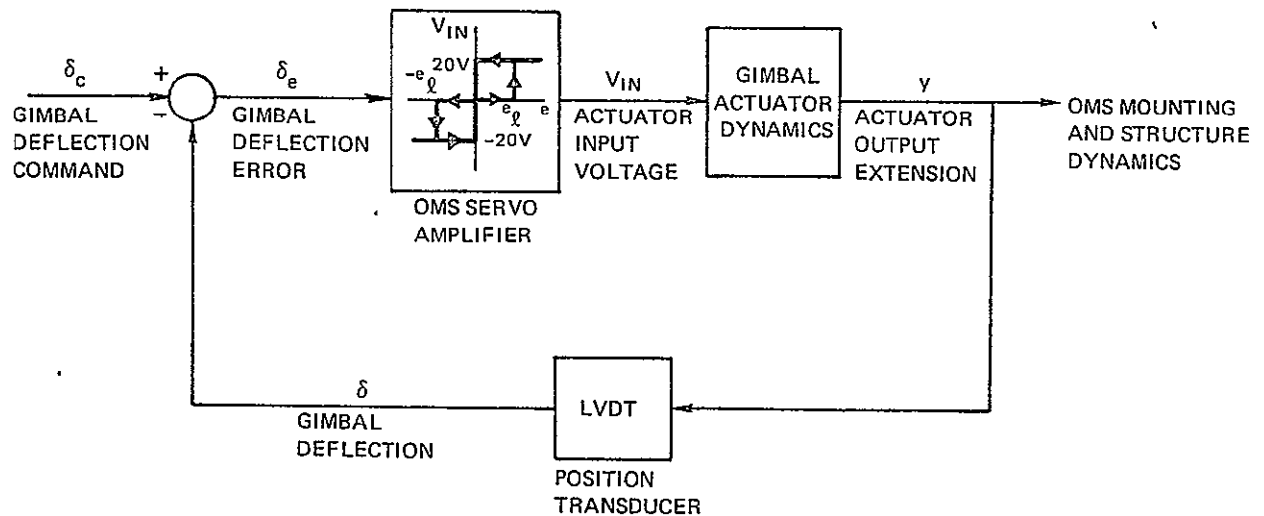


Figure 1.4.2-1. Simplified block diagram of OMS gimbal actuator servo loop.

In summary, if any actuator is being commanded to extend or retract continuously for three successive minor cycles, then the measured increment in the gimbal deflection is compared to a threshold deflection to test the actuator performance. Two successive failure indications (one second apart) are necessary before an actuator fail flag is set to ON. If the gimbal deflection error of any actuator is inside the deadzone on the first pass or moves into or through the deadzone after the first pass, no gimbal deflection increment threshold test is performed during that second, either because the actuator is not being commanded to extend or retract for three successive minor cycles or because such behavior is an indication of nominal actuator performance.

It is assumed that the error in the measured gimbal deflection increment (i.e., deflection rate) is small enough so that:

- (1) An actuator which has experienced a full-off failure and is not moving has zero probability of passing the threshold test.
- (2) An actuator which is performing nominally has zero probability of failing the threshold test.

OMS_ACTUATOR_FDI is specifically designed to detect full-off failures by the nature of the threshold test. That is, if during the checks the command is or changes to "do not move" or if the command is to reverse direction, no test on the gimbal deflection increment will be made. However, if a full-on failure occurs, then eventually the gimbal deflection error will remain outside the servo amplifier deadzone, and threshold tests will occur resulting in failure indications. How long it takes the error to stabilize outside the deadzone depends upon how long it takes the OMS TVC autopilot loop to sense that the engine is not pointing in the desired direction and subsequently change the deflection command appreciably. Consequently one would expect full-on failures to take longer to detect than full-off failures.

An OMS actuator FDI scheme which checks the gimbal deflection error only at periodic intervals would of course be much simpler. However, such a scheme would be undesirable for two reasons. First, the probability of false alarms could become quite large. The reason for this is that on several successive checks, the gimbal deflection error could be quite large due to changes in the gimbal deflection command just before the check is made, whereas the actuator might be performing nominally at all times. The obvious modification to reduce the probability of false alarms would be to raise the threshold level on the deflection error check. But the higher the threshold level, the lower the probability of detecting a failure. Eliminating false alarms could mean eliminating failure detection. Secondly, if the threshold level for the deflection error check were at all larger than the deadzone size of the servo amplifier, an actuator which had experienced a full-off failure could pass the test several times until the error increased enough to cross the threshold level. A detection time penalty is the net result. OMS_ACTUATOR_FDI is designed to eliminate both of the above problems.

1.4.3 RCS Jet FDI

RCS jet failures can occur in any of three forms:

- (1) Full ON failure.
- (2) Leak.
- (3) OFF failure.

A full ON failure is one in which the jet is ON at full thrust, and does not respond to OFF commands. A leak may result from the fuel valve and/or the oxidizer valve jamming open, or a crack in one of the lines. An OFF failure occurs when the fuel and/or oxidizer valves do not respond to ON commands.

The jet FDI compares the jet commands with pressure sensor outputs, leak detector outputs, and jet driver talkbacks. Discrepancies in these outputs are taken as failure indications, and appropriate action is taken.

If a jet is failed OFF for three successive minor cycles, the routine OFFFAIL sends a flag indicating that the jet has failed to the Jet Selection routine.

If a jet is failed ON for two successive major cycles, the routine ONFAIL sends a flag to the Jet Selection routine indicating that the jet has failed. The jet select then defaults the jet command to OFF. The jet is rechecked three cycles later. In the event that the jet is still ON, the valves to its fuel/oxidizer manifold are closed, and all jets on that manifold are flagged as failed.

The Jet Selection routine uses the jet failure data to avoid trying to use failed jets for maneuvering. The crew or ground controllers can check the jet fail status by displaying the appropriate failure words and noting whether bits are ON or OFF. To reenable a jet after failure, the crew must set the appropriate bit of the failure word OFF. The manifold valves are available for the crew to reopen.

Input-output requirements for the routines ONFAIL and OFFFAIL are given in Tables 1.4.3-1 and 1.4.3-2 respectively.

1.5 Remote Manipulator System

To be determined.

Table 1.4.3-1. Input-output requirements for ONFAIL.

Category	Name of Variable or Constant		Description of Variable or Constant	Units	Value	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to ONFAIL	DRIVERA DRIVERB DRIVERC DRIVERD DRIVERE DRIVERF	Same	Driver talkback words	(None)	ON/OFF	25
	JETCOMA JETCOMB JETCOMC JETCOMD JETCOME JETCOMF					
Outputs of ONFAIL	MANIFOLDOFFCOM	Same	Manifold shutdown commands	(None)	ON/OFF	25
	JFAILA JFAILB JFAILC JFAILD JFAILE JFAILF	Same	Jet fail flags	(None)	ON/OFF	25

Table 1.4.3-2. Input-output requirements for OFFAIL.

Category	Name of variable or constant		Description of Variable or Constant	Units	Value	Sample Rate (words/s)
	Computer Notation	Mathematical Notation				
Inputs to OFFAIL	JETCOMA JETCOMB JETCOMC JETCOMD JETCOME JETCOMF	Same	Jet ON/OFF command words	(None)	ON/OFF	25
	PRESSA PRESSB PRESSC PRESSD PRESSE PRESSF					
Outputs of OFFAIL	JFAILA JFAILB JFAILC JFAILD JFAILE JFAILF	Same	Jet fail flags	(None)	ON/OFF	25

SECTION 2

SOFTWARE FORMULATION

This section contains structured flowcharts for each of the modules described in Section 1. A glossary of the symbols used appears in Section 3.

2.1 Overview

2.2 Reconfiguration Logic

2.2.1 Supervisor

A structured flowchart of the FC Reconfiguration Supervisor (OODAP_RECON) is shown in Figure 2.2.1-1. OODAP_RECON checks a variety of flags which are set by crew action via the keyboard, in the context of Major Mode and Specialist functions. The crew may also reconfigure the FC modes by means of pushbuttons on the cockpit panel. These switches are interrogated by an external program that creates packed bit words. The driver and DAP routines are invoked by OODAP_RECON as a function of the state of those inputs which have been configured by crew action.

On each FC pass, dynamic inputs are read, GP Matrix Calculation is performed, and the panel switches are checked for changes in state. If there has been a change since the last pass, PANEL_SWITCH_INTERP sets new flags and/or data values for the use of the driver(s) and DAP to be executed subsequently. Next PART1_FILTER is executed. (PART2_FILTER will follow the driver/DAP execution.)

OODAP_RECON can invoke either the TVC_DAP or RCS_DAP, but not both. The TVC_DAP and RCS_DAP can both be executed in a single pass, but only when the TVC_DAP itself invokes the RCS_DAP. If the requests for OMS arming and OMS firing have been made, then the FC program executes the TVC_DAP-related driver modules and invokes the TVC_DAP. On the first pass through the TVC mode, certain initialization steps

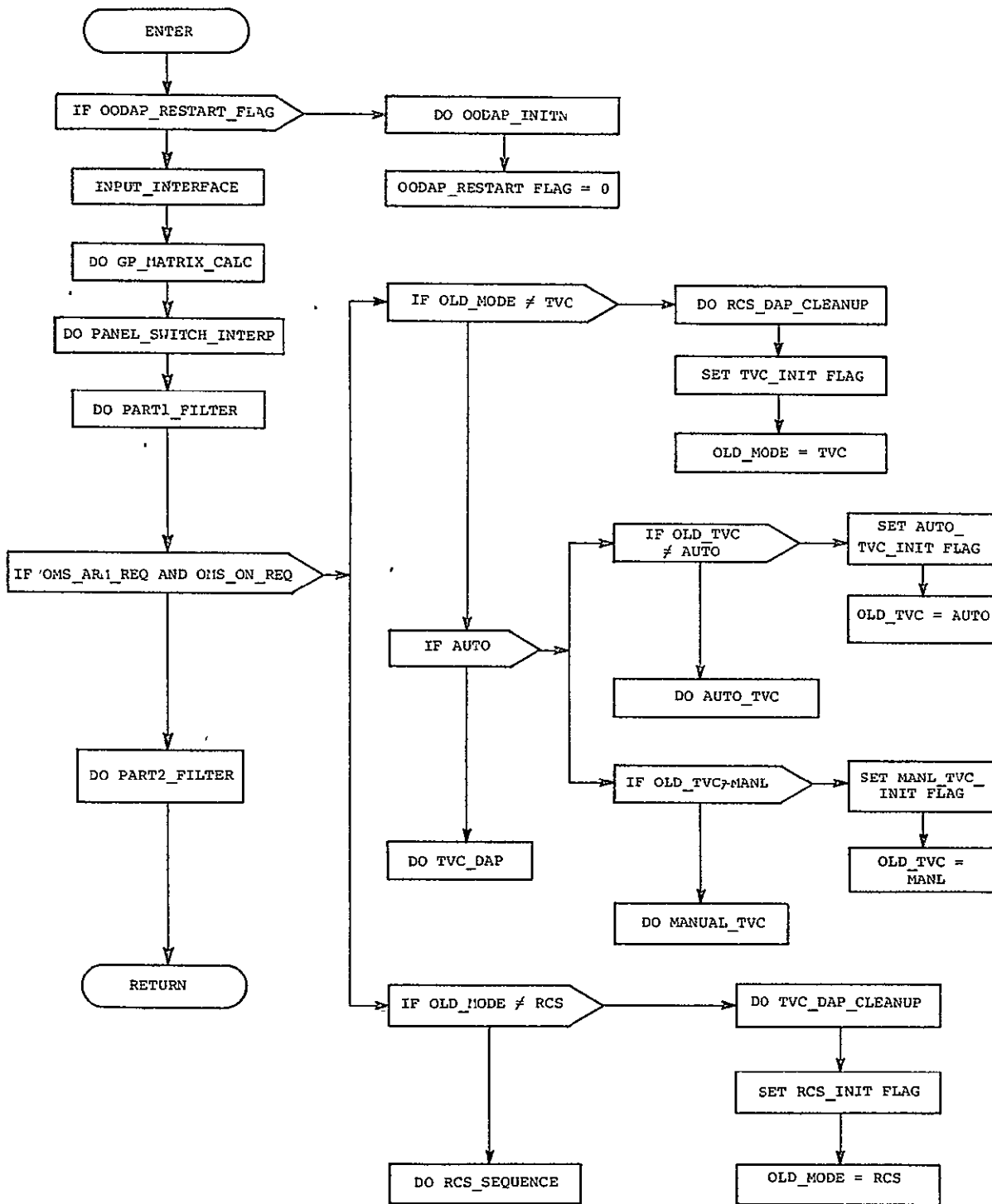


Figure 2.2.1-1. OODAP_RECON: PROCEDURE

are taken for the benefit of the drivers and the TVC_DAP. Checks are then made regarding manual and automatic modes of operation; change from one mode to the other will cause reinitialization of certain parameters for the respective drivers.

If either the OMS arm or fire request is not present, then the FC program remains in, or re-enters, the RCS control mode of operation. If a change of mode since the last pass is detected, as would occur at OMS cut-off, initialization steps are taken for the benefit of the RCS driver modules and the RCS_DAP. Then RCS_SEQUENCE (Figure 2.2.1-2) is performed. The RCS_DAP has no knowledge as to which drivers are responsible for providing its input data, nor whether it has been invoked by the TVC_DAP or by RCS_SEQUENCE directly. RCS_SEQUENCE invokes various RCS_DAP driver modules as a function of flag states which reflect crew-selected options. These options include: OMS prethrust maneuver (alignment to a desired vector of the total thrust vector of the gimbaled OMS engines through the vehicle cg), attitude control during payload handling, vehicle axis pointing options, inertial or local vertical barbecue, local vertical attitude hold, 2- and 3-axis attitude maneuvers, and manual and automatic translation maneuvers. The driver(s) necessary for performance of the selected options will be invoked by RCS_SEQUENCE as a function of the flag settings; certain options are exclusive and others are not. OMS prethrust, payload handling, barbecue and pointing are mutually exclusive and cannot be accomplished simultaneously. RCS rotation and translation may be achieved in the context of any of the other options, and will supersede the inputs of those other options when there is logical conflict between their objectives.

2.2.2 Panel Switch Interpretation

Switch discrettes enter the PANEL_SWITCH_INTERP procedure (Figure 2.2.2-1) as three half words, hence the logic is broken into three segments, one for each word. NEWORD1 is tested to see if it differs from its value on the previous pass. If so, it is checked bit-by-bit for each option. Otherwise, it is bypassed and NEWORD2 checked, and similarly for NEWORD3. Hence, if no new options have been selected, PANEL_SWITCH_INTERP is essentially bypassed.

The bit-by-bit checking is accomplished by ANDing the word with various masks and noting if the result is null. For example, the statement

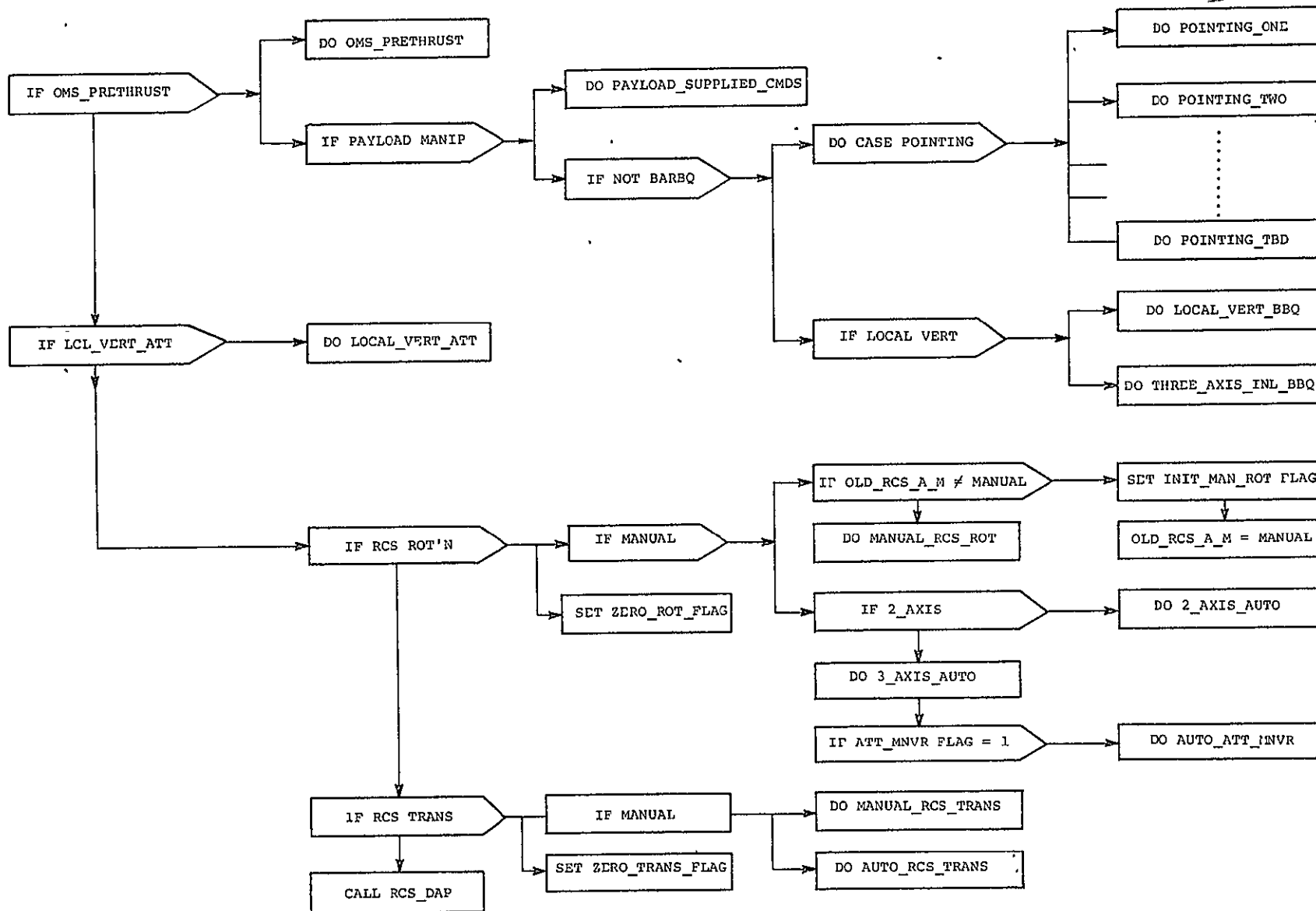


Figure 2.2.1-2. RCS_SEQUENCE: PROCEDURE.

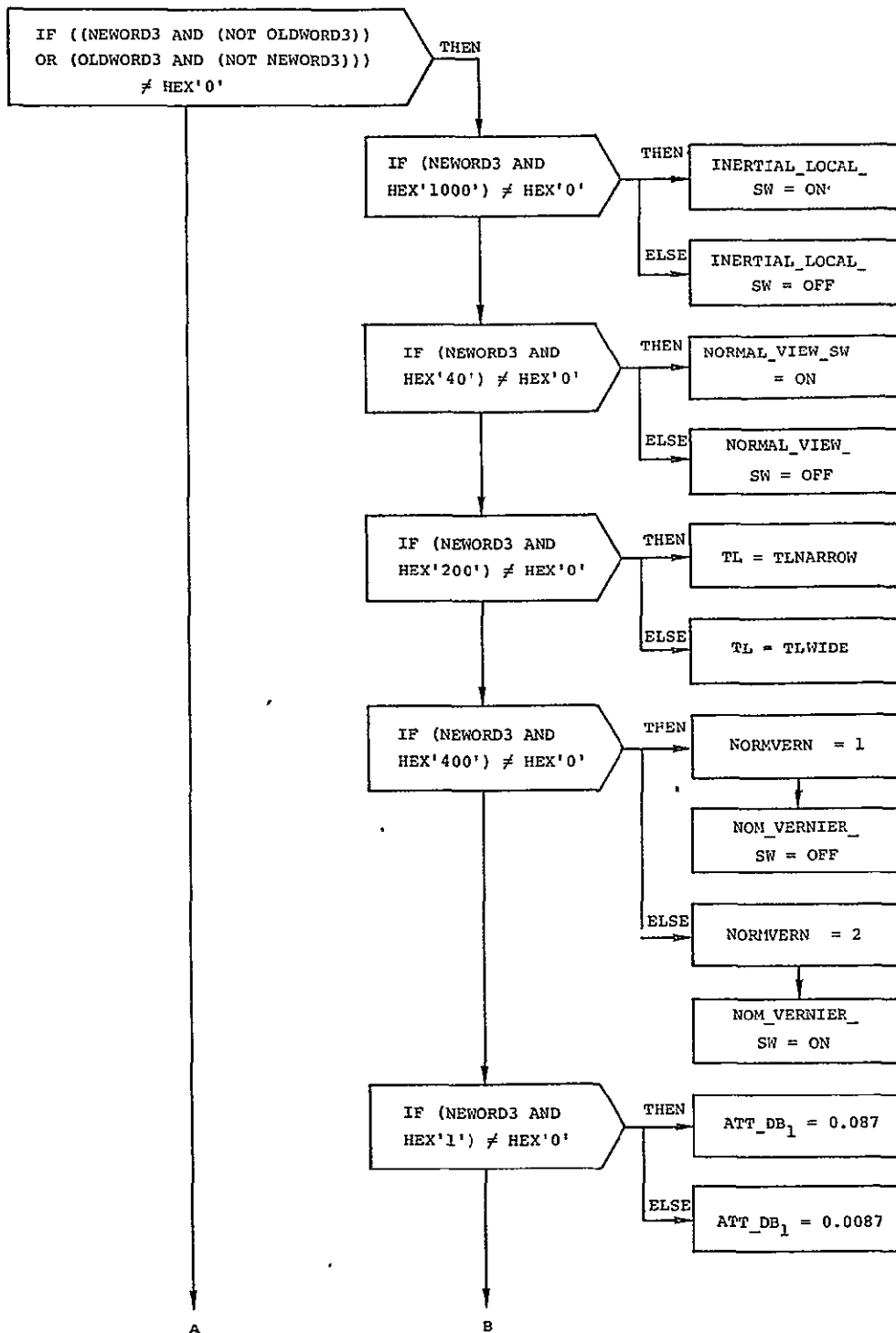


Figure 2.2.2-1. PANEL_SWITCH_INTERP: PROCEDURE.

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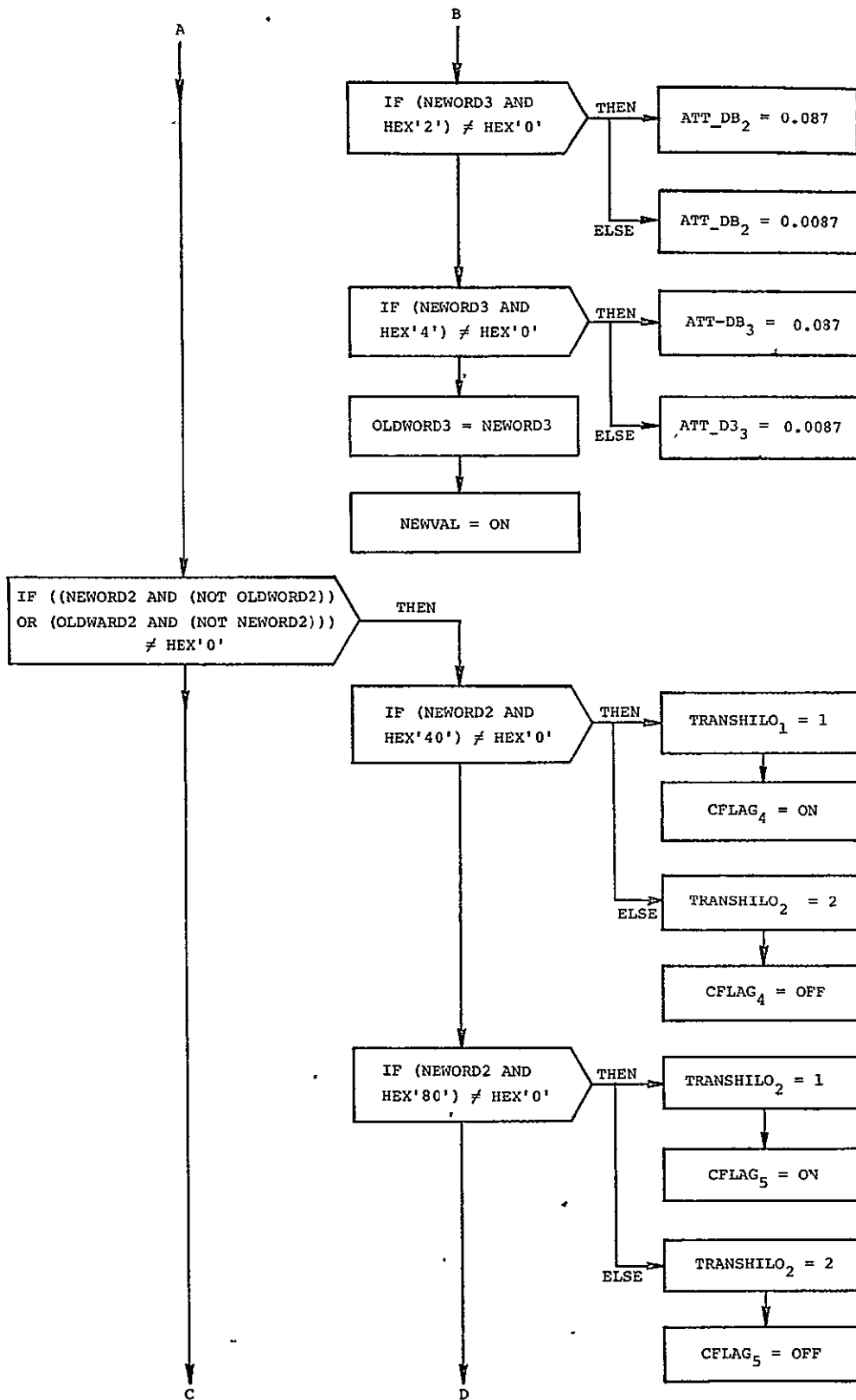


Figure 2.2.2-1. PANEL_SWITCH_INTERP: PROCEDURE (Cont.).

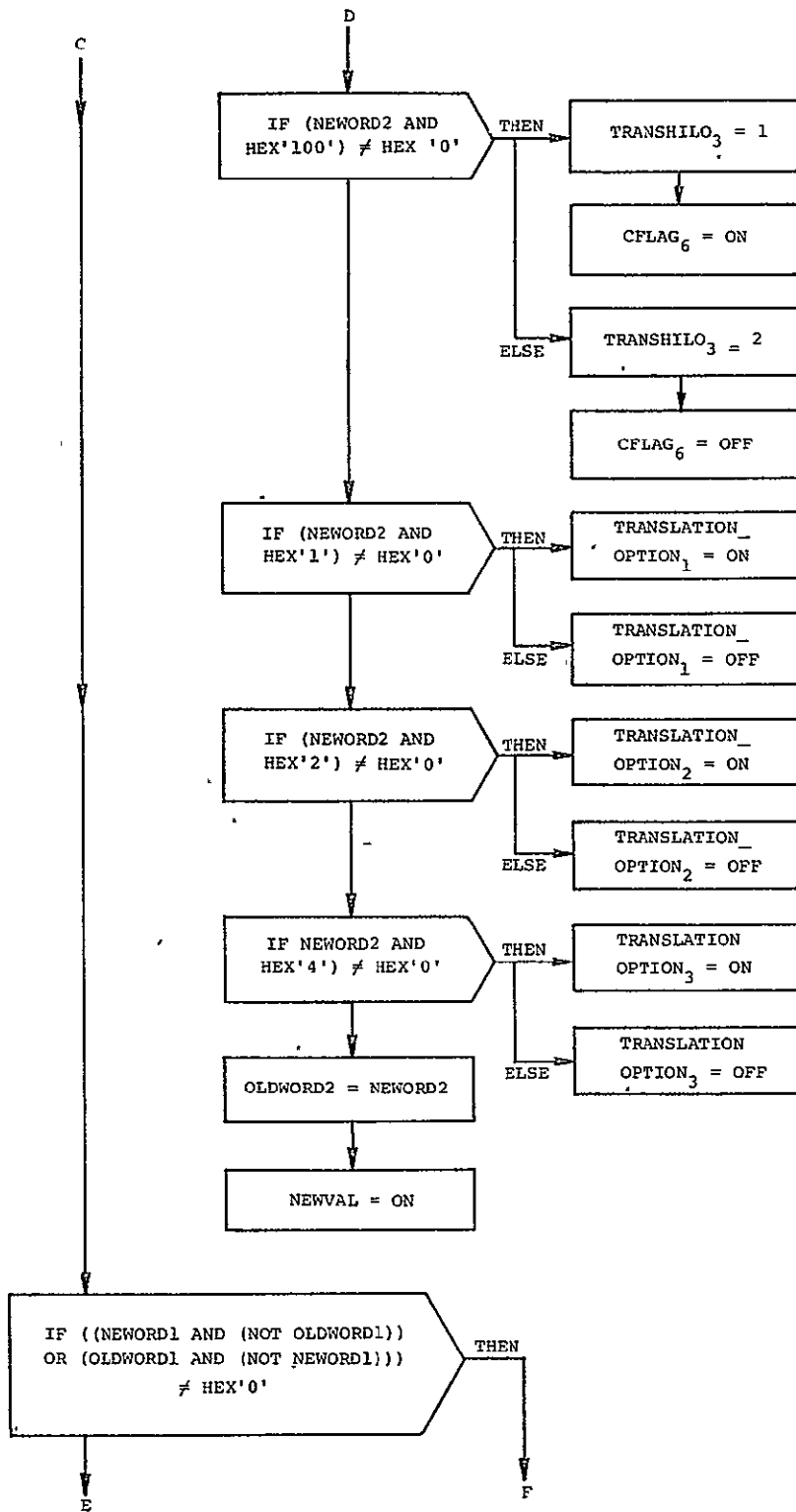


Figure 2.2.2-1. PANEL_SWITCH_INTERP: PROCEDURE (Cont.).

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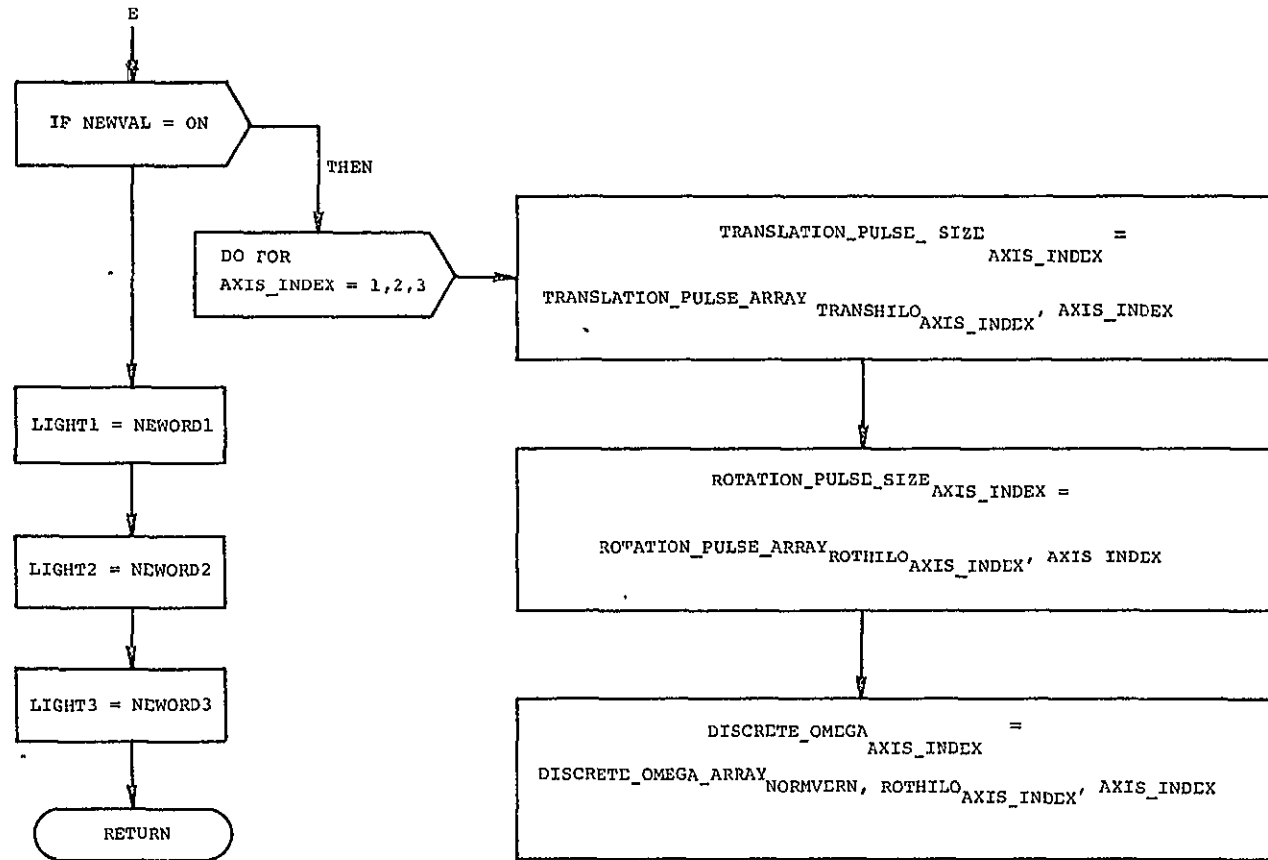


Figure 2.2.2-1. PANEL_SWITCH_INTERP: PROCEDURE (Cont.).

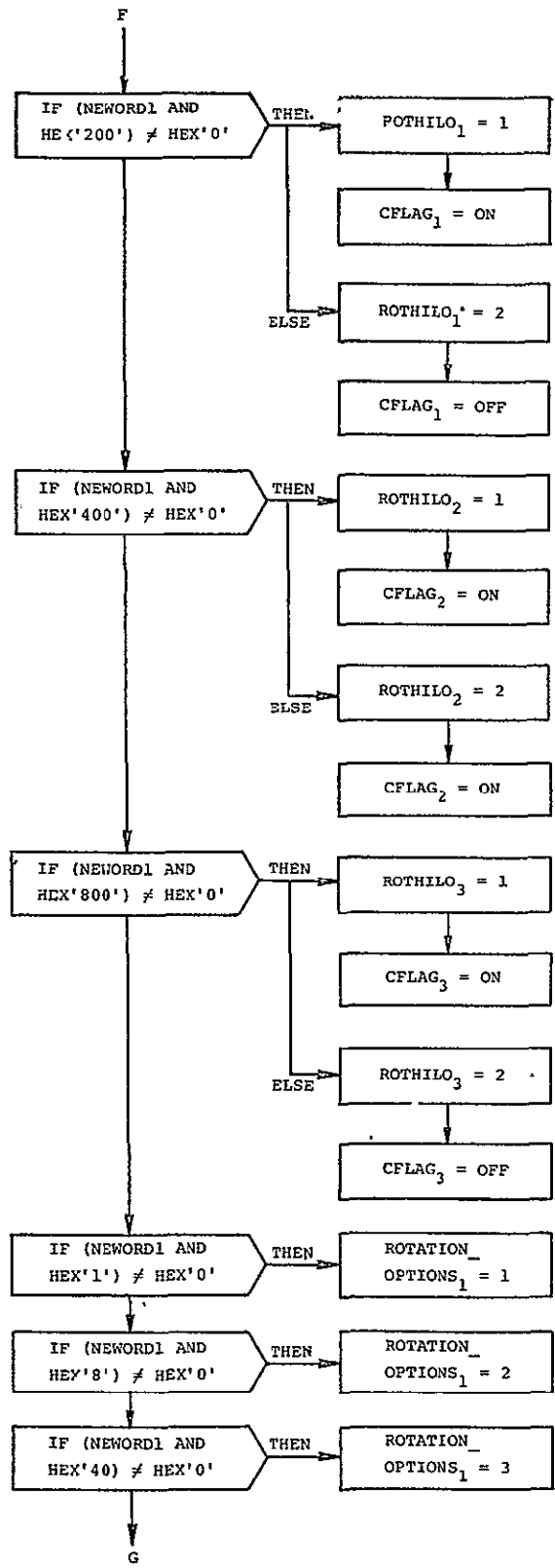


Figure 2.2.2-1. PANEL_SWITCH_INTERP: PROCEDURE (Cont.).

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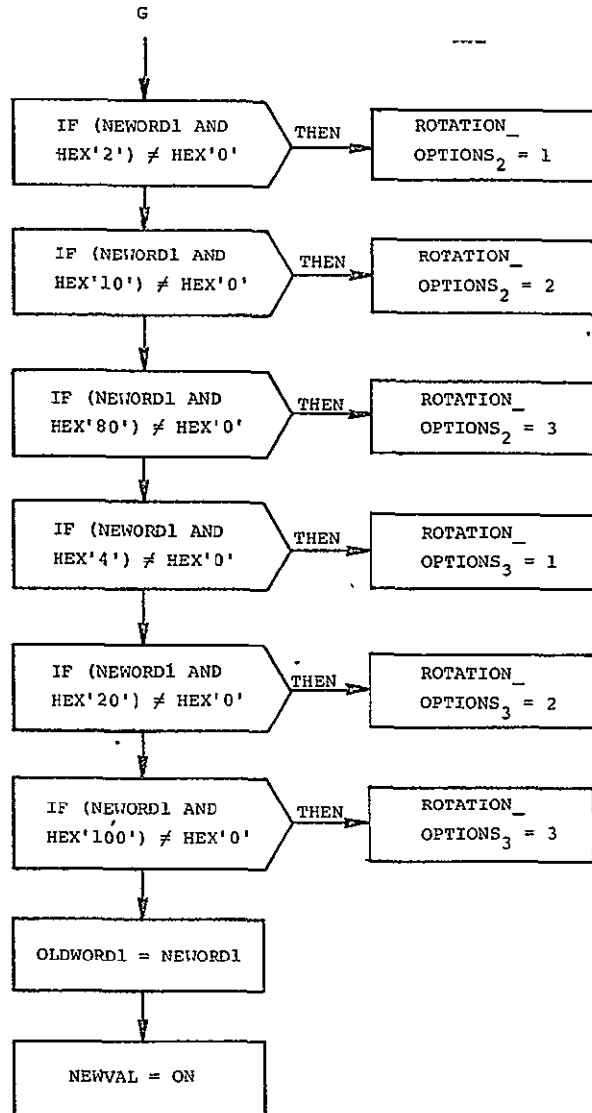


Figure 2.2.2-1. PANEL_SWITCH_INTERP: PROCEDURE (Cont.).

IF(NEWORD1 AND MASK4) NOT = MASK0

where

MASK4 = BIN'0001000000000000'

MASK0 = BIN'0000000000000000'

is true if BIT 4 of NEWORD1 is ON and false if it is OFF.

The flag INERTIAL_LOCAL_SW is set ON if the inertial axes option is selected, OFF if the local vertical option is selected. This flag is used by OODAP_RECON to determine whether to call THREE_AXIS_INTL_BBQ or LOCAL_VERT_BBQ.

The flag NORMAL_VIEW_SW is set ON if the normal axes option is selected, OFF if view axes are selected. This is used by the external SOP to determine if RHC and THC inputs from the aft station are to be phased for -x facing or -z facing operation.

Selecting the pure moment option sets the PURE_MOM_FLAG ON, causing PANEL_SWITCH_INTERP to set the off-axis compensation threshold TL used by Jet Selection to a narrow value so that off-axis drift is kept to a preset minimum. Otherwise, TL is set wide so that Jet Selection does not command compensation firings, thus conserving fuel.

The normal/vernier switches set a flag to determine if the Jet Selection uses the nominal or vernier RCS jets.

The deadband wide/narrow switches (one per rotation axis) cause selection of either wide or narrow attitude deadbands to be passed to the Phase Plane Switching Logic.

The translation high switch for each axis sets a flag which causes the routine to select the larger-valued of two sets of translation parameters (specified in Subsection 1.2.2), and to set the multiple-jet option flag CLSTRF ON for the Jet Selection routine. The translation low switch sets a flag to cause selection of the smaller-valued set of parameters, and to set CLSTRF OFF for the Jet Selection if the translation acceleration submode is in effect.

Similarly, for each rotation axis, the rotation high switch sets a flag which causes PANEL_SWITCH_INTERP to select the larger-valued of two sets of rotation parameters (specified in Subsection 1.2.2), and to set CLSTRF ON for the Jet Selection routine. The rotation low switch sets a flag to cause selection of the smaller-valued set of

parameters, and to set CLSTRF OFF for the Jet Selection if the rotation acceleration submode is in effect.

The translation submode switches set the flags TRANSLATION_OPTION which MAN_RCS_TRANS uses to determine whether the translation pulse or translation acceleration submode is in effect by axis.

Similarly, the rotation submode switches set the flags ROTATION_OPTIONS, used by MAN_RCS_ROT to determine which rotation submode is in effect by axis.

Since the actual structure of the switch panel (i.e., options, number of keys, etc.) is not fixed, the options represented by NEWORD1, NEWORD2, and NEWORD3 are subject to change. Their current configuration is shown in Table 2.2.2-1. Several of these options are mutually exclusive; i.e., the pulse command submode and the discrete rate command submode cannot coexist in the same axis. The SOP, in receiving inputs from the switch panel, cancels all inputs complementing the current inputs. PANEL_SWITCH_INTERP thus only checks one of a pair of mutually exclusive options, or all but one of several mutually exclusive options, selecting the remaining option by default if those examined are OFF. PANEL_SWITCH_INTERP generates commands to illuminate those keys reflecting the new options, except where the options may be cancelled elsewhere, as in the rotation options.

2.3 Control Laws

2.3.1 RCS/OMS Interface

The flag OMS_ON_REQ, which is set external to FC, is used with the flag OMS_ARM_REQ to cause FC to suspend execution of the RCS DAP and initiate execution of the TVC DAP. The TVC DAP monitors the OMS engine FDI for failure of one or both of the OMS engines, and invokes the RCS DAP as necessary to maintain required attitude rates in the event of OMS failures.

2.3.2 RCS DAP

2.3.2.1 Error Computation

The routine RCS_ERRORS (Figure 2.3.2.1-1) computes a number of sums and differences required for PHASE_PLANE and also transforms the gimbals angles to body angles. Body angles are defined as the integral of the body rates.

Table 2.2.2-1. Function of bits in NEWORD1, 2, 3.

Bit#	NEWORD1	NEWORD2	NEWORD3
1	DISC RATE (ROLL)	TRANS ACCEL (X)	WIDE DB (ROLL)
2	DISC RATE (PITCH)	TRANS ACCEL (Y)	WIDE DB (PITCH)
3	DISC RATE (YAW)	TRANS ACCEL (Z)	WIDE DB (YAW)
4	ROT ACCEL (ROLL)	TRANS PULSE (X)	NARROW DB (ROLL)
5	ROT ACCEL (PITCH)	TRANS PULSE (Y)	NARROW DB (PITCH)
6	ROT ACCEL (YAW)	TRANS PULSE (Z)	NARROW DB (YAW)
7	ROT PULSE (ROLL)	TRANS HIGH (X)	NORMAL AXES
8	ROT PULSE (PITCH)	TRANS HIGH (Y)	VIEW AXES
9	ROT PULSE (YAW)	TRANS HIGH (Z)	XCPL
10	ROT HIGH (ROLL)	TRANS LOW (X)	PURE MOM
11	ROT HIGH (PITCH)	TRANS LOW (Y)	NORM RCS
12	ROT HIGH (YAW)	TRANS LOW (Z)	VERN RCS
13	ROT LOW (ROLL)	NULL	INRTL
14	ROT LOW (PITCH)	NULL	LOCAL VERTEL
15	ROT LOW (YAW)	NULL	NULL
16	NULL	NULL	NULL

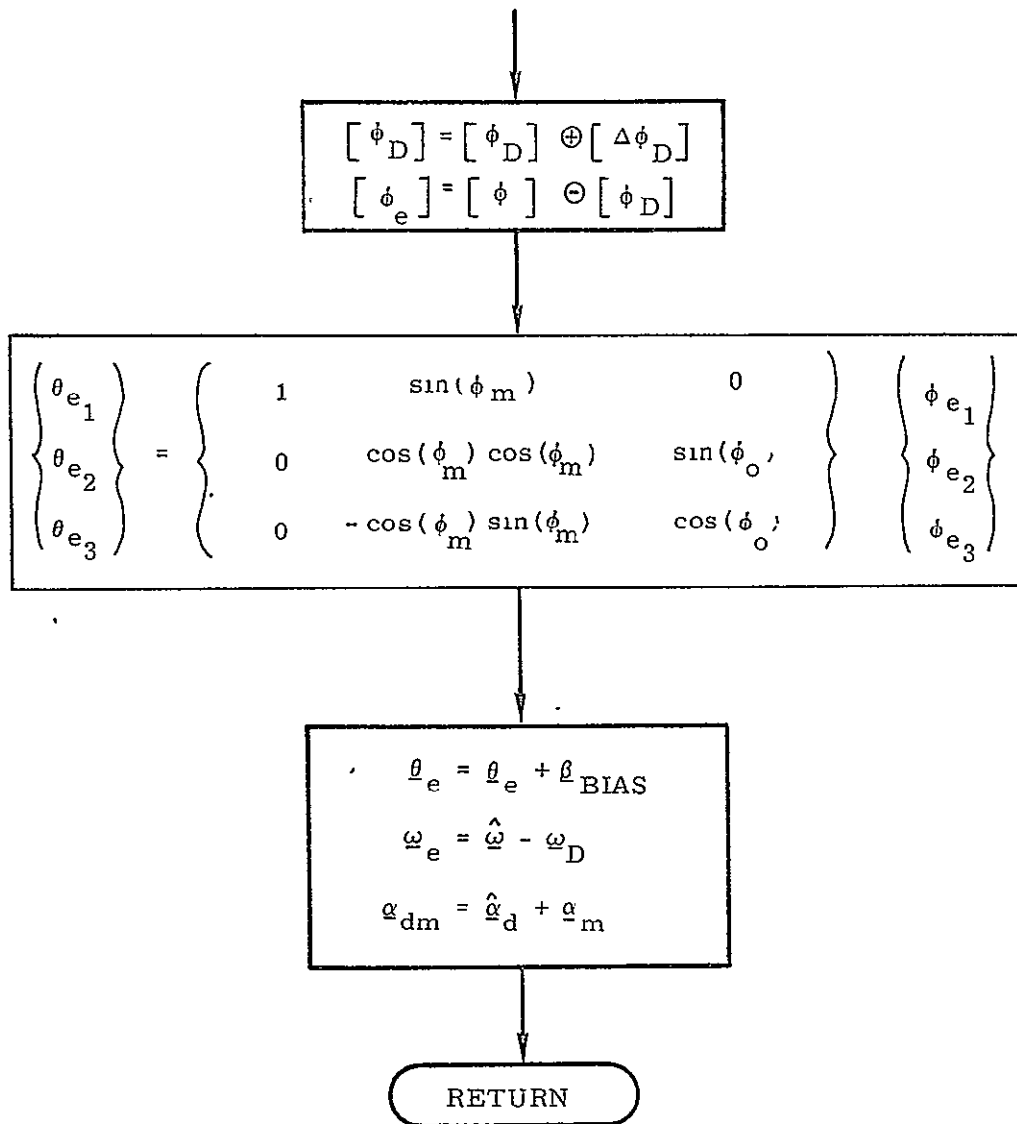


Figure 2.3.2.1-1. RCS_ERRORS: PROCEDURE.

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The attitude error, θ_e , is basically the difference between the gimbal angles, as received from the IMU, and the desired attitude. The angles, however, must be transformed to body angles as noted above.

The angular velocity error, ω_e , is computed by taking the difference between the estimated true velocity and desired velocity.

The total undesired acceleration, α_{dm} , which is passed to the Phase Plane Switch Logic for use in computing limit cycle parameters, is the sum of the estimated disturbance and modelled bias accelerations.

2.3.2.2 State Estimator

The State Estimator is processed in two steps, as described in Subsection 1.3.2.2. PART1_FILTER utilizes the extrapolated state calculated in the previous iteration of PART2_FILTER to obtain the latest filtered estimates for angular rate and angular acceleration separately by means of recursive linear filtering.

PART1_FILTER (Figure 2.3.2.2-1) is performed in two stages. The first is a transformation of gimbal angles into a set of "body angles". These body angles are defined as the integral of the body rates. The equations for $\tilde{\theta}_j(t_n)$ yield a good approximation to the body angles.

The second stage of PART1_FILTER is the measurement incorporation process. The updated estimates of the rate portion $\hat{\omega}_r$ and $\hat{\omega}_r$, and the acceleration portion $\hat{\alpha}_a$, $\hat{\omega}_a$ and $\hat{\alpha}_a$ for each axis are made here.

The equations for the extrapolation of the vehicle state to the next time cycle by PART2_FILTER are shown in Figure 2.3.2.2-2. The extrapolation takes into account the control acceleration as well as the angular disturbance acceleration.

The estimated state which is supplied to the autopilot by the State Estimator is

$$\hat{\omega}(t_n) = \hat{\omega}_r(t_n)$$

and a smoothed acceleration quantity

$$\hat{\alpha}_d(t_n) = \frac{1}{10} \sum_{i=n-9}^{i=n} \hat{\alpha}_a(t_i)$$

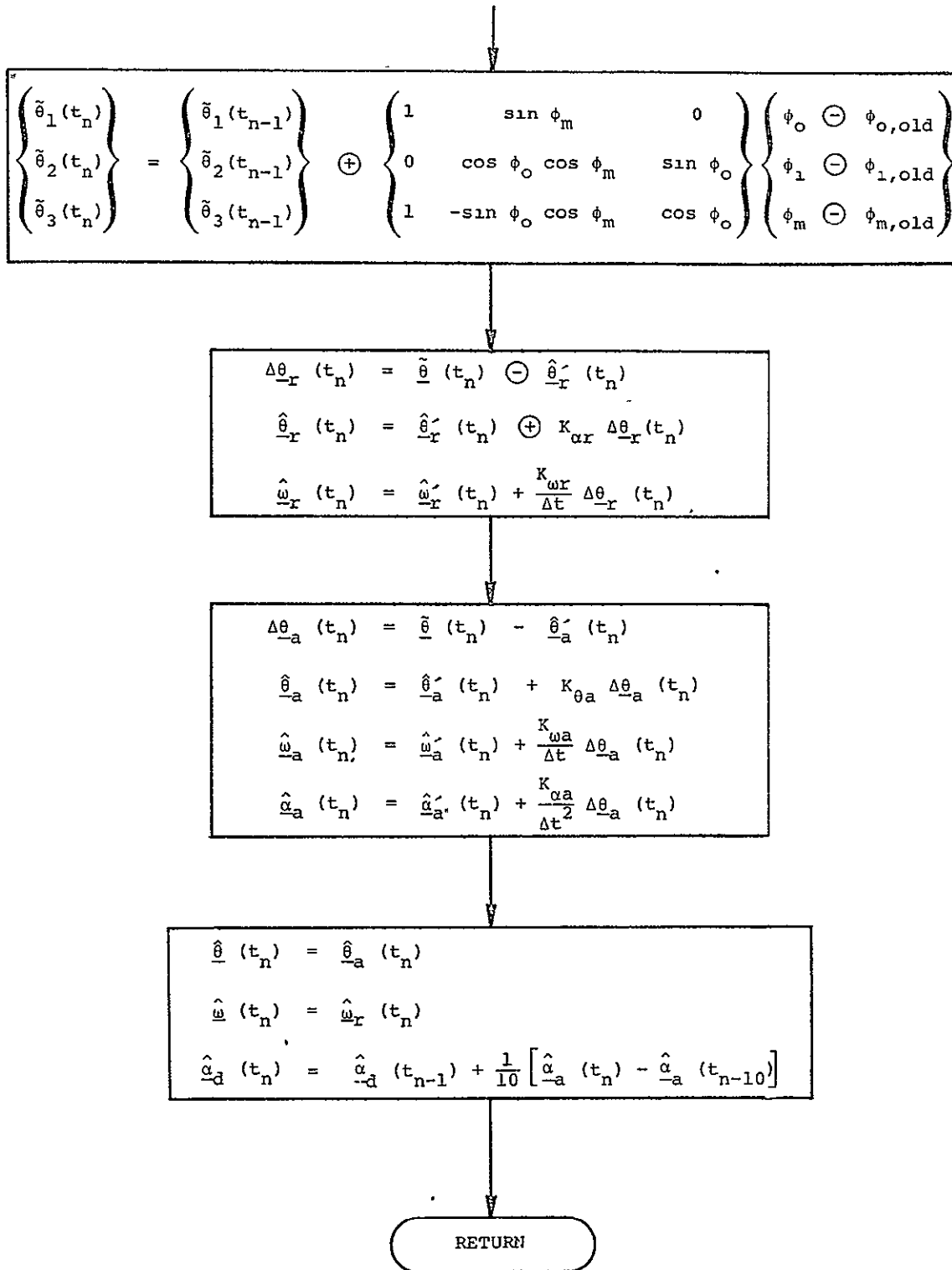


Figure 2.3.2.2-1. PART1_FILTER: PROCEDURE.

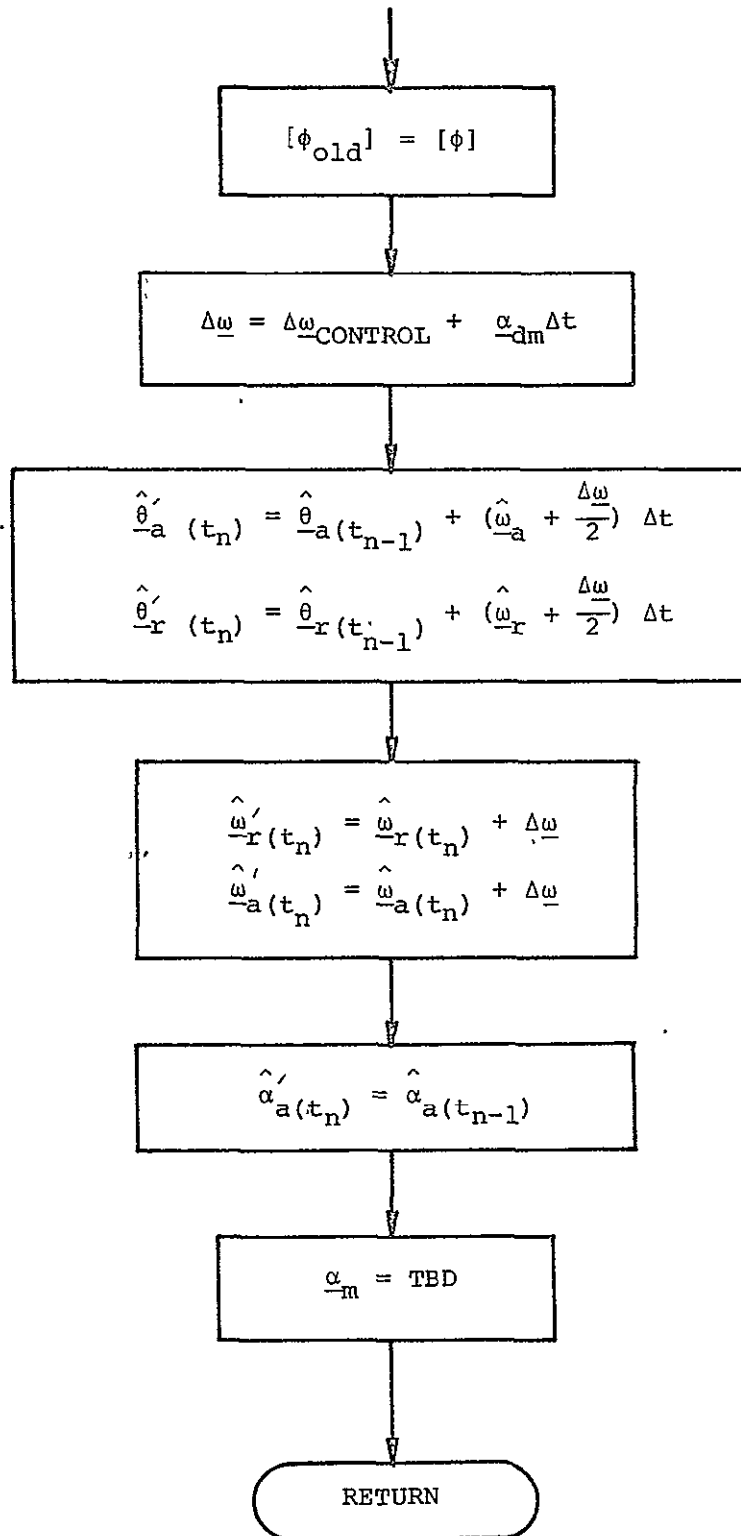


Figure 2.3.2.2-2. PART2_FILTER: PROCEDURE.

2.3.2.3 Phase Plane Switching Logic

The Phase Plane Switching Logic is implemented by the structured flowcharts appearing in Figures 2.3.2.3-1 through 2.3.2.3-5. The function PHASE_PLANE is called by the procedure TVC_DAP and is composed of three principal routines: PHASE_PLANE, LARGE_ERROR_CONTROL_LOGIC, and SMALL_ERROR_CONTROL_LOGIC.

PHASE_PLANE

The function PHASE_PLANE selects the appropriate sign to be attached to the computed change in angular rate, computes position error intercepts, and also computes the boundaries between the small error control logic and the large error control logic, as detailed in Subsection 1.3.2.3. PHASE_PLANE then selects either the small error control logic or the large error control logic to compute the desired change in rate.

LARGE_ERROR_CONTROL_LOGIC

The procedure LARGE_ERROR_CONTROL_LOGIC computes the change in rate, X_D , required to drive the state into the small error control region. The switching lines are described in Subsection 1.3.2.3.2, and the equations which define them are presented in Table 2.3.2.3-1. As illustrated in Figure 2.3.2.3-2, the region in which the state lies is singled out, and then the appropriate control action is computed.

Table 2.3.2.3-1. Definitions of boundaries of large error control regions.

Boundary/Parameter	Definition
COAST_IV_BOUNDARY	$\omega_e = RL'$
COAST_I_BOUNDARY	$\omega_e = -RL'$
TARGET_ARL	$\omega_e = (RL + RL')/2$
PLR	$\theta_e = + \frac{(RL')^2}{2CD(U_C + U_D)} + DR'$
PLL	$\theta_e = - \frac{(RL')^2}{2CD(U_C - U_D)} - DL'$

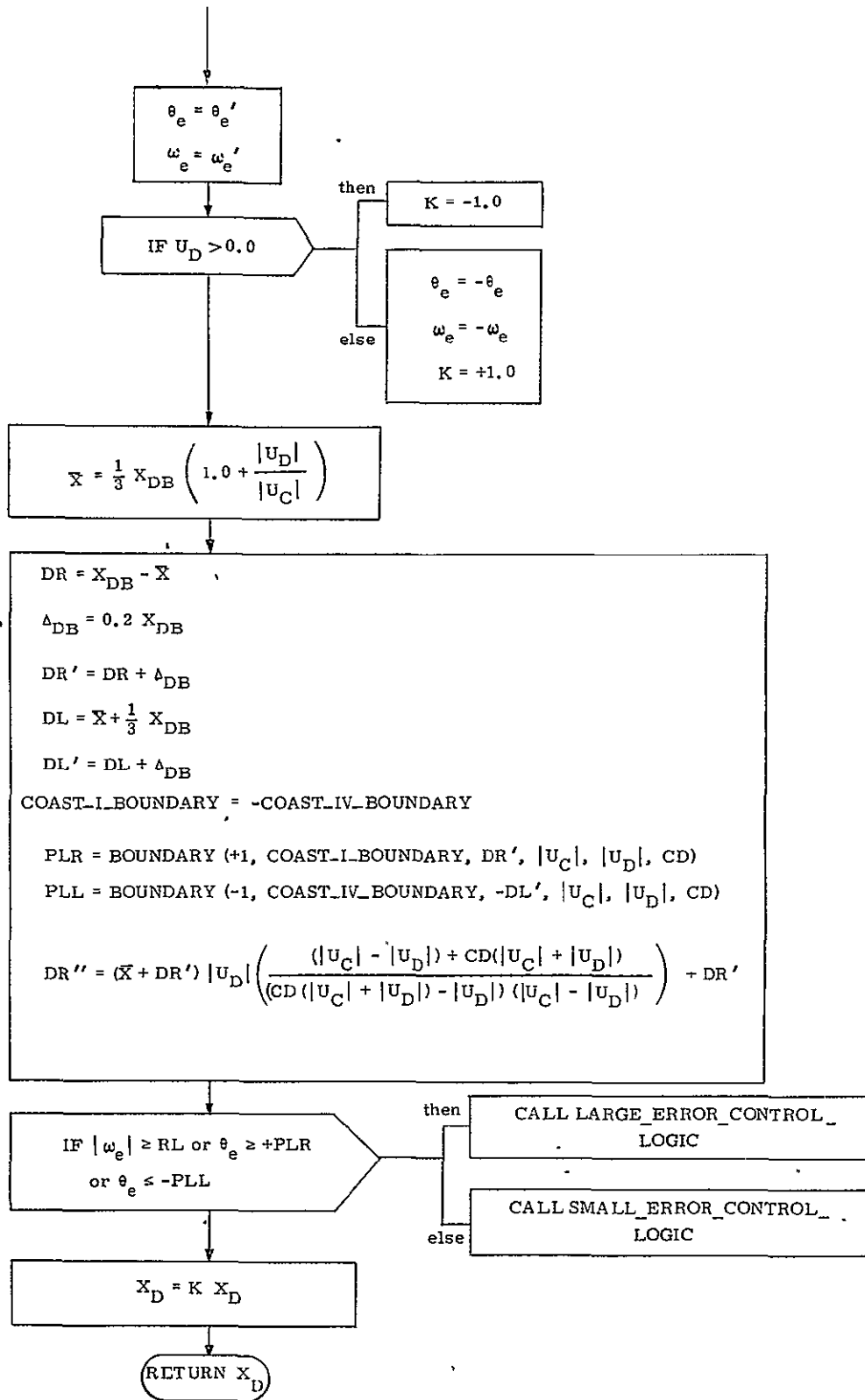


Figure 2.3.2.3-1. PHASE_PLANE: FUNCTION ($\theta_e', \omega_e', |U_C|, U_D, X_{Dold}$).

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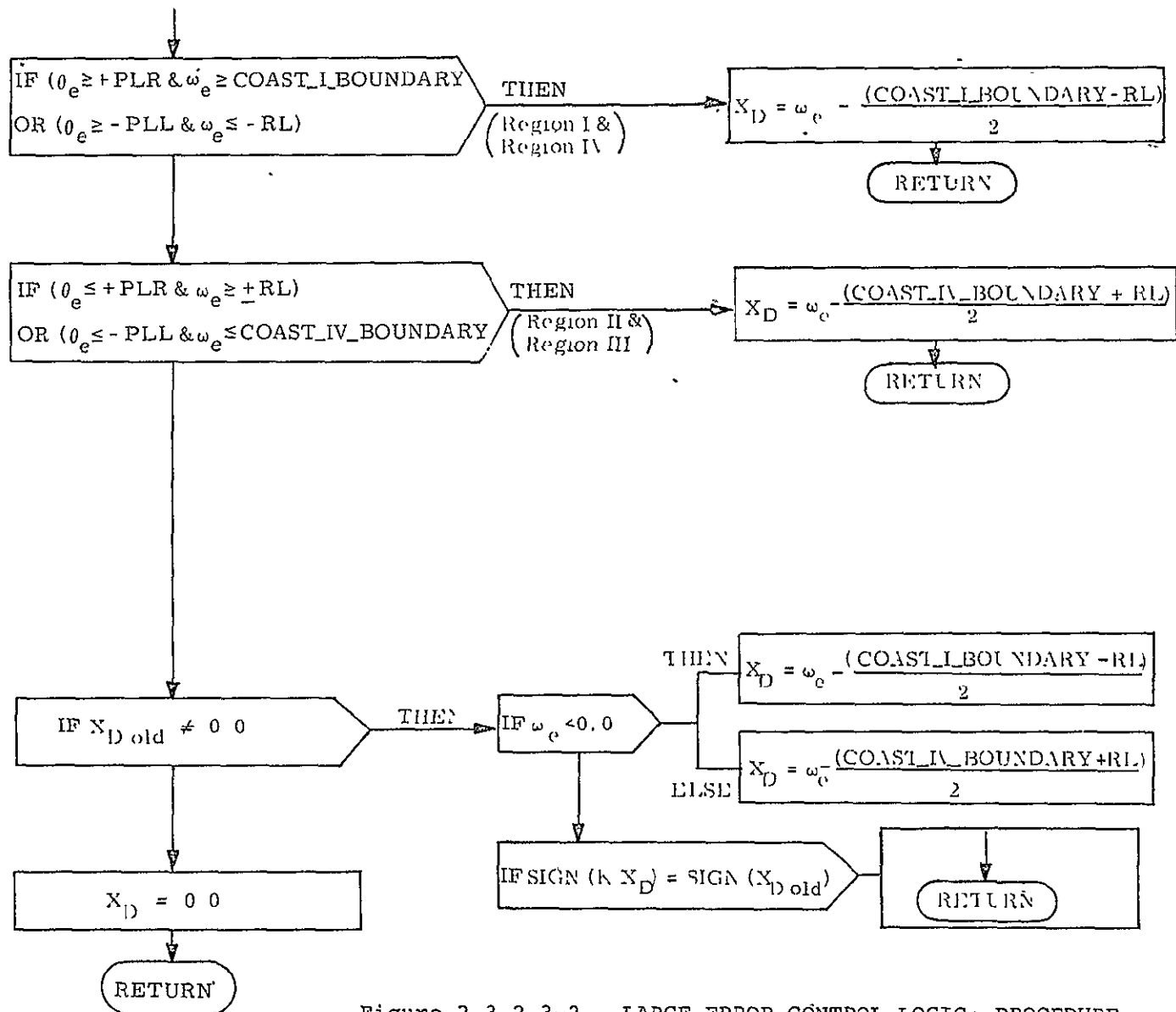


Figure 2.3.2.3-2. LARGE_ERROR_CONTROL_LOGIC: PROCEDURE.

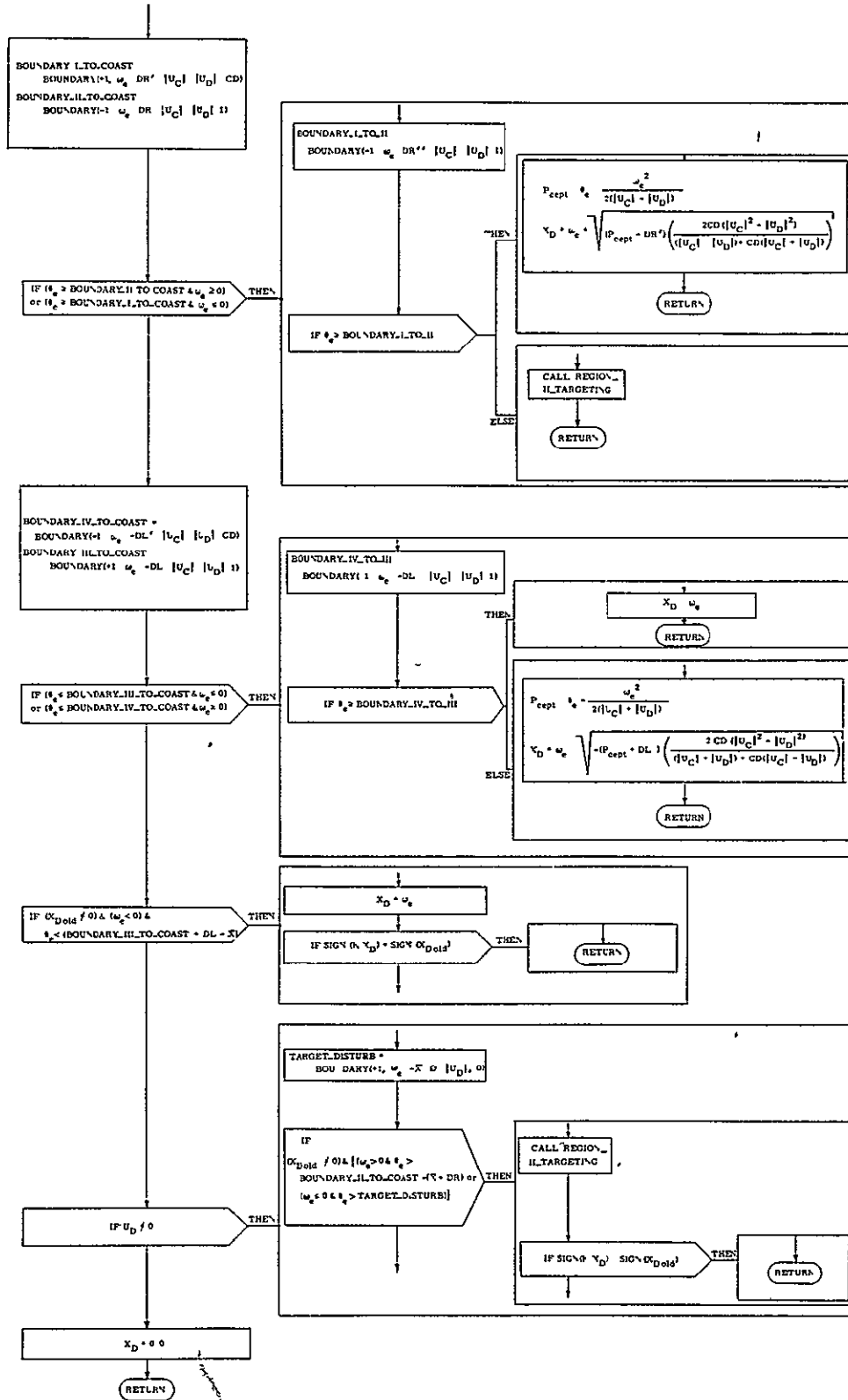


Figure 2.3.2.3-3. SMALL_ERROR_CONTROL_LOGIC: PROCEDURE.

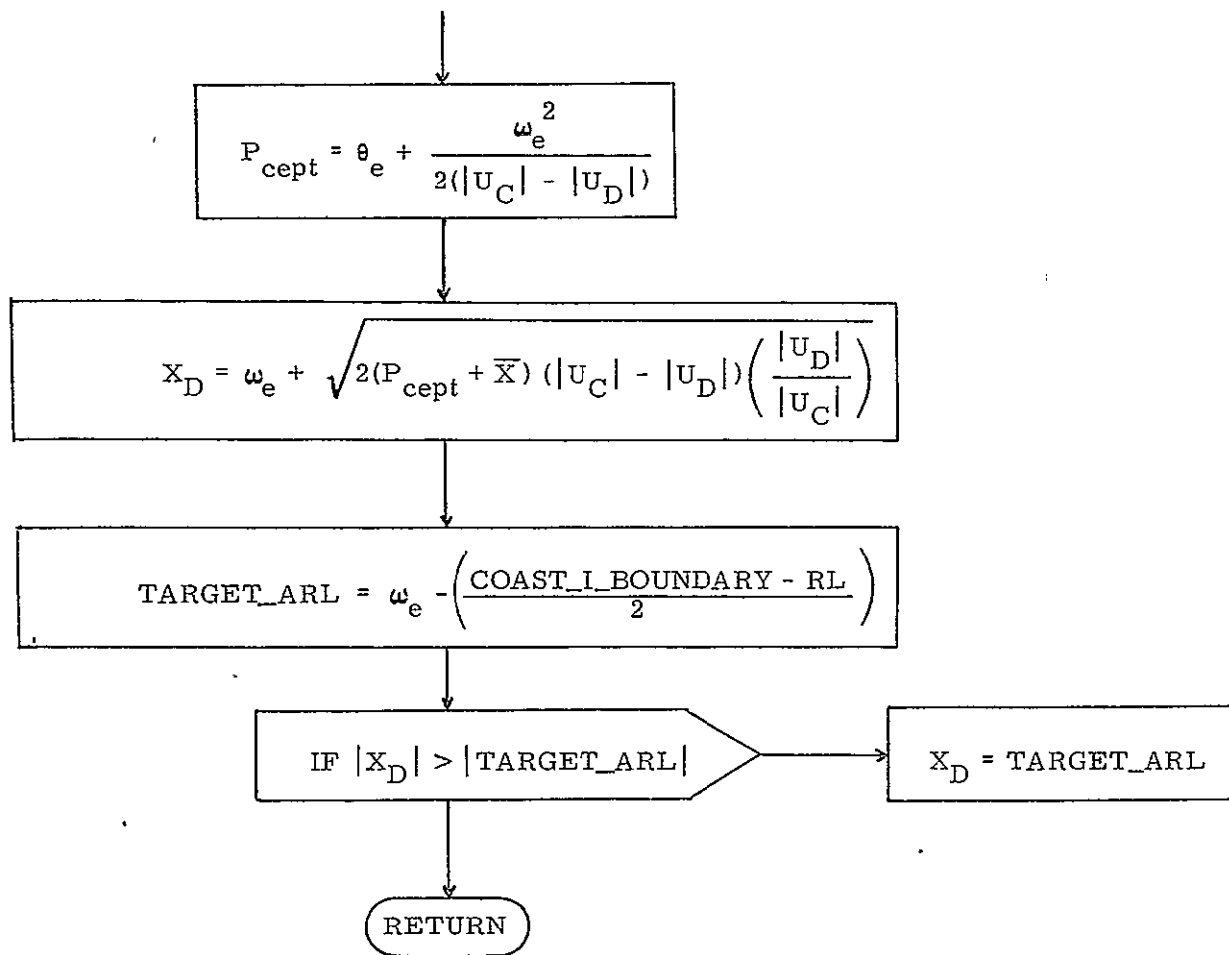


Figure 2.3.2.3-4. REGION_II_TARGETTING: PROCEDURE.

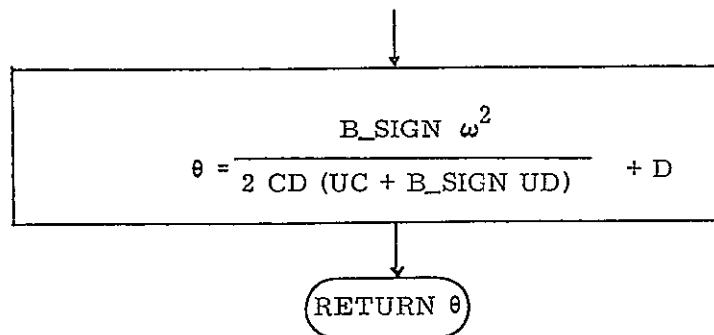


Figure 2.3.2.3-5. BOUNDARY: FUNCTION (B_SIGN, ω , D, UC, UD, CD).

SMALL_ERROR_CONTROL_LOGIC

The procedure SMALL_ERROR_CONTROL_LOGIC computes the change in rate, X_D , required to drive the state into a limit cycle with the specified deadband about the desired attitude and rate. Testing to date has used deadbands of 0.5 and 5.0 degrees. The switching curves are described in Subsection 1.3.2.3.1, and the equations which define them are presented in Table 2.3.2.3-2. As illustrated in Figures 2.3.2.3-3 and 2.3.2.3-4, the region in which the state lies is singled out and then the appropriate control action is computed.

The function BOUNDARY, illustrated in Figure 2.3.2.3-5, is implemented to compute the various switching curves.

Table 2.3.2.3-2. Definitions of boundaries of small error control regions.

Boundary/Parameter	Definition
BOUNDARY_I_TO_II	$\theta_e = -\frac{\omega_e^2}{2(U_C - U_D)} + DR''$
BOUNDARY_II_TO_COAST	$\theta_e = -\frac{\omega_e^2}{2(U_C - U_D)} + DR$
BOUNDARY_I_TO_COAST	$\theta_e = +\frac{\omega_e^2}{2CD(U_C + U_D)} + DR'$
BOUNDARY_III_TO_COAST	$\theta_e = +\frac{\omega_e^2}{2(U_C + U_D)} - DL$
BOUNDARY_IV_TO_III	$\theta_e = +\frac{\omega_e^2}{2(U_C + U_D)} - DL'$
BOUNDARY_IV_TO_COAST	$\theta_e = -\frac{\omega_e^2}{2CD(U_C - U_D)} - DL'$
TARGET_DISTURB	$\theta_e = +\frac{\omega_e^2}{2 U_D } - \bar{X}$

2.3.2.4 Jet Selection

A decision, based on the flag NOM_VERNIER_SW, is made as to which jet selection scheme is to be used (see Figure 2.2.2-1). The procedure NOMINAL is called if the main RCS jets are to be used, and the procedure VERNIER is called if the vernier jets are to be used.

2.3.2.4.1 Jet Selection for Main RCS Jets (NOMINAL). - The equations used to select the jets are Boolean algebra equations relating the jet failure condition to the jet on/off state desired. The equations were derived by first determining which jets should be fired for all different control actions and all required jet failure conditions. Logical equations were then written which would result in the firing of those jets. This is basically a table look-up method of jet selection, since a different set of equations is used for each control action.

A flowchart is given in Figure 2.3.2.4.1-1. This module has not yet been structured. The flowchart uses the "old" jet numbering scheme (see Subsection 4.3.2.4).

2.3.2.4.2 Jet Selection for Vernier Jets (VERNIER). - The vernier jet selection logic selects the jet(s) corresponding to the rotational acceleration unit vector which provides the maximum dot product with the command vector.

The flowchart for the vernier jet selection appears in Figure 2.3.2.4.2-1. This module has not yet been structured.

2.3.3 TVC DAP

2.3.3.1 Automatic Pitch/Yaw TVC Law

The guidance pitch/yaw rate command ω_c is processed in the TVC DAP in the following way. It is first multiplied by the guidance loop gain K_{steer} and integrated to form attitude increments. These are then passed through the guidance loop compensation filter whose z-transform $S(z)$ is given by

$$S(z) = \frac{0.34 - 0.3332 z^{-1}}{1 - 0.9932 z^{-1}}$$

The output of this filter represents the attitude command θ_c . It is summed with the measured attitude θ (feedback) to yield the attitude error signal θ_e as follows:

$$\theta_e = \theta_c - \theta$$

This sampled attitude error signal then goes through the following digital compensation filter (the w-transform of this filter is given in Subsection 4.3.3.1):

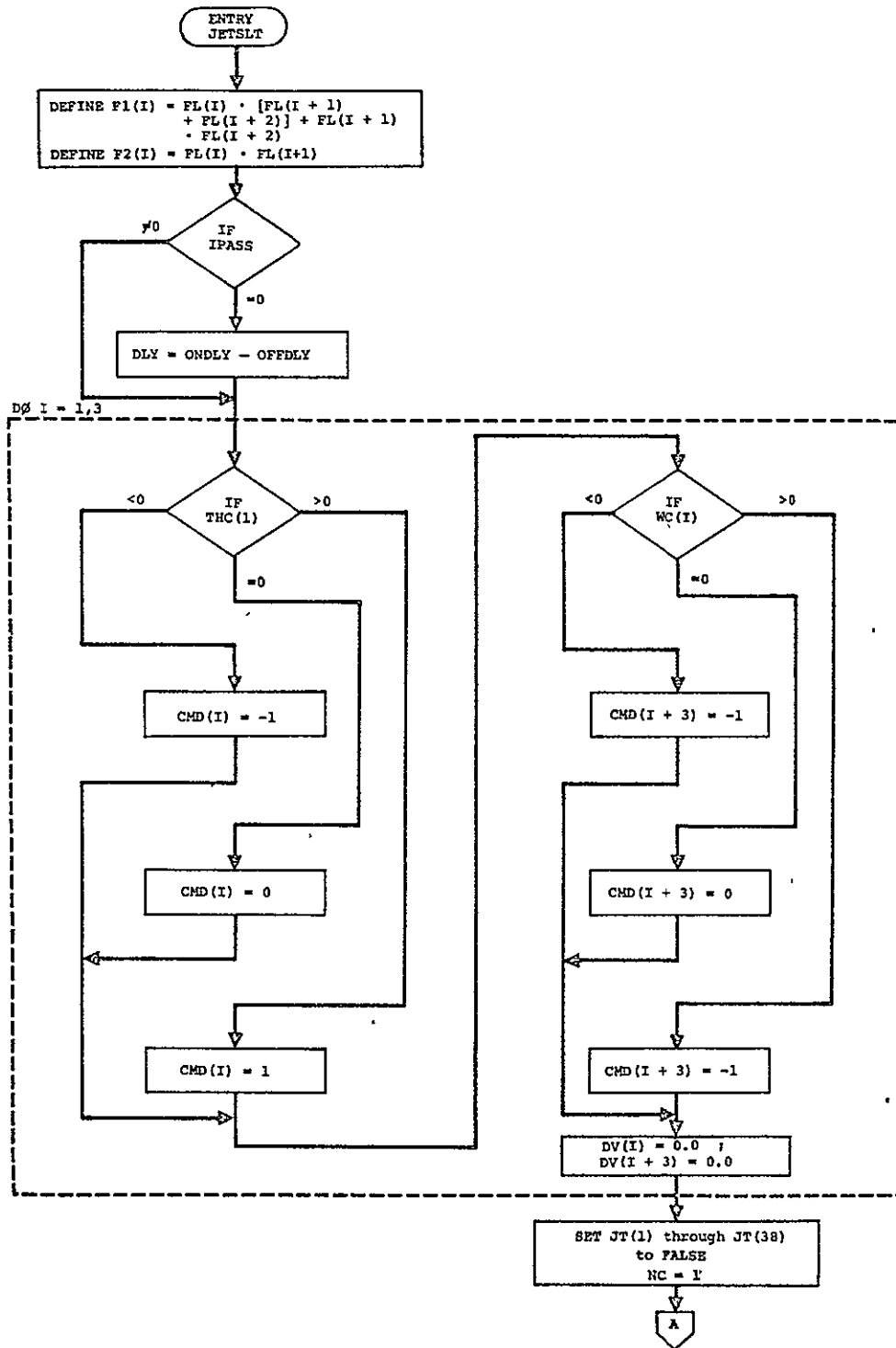


Figure 2.3.2.4.1-1. NOMINAL.

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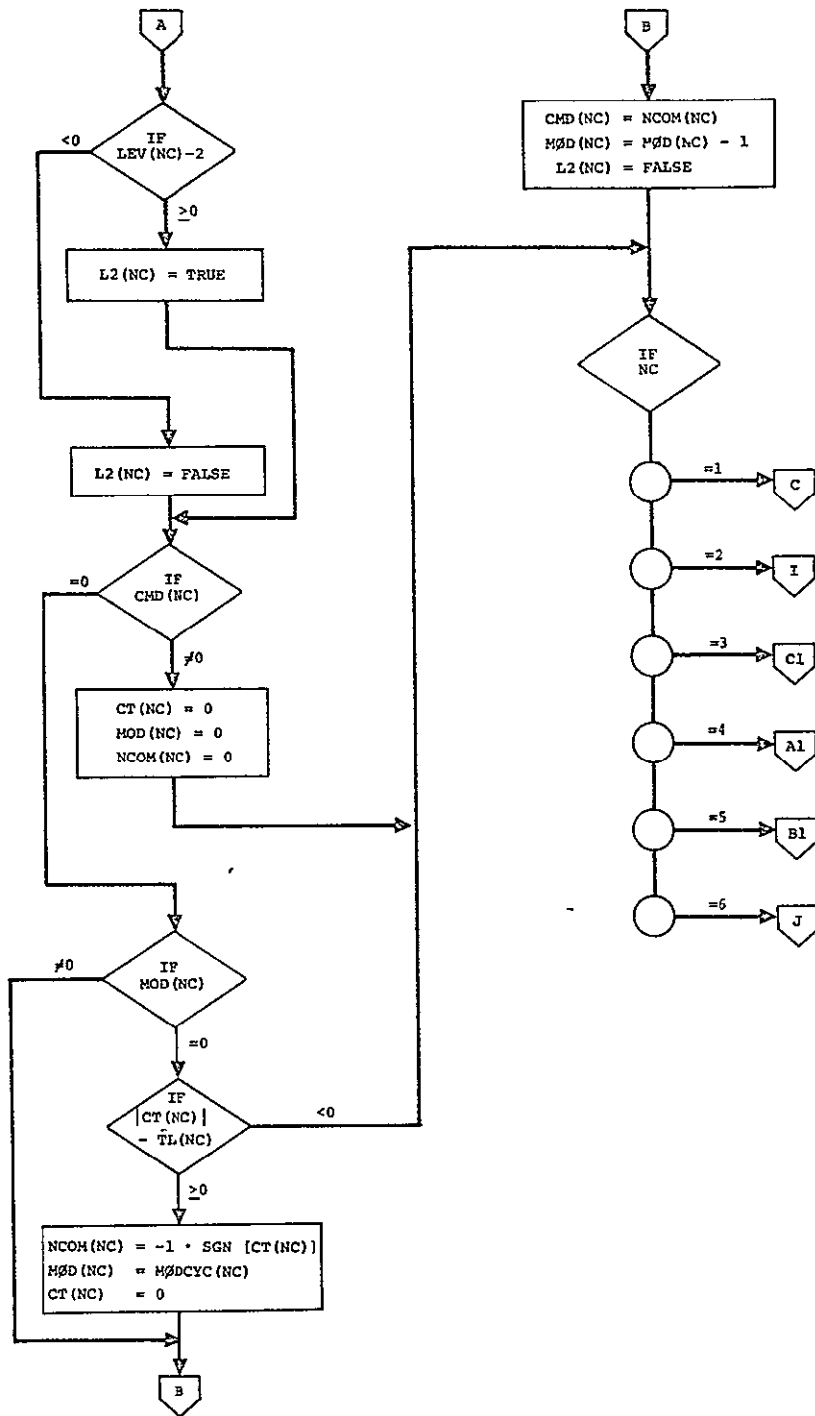


Figure 2.3.2.4.1-1. NOMINAL (Cont).

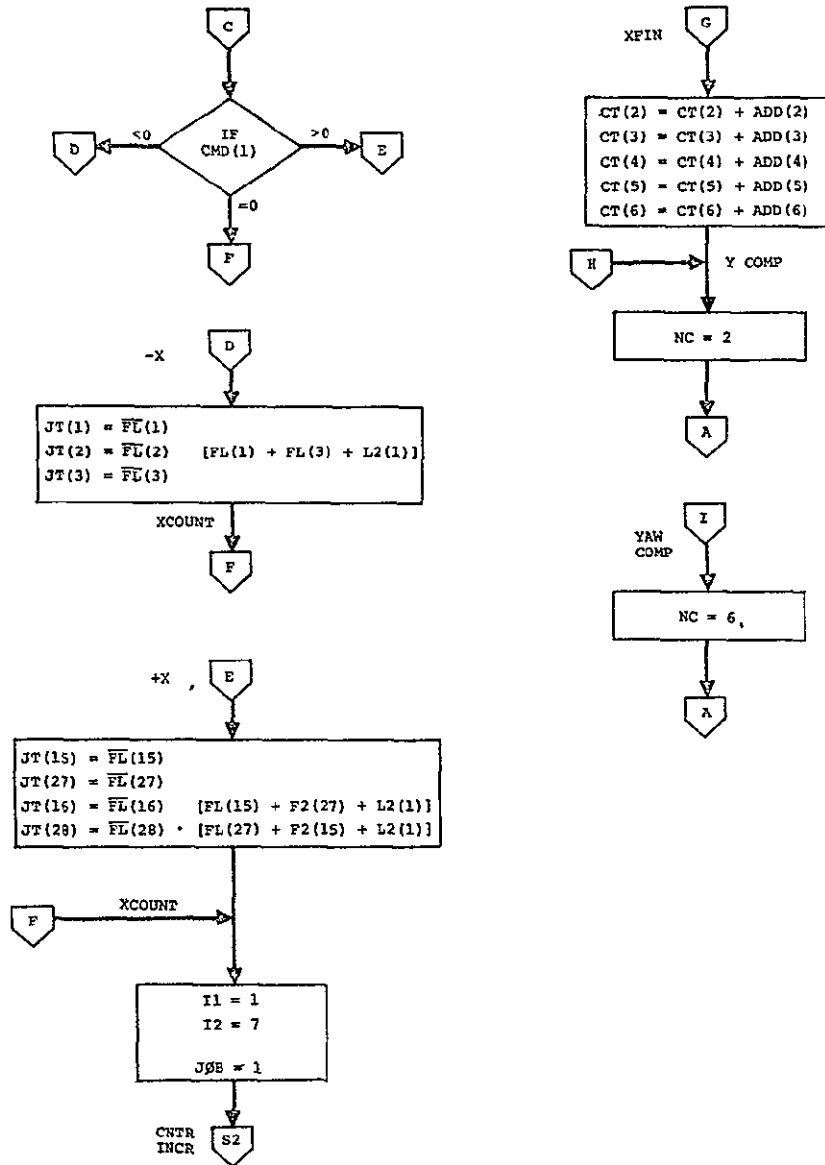


Figure 2.3.2.4.1-1. NOMINAL (Cont)

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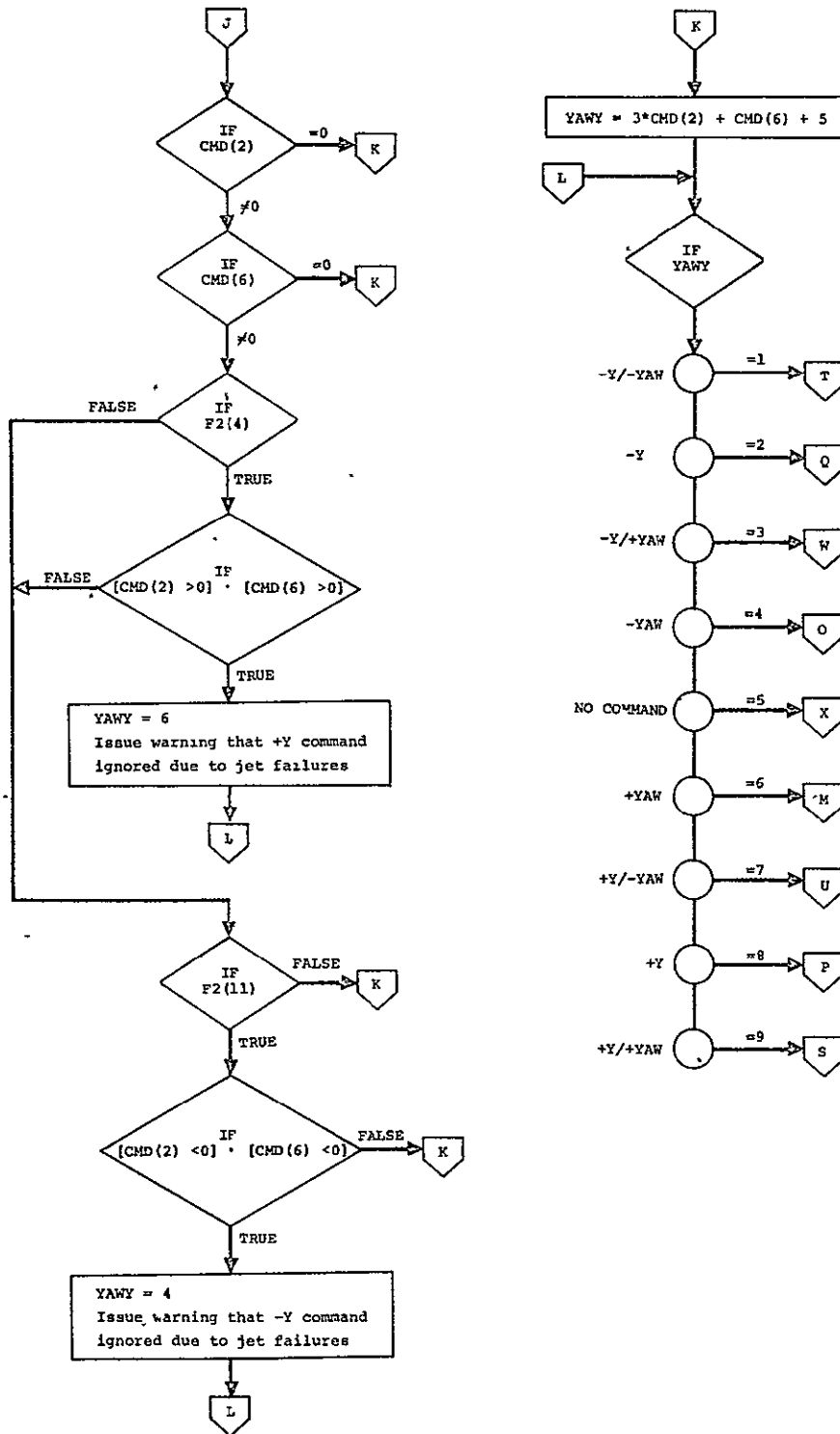


Figure 2.3.2.4.1-1. NOMINAL (Cont).

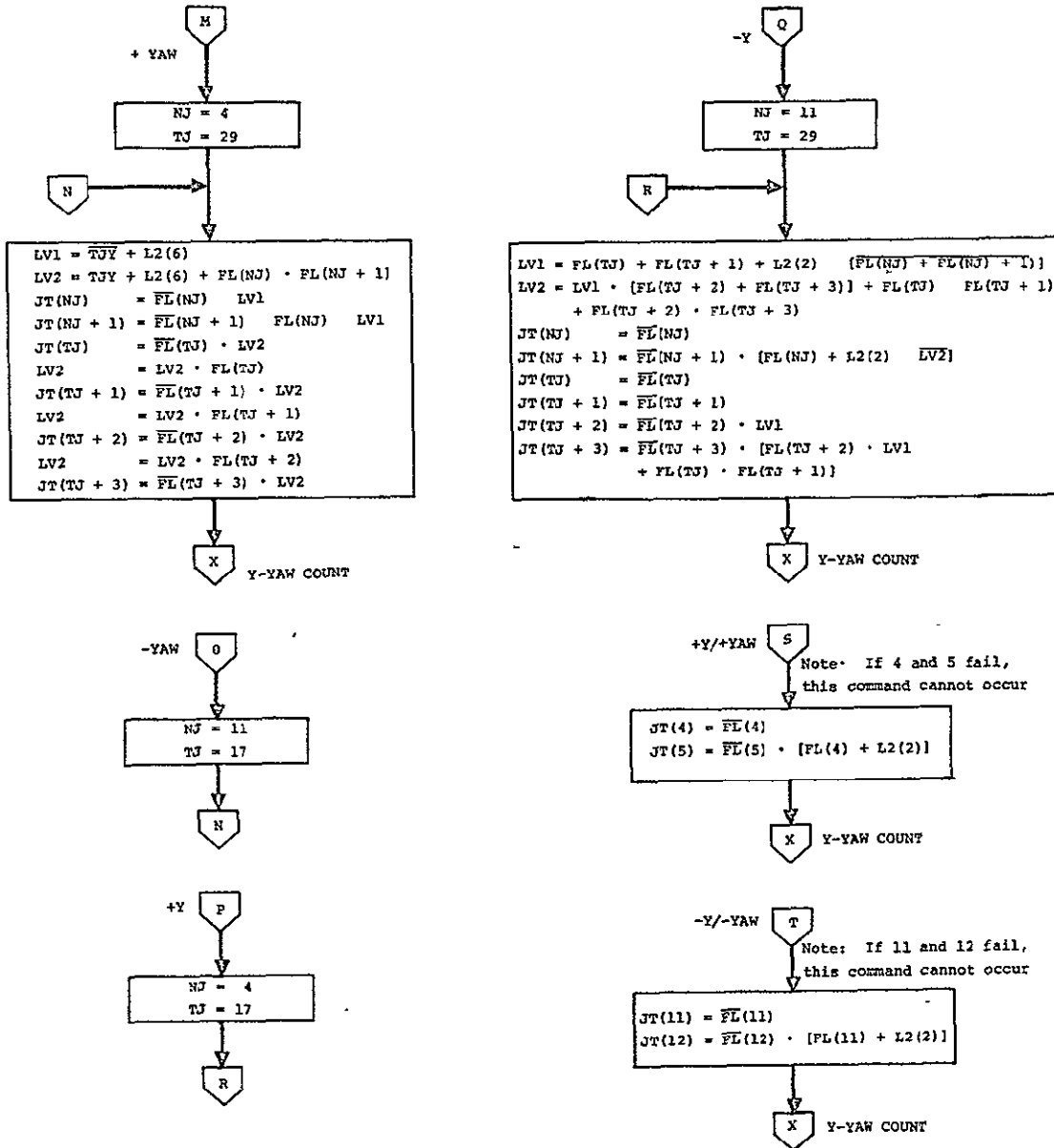


Figure 2.3.2.4.1-1. NOMINAL (Cont).

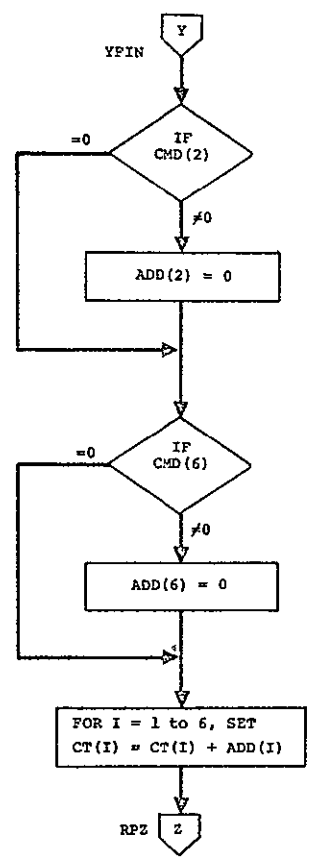
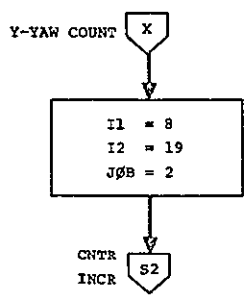
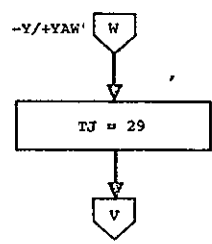
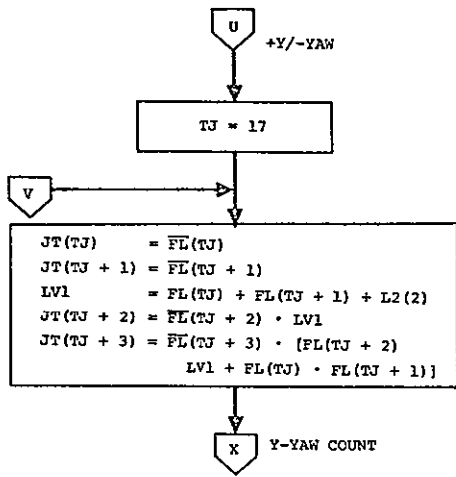


Figure 2.3.2.4.1-1 NOMINAL (Cont).

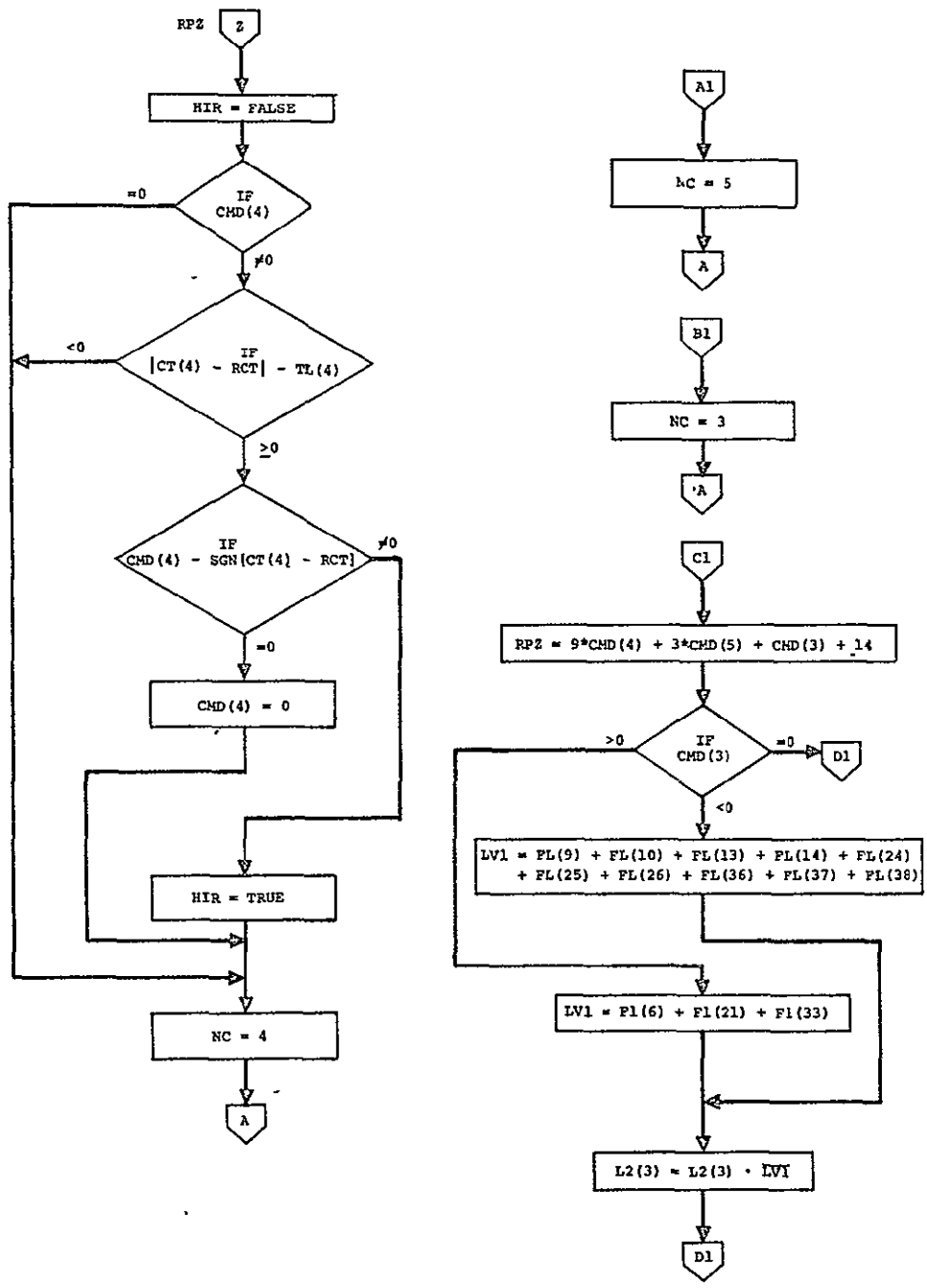


Figure 2.3.2.4.1-1. NOMINAL (Cont.).

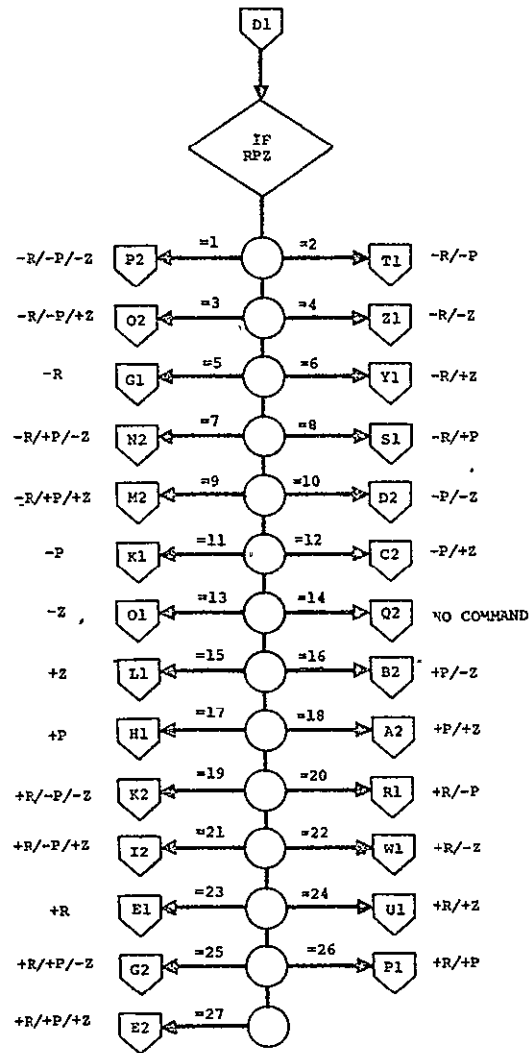


Figure 2.3.2.4.1-1. NOMINAL (Cont).

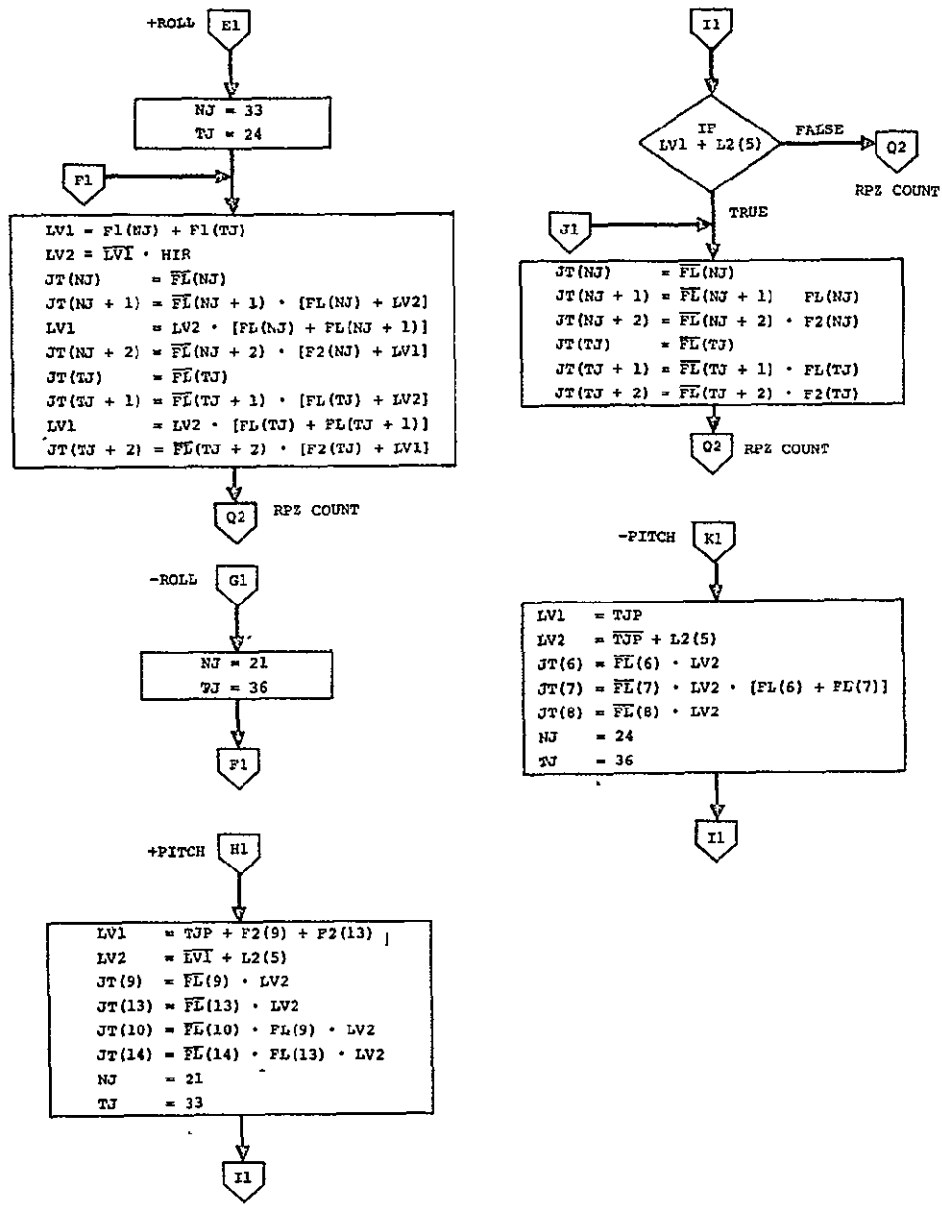


Figure 2.3.2.4.1-1. NOMINAL (Cont).

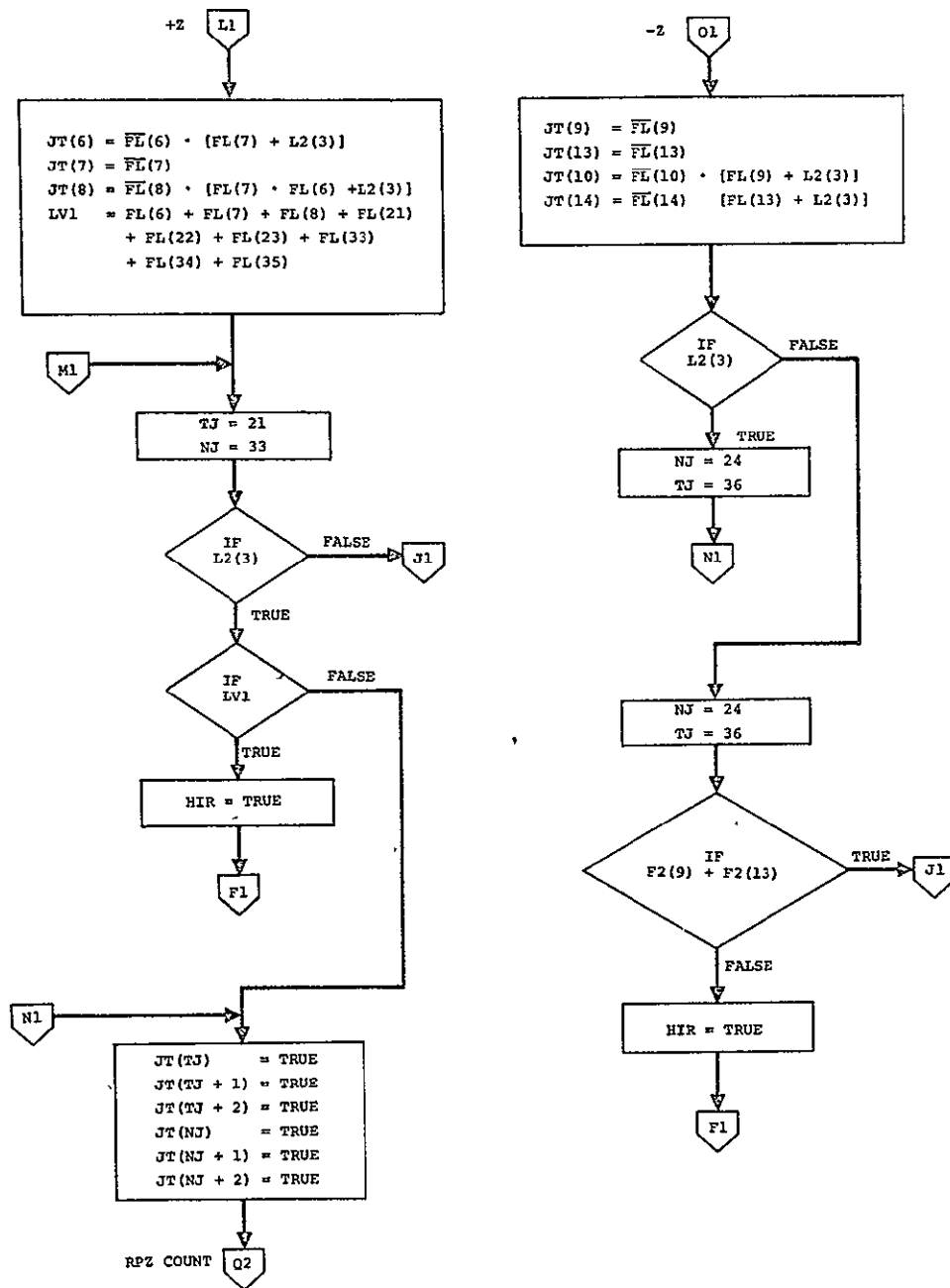


Figure 2.3.2.4.1-1. NOMINAL (Cont).

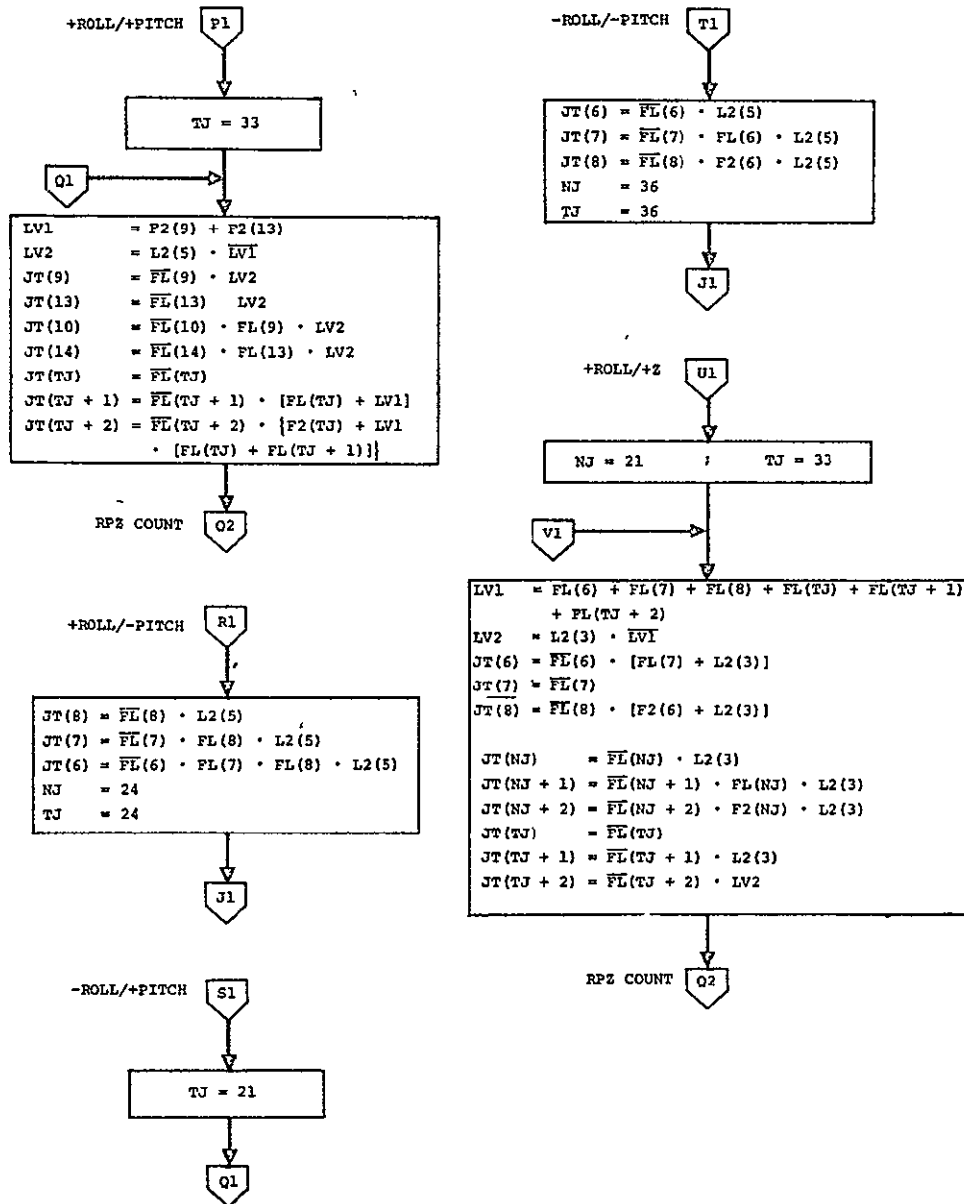


Figure 2.3.2.4.1-1. NOMINAL (Cont).

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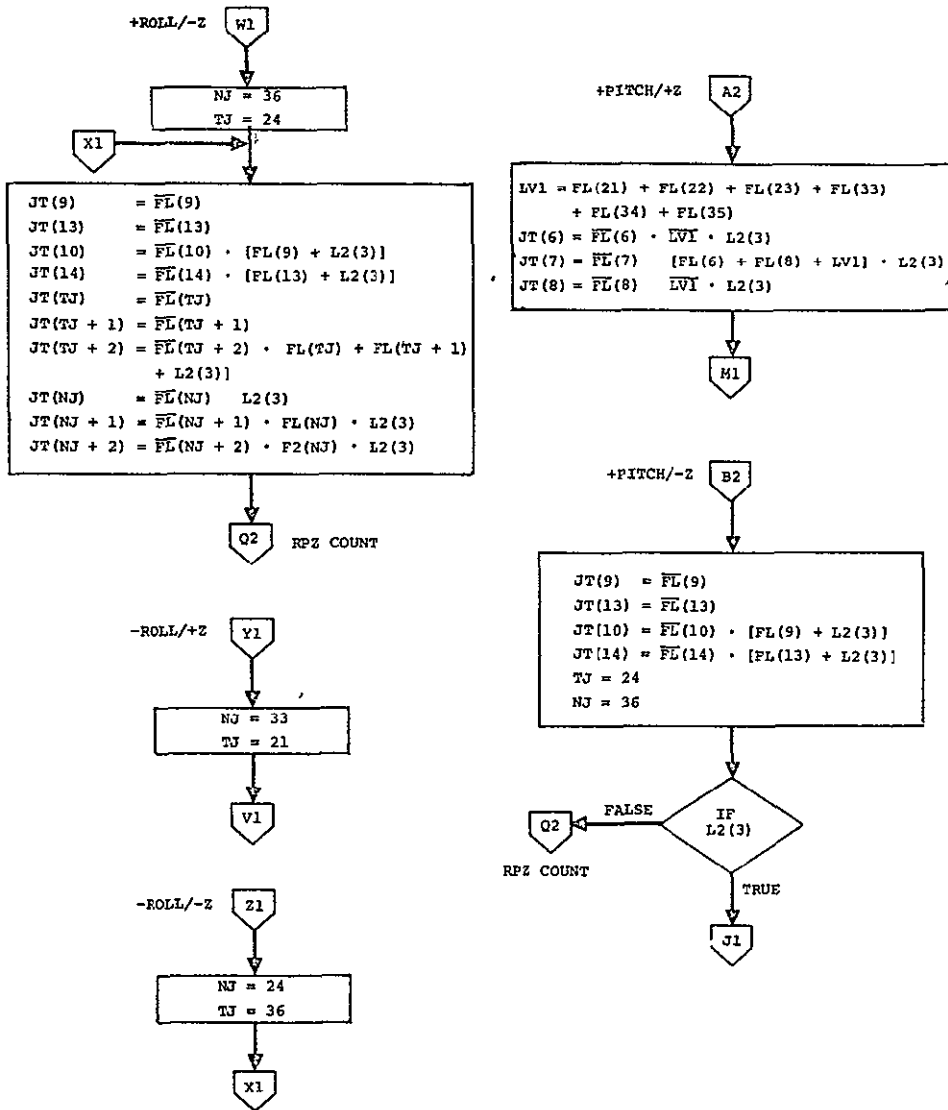


Figure 2.3.2.4.1-1. NOMINAL (Cont).

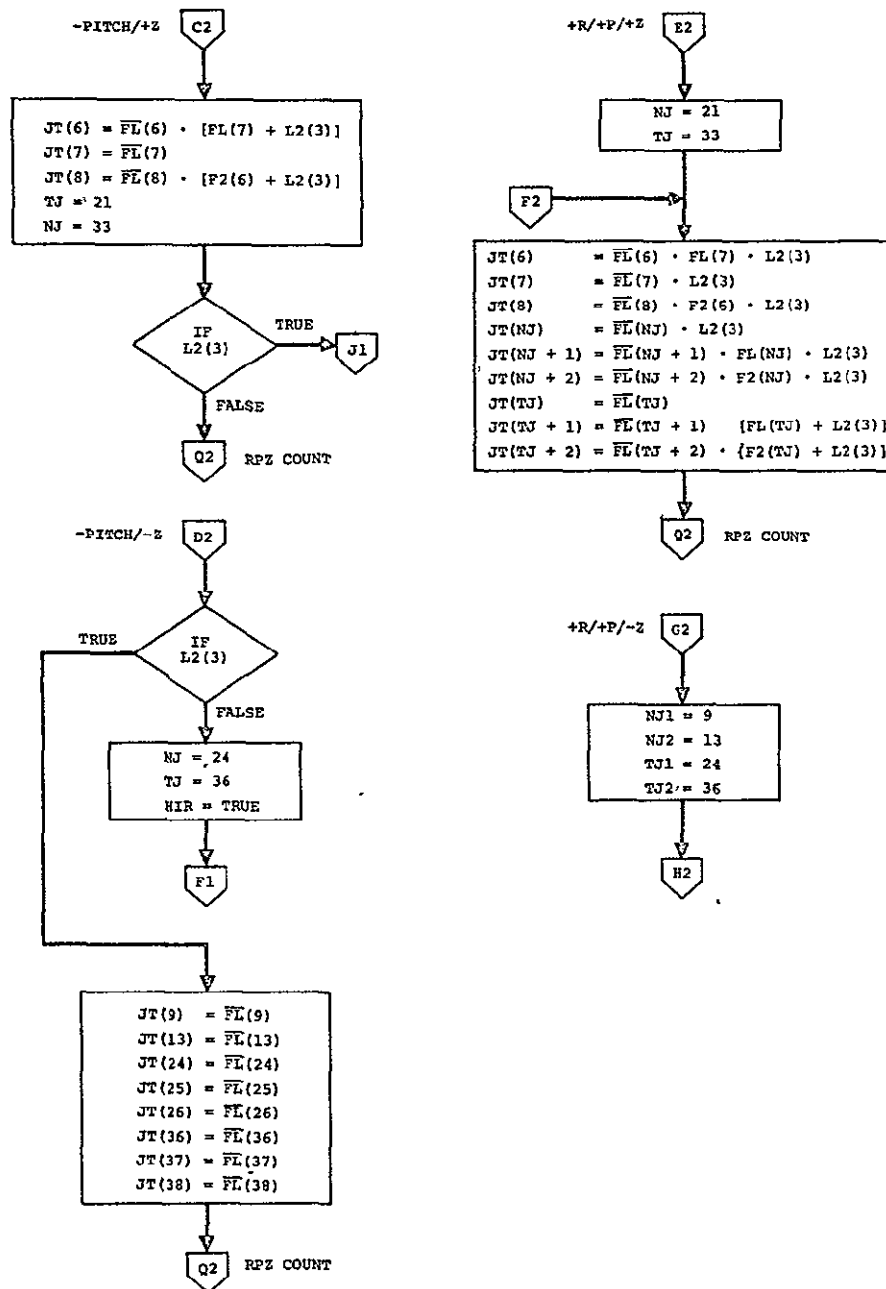


Figure 2.3.2.4.1-1. NOMINAL (Cont).

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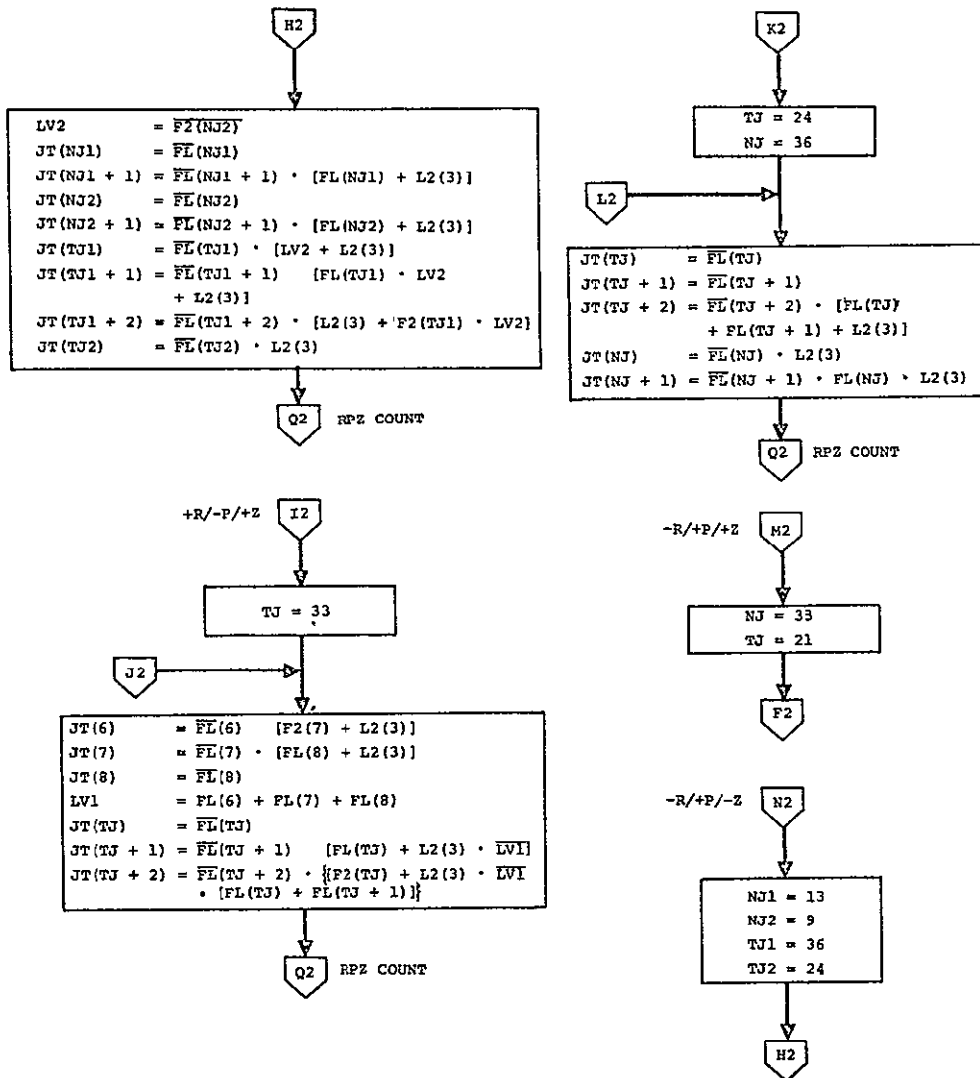


Figure 2.3.2.4.1-1. NOMINAL (Cont).

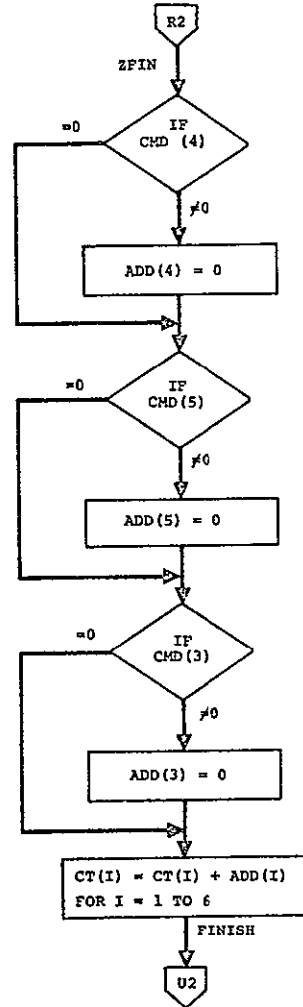
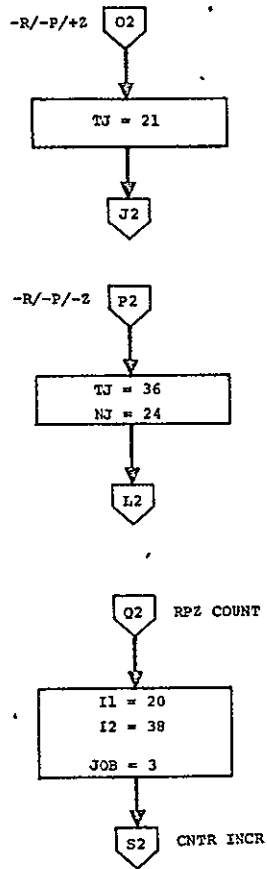


Figure 2.3.2.4.1-1. NOMINAL (Cont).

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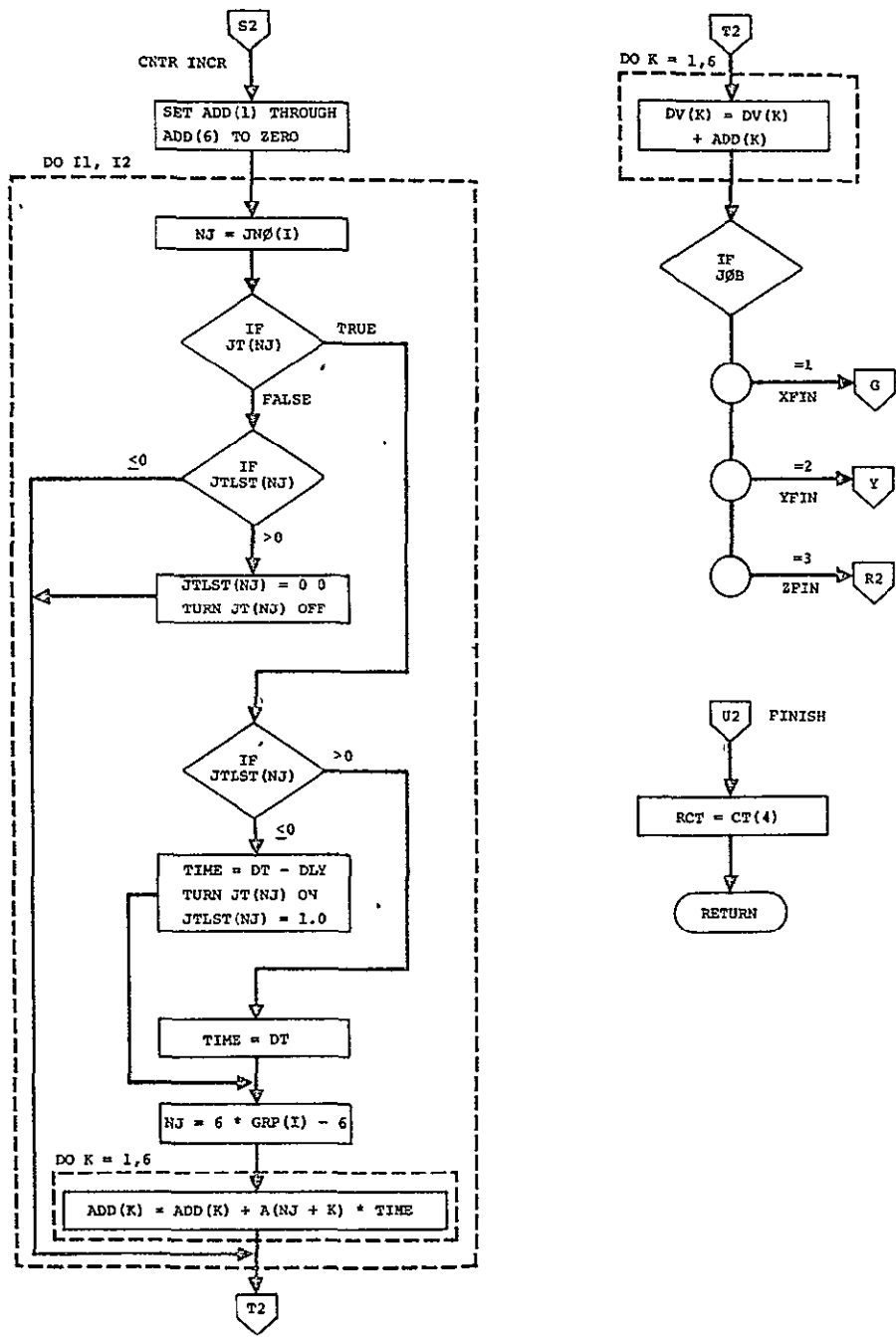


Figure 2.3.2.4.1-1. NOMINAL (Cont).

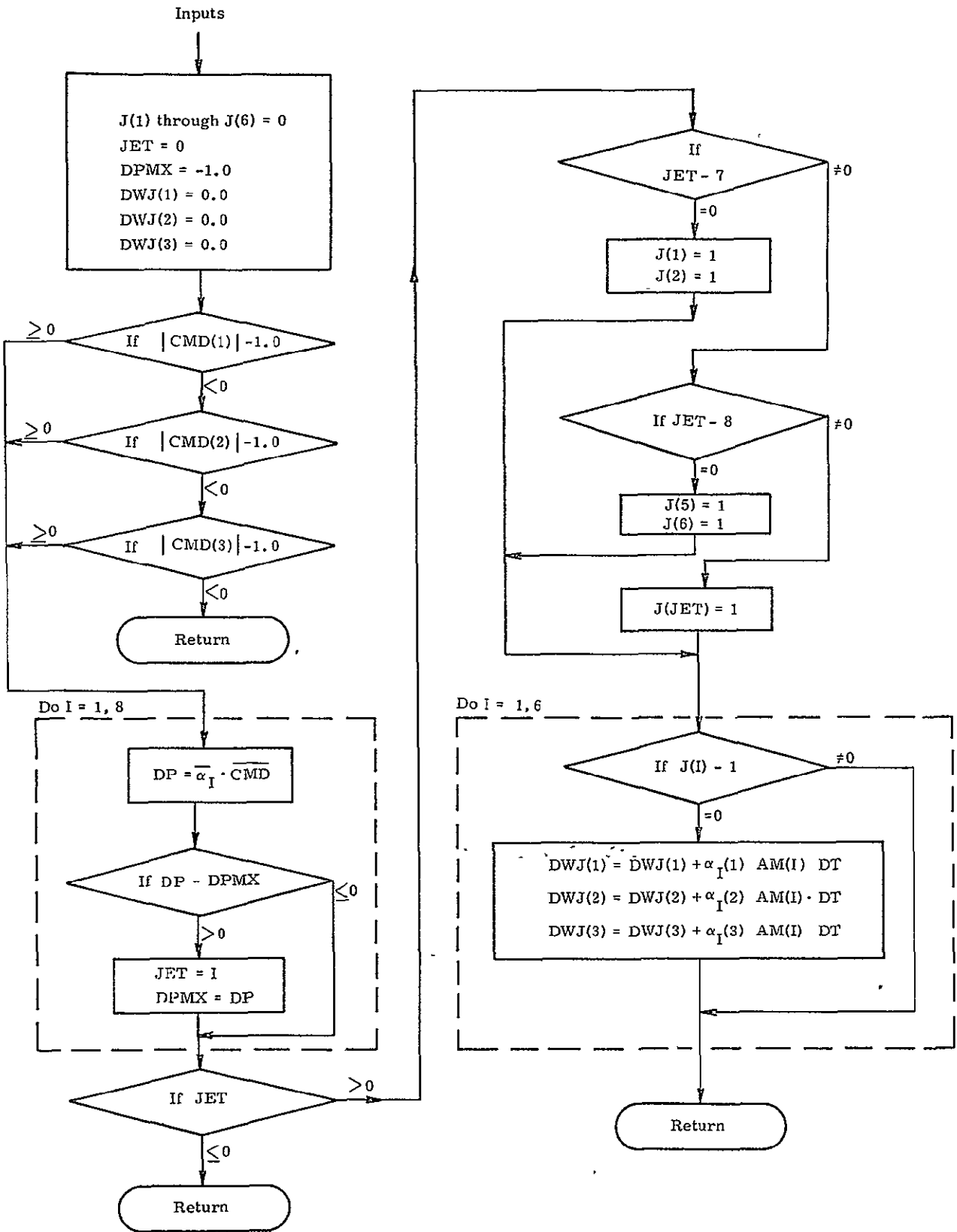


Figure 2.3.2.4.2-1. VERNIER: PROCEDURE.

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$$D_1(z) = K_D \frac{(1 - 0.5974 z^{-1} + 0.08922 z^{-2})(1 - 0.98807 z^{-1})}{(1 - 1.7376 z^{-1} + 0.78845 z^{-2})(1 - 0.78571 z^{-1})}$$

The filter gain K_D is computed from the following:

$$K_D = \frac{0.534}{K_V}$$

where

$$K_V = \frac{T \ell_x}{I_{YY}} \quad \text{for the pitch autopilot}$$

$$K_V = \frac{T \ell_z}{I_{ZZ}} \quad \text{for the yaw autopilot}$$

T is total thrust in pounds

ℓ_x is distance parallel to x axis from OMS engines to vehicle cg in feet

I_{YY}, I_{ZZ} are moments of inertia about y, z axes in slug-ft²

The output DAPOUT of the digital compensation filter is the input to the TMC filter.

For computational accuracy the above filter is broken up into two cascaded sections, the first section containing the first-order part of the filter, and the second section being the remaining second-order section. The output of the first-order section DAP1 becomes an input for the second section. This arrangement results in the following difference equations for computing the filter output at the nth autopilot sampling time:

$$DAP1_n = K_D (\theta_{e_n} - 0.98807 \theta_{e_{n-1}}) + 0.78571 DAP1_{n-1}$$

$$DAPOUT_n = DAP1_n - 0.5974 DAP1_{n-1} + 0.08922 DAP1_{n-2} \\ + 1.7376 DAPOUT_{n-1} - 0.78845 DAPOUT_{n-2}$$

The z-transform of the TMC filter is:

$$M(z) = \frac{(1 - 0.998 z^{-1})^2}{(1 - z)^{-1} (1 - 0.996 z^{-1})}$$

The difference equations for two cascaded first-order sections of this filter are:

$$\delta'_{c_n} = \text{DAPOUT}_n - 0.998 \text{ DAPOUT}_{n-1} + \delta'_{c_{n-1}}$$

$$\delta_{c_n} = \delta'_{c_n} - 0.998 \delta'_{c_{n-1}} + 0.996 \delta_{c_{n-1}}$$

$$\delta_{e_n} = \delta_{c_n} - \delta_n$$

δ_{c_n} is the engine command, δ_n engine position, and δ_{e_n} engine servo error at the n^{th} autopilot sampling time. Upon conversion to analog form, this error is sent to the engine servo amplifier.

It should be pointed out that in the case of pitch-plane engine servos, the total command and thus the error signal sent to the servo amplifiers is modified by differential commands from the roll autopilot. Thus, if δ_{c_p} is the engine command produced by the pitch autopilot and δ_{c_r} is the engine command produced by the roll autopilot, the total error δ_{e_1} sent to engine servo amplifier number one is

$$\delta_{e_1} = \delta_{c_p} + \delta_{c_r} - \delta_1$$

and for engine two the error is

$$\delta_{e_2} = \delta_{c_p} - \delta_{c_r} - \delta_2$$

A flowchart of the algorithm which implements all equations without a pushdown list for the variables is shown in Figure 2.3.3.1-1.

2.3.3.2 Automatic Roll TVC Law

The compensation filter for the automatic roll control is given by the z-transform

$$D_2(z) = K_r \frac{1 - 0.984 z^{-1}}{1 - 0.88 z^{-1}}$$

where

$$K_r = 26.4/K_v$$

$$K_v = T l_y / I_{xx}$$

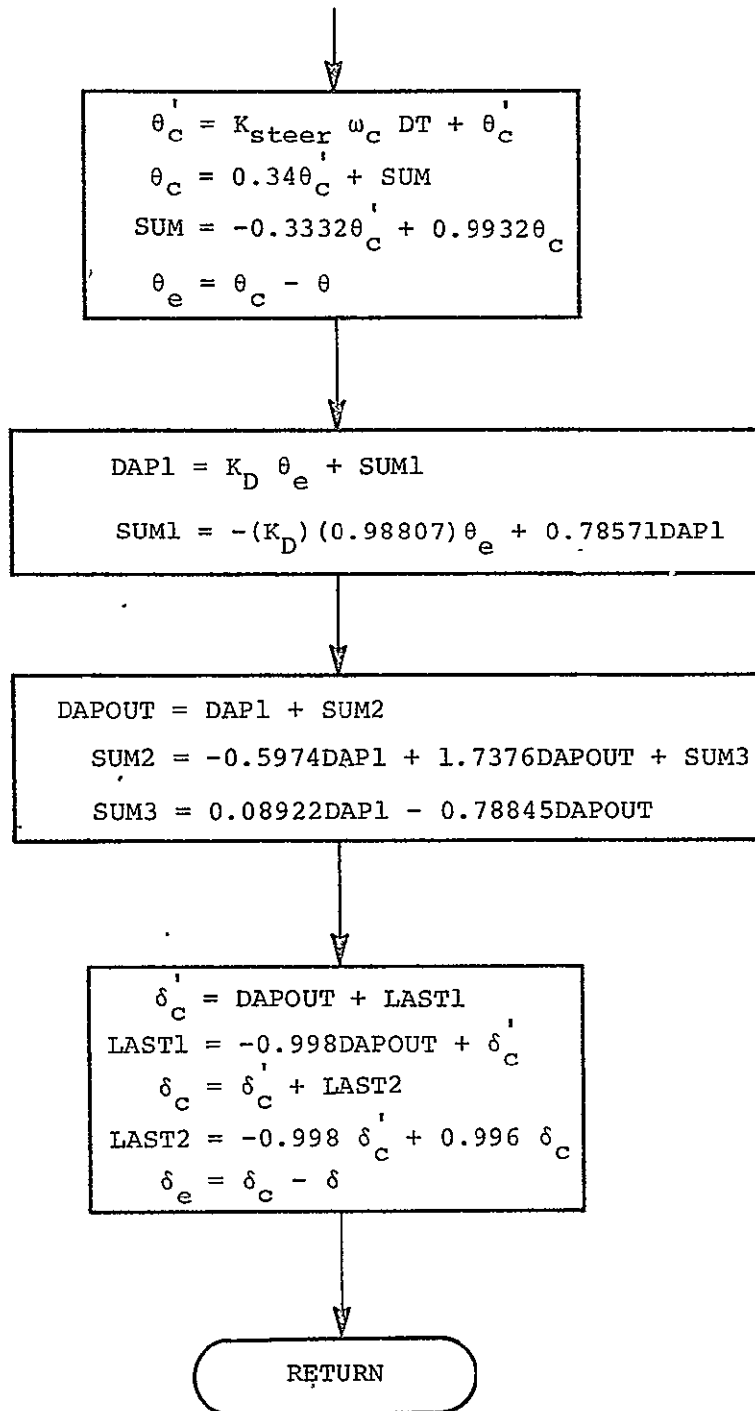


Figure 2.3.3.1-1. TVC filter for pitch or yaw attitude control.

T is thrust in pounds

l_y is distance parallel to y axis from OMS engine to vehicle cg in feet

I_{xx} is vehicle moment of inertia about x axis in slug-ft²

The input to this filter is the roll attitude error θ_e which is the difference between the roll command θ_c and the measured roll angle θ .

$$\theta_e = \theta_c - \theta$$

Implementation of this compensation would result in the following equations:

$$\begin{aligned}\delta_d &= K_r \theta_e + \text{sum3} \\ \text{sum3} &= -0.984 K_r \theta_e + 0.88 \delta_d\end{aligned}$$

δ_d is the engine command to the pitch plane engine servos, which is combined with pitch autopilot commands as described in the previous subsection.

2.3.3.3 Manual TVC Law

For the manual mode of TVC in pitch and yaw, the error signal is the rate error ω_e resulting from differencing the pilot RHC rate command ω_c and the rate ω derived from IMU gimbale angle measurements transformed to body axes:

$$\omega_e = \omega_c - \omega$$

This error is passed through the compensation filter whose z-transform is $D_3(z)$:

$$D_3(z) = K_M \frac{1 - 0.994 z^{-1}}{(1 - z^{-1})(1 - 0.7857 z^{-1})(1 - 1.7376 z^{-1} + 0.78845 z^{-2})}$$

where

$$K_M = 0.0109/K_V$$

and K_V is the vehicle gain as defined in Subsection 2.3.3.1. Implementation of this filter results in equations similar to those for the automatic mode given in Figure 2.3.3.1-1.

The roll autopilot envisioned for this mode would also be a rate control system and would probably involve a simple gain compensation which is to be determined.

2.3.4 RCS DAP and TVC DAP Drivers

2.3.4.1 RCS DAP Drivers

2.3.4.1.1 Manually Commanded RCS DAP Drivers. - The manual RCS modes accept RHC and THC commands referenced to the Commander's station (+X facing) axes. Thus, inputs from the aft station must be transformed from either -Z facing or -X facing coordinates to +X facing coordinates. The transformations to accomplish this are:

-X Facing

$$\begin{bmatrix} \text{RHC (1)} \\ \text{RHC (2)} \\ \text{RHC (3)} \end{bmatrix}_{+X} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & +1 \end{bmatrix} \begin{bmatrix} \text{RHC (1)} \\ \text{RHC (2)} \\ \text{RHC (3)} \end{bmatrix}_{-X}$$

$$\begin{bmatrix} \text{THC (1)} \\ \text{THC (2)} \\ \text{THC (3)} \end{bmatrix}_{+X} = \begin{bmatrix} +1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \text{THC (1)} \\ \text{THC (2)} \\ \text{THC (3)} \end{bmatrix}_{-X}$$

-Z Facing

$$\begin{bmatrix} \text{RHC (1)} \\ \text{RHC (2)} \\ \text{RHC (3)} \end{bmatrix}_{+X} = \begin{bmatrix} 0 & 0 & -1 \\ 0 & -1 & 0 \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \text{RHC (1)} \\ \text{RHC (2)} \\ \text{RHC (3)} \end{bmatrix}_{-Z}$$

$$\begin{bmatrix} \text{THC (1)} \\ \text{THC (2)} \\ \text{THC (3)} \end{bmatrix}_{+X} = \begin{bmatrix} 0 & 0 & -1 \\ 0 & -1 & 0 \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \text{THC (1)} \\ \text{THC (2)} \\ \text{THC (3)} \end{bmatrix}_{-Z}$$

where the following conventions are used:

$$+RHC = \begin{bmatrix} \text{RIGHT} \\ \text{AFT} \\ \text{TWIST TO RIGHT} \end{bmatrix} \quad +THC = \begin{bmatrix} \text{DOWN} \\ \text{RIGHT} \\ \text{FORWARD} \end{bmatrix}$$

2.3.4.1.1.1 Rotation. - The procedure MAN_RCS_ROT, flowcharted in Figure 2.3.4.1.1.1-2, first checks whether INIT_MAN_ROT_FLAG is on. If so, it selects the direct rotation acceleration command submode in all three axes. On subsequent passes, if the RHC is out of detent, the rotation submode is always the same as on the previous pass, effecting inhibition of mode switching. If the RHC is in detent, new submode selections are accepted, with the submodes of the previous pass as default selections.

In all cases, appropriate switch lamps are commanded on, confirming the new submode selections, or retention of previous selections. MAN_RCS_ROT then executes the selected submode in each of the three rotation axes.

RHC hysteresis (see Figure 2.3.4.1.1.1-1) is incorporated in the procedure RHC_READ, flowcharted in Figure 2.3.4.1.1.1-3.

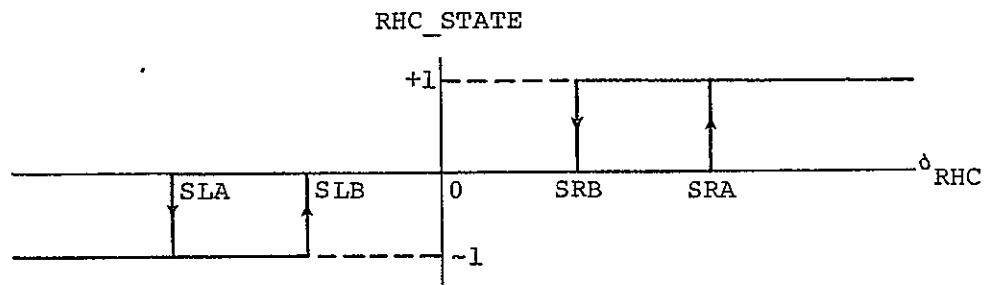
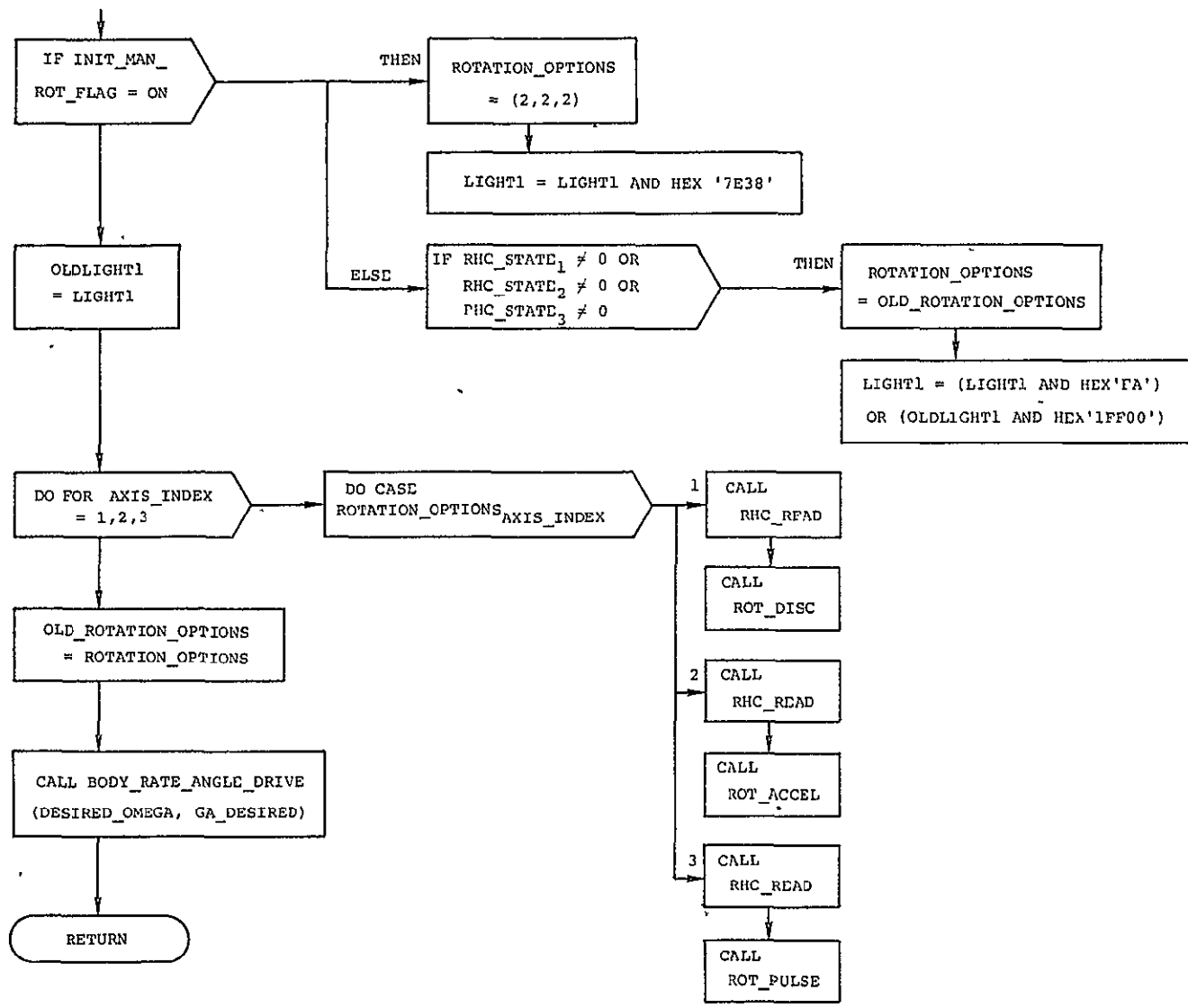


Figure 2.3.4.1.1.1-1. RHC hysteresis incorporated by RHC_READ.

RHC_READ compares the RHC deflection with four deadband limits to determine if it is out of detent. If the deflection is greater than SRA, RHC_STATE = +1. If it is less than SLA, RHC_STATE = -1. If the RHC deflection is between SLB and SRB, it is considered in detent, and RHC_STATE = 0.

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Figure 2.3.4.1.1.1-2. MAN_RCS_ROT: PROCEDURE.

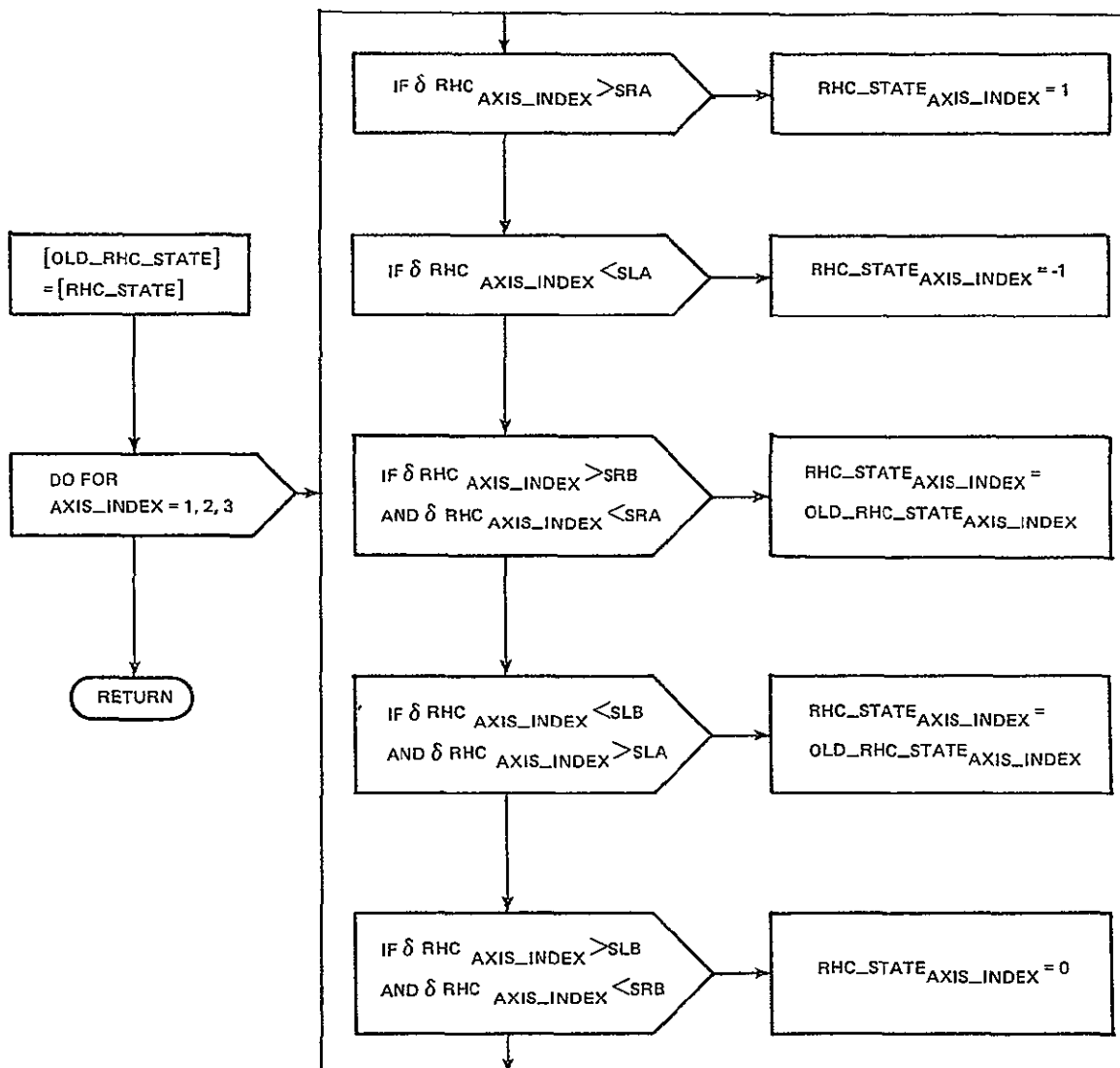


Figure 2.3.4.1.1.1-3. RHC_READ: PROCEDURE.

If the RHC deflection is in the hysteresis zone between SLA and SLB or between SRA and SRB, RHC-STATE is set equal to its value on the last FC pass. By this logic RHC_STATE remains at the value it had upon entering the hysteresis zone, as long as the RHC deflection remains in that zone. Thus small-amplitude RHC vibrations will cause at most one change in the value of RHC_STATE, which prevents system dither.

2.3.4.1.1.1.1 Discrete Rate Command Submode. - The routine ROT_DISC, flowcharted in Figure 2.3.4.1.1.1-4, first sets the components of CLSTRF for the affected axis to ON, commanding the higher of two levels of angular acceleration. BYPASS_PHASE_PLANE is set to OFF for this axis, indicating that the Phase Plane Switching Logic will be used in this axis. A new value of desired omega is obtained, equal to the selected discrete omega, with the sense of RHC deflection. If the RHC is in detent, this value is zero. If the difference between desired omega and the current estimated angular rate, ω_{hat} , is larger than a preset deadband, the new desired omega is used in conjunction with BODY_RATE_ANGLE_DRIVE (Subsection 2.3.4.1.2.1.5) to generate appropriate commands for RCS_ERRORS.

2.3.4.1.1.1.2 Direct Rotation Acceleration Command Submode. - On the first pass of the procedure ROT_ACCEL, flowcharted in Figure 2.3.4.1.1.1-5, CLSTRF is set ON or OFF depending on whether the crew selected the high or low rotation option in this axis. BYPASS_PHASE_PLANE is set ON so that the Jet Select Logic is directly driven by this submode. The jet select rate change command is set equal to a nominal value with the sense of RHC deflection. If the RHC is in detent, the jets are commanded OFF.

2.3.4.1.1.1.3 Direct Rotation Pulse Command Submode. - The procedure ROT_PULSE, flowcharted in Figure 2.3.4.1.1.1-6, first sets the component of CLSTRF for the affected axis ON, selecting the higher of two available levels of angular acceleration. BYPASS_PHASE_PLANE is set ON in this axis, indicating that the Jet Selection Logic will be driven directly by this routine. On the first pass in this submode, desired omega in the affected axis is initialized to the current estimated angular rate, ω_{hat} .

On passes for which the RHC is out of detent, and was in detent on the previous pass, desired omega is incremented by the selected pulse size, with the sense of RHC deflection. If the RHC is in detent, the value of desired omega is not incremented.

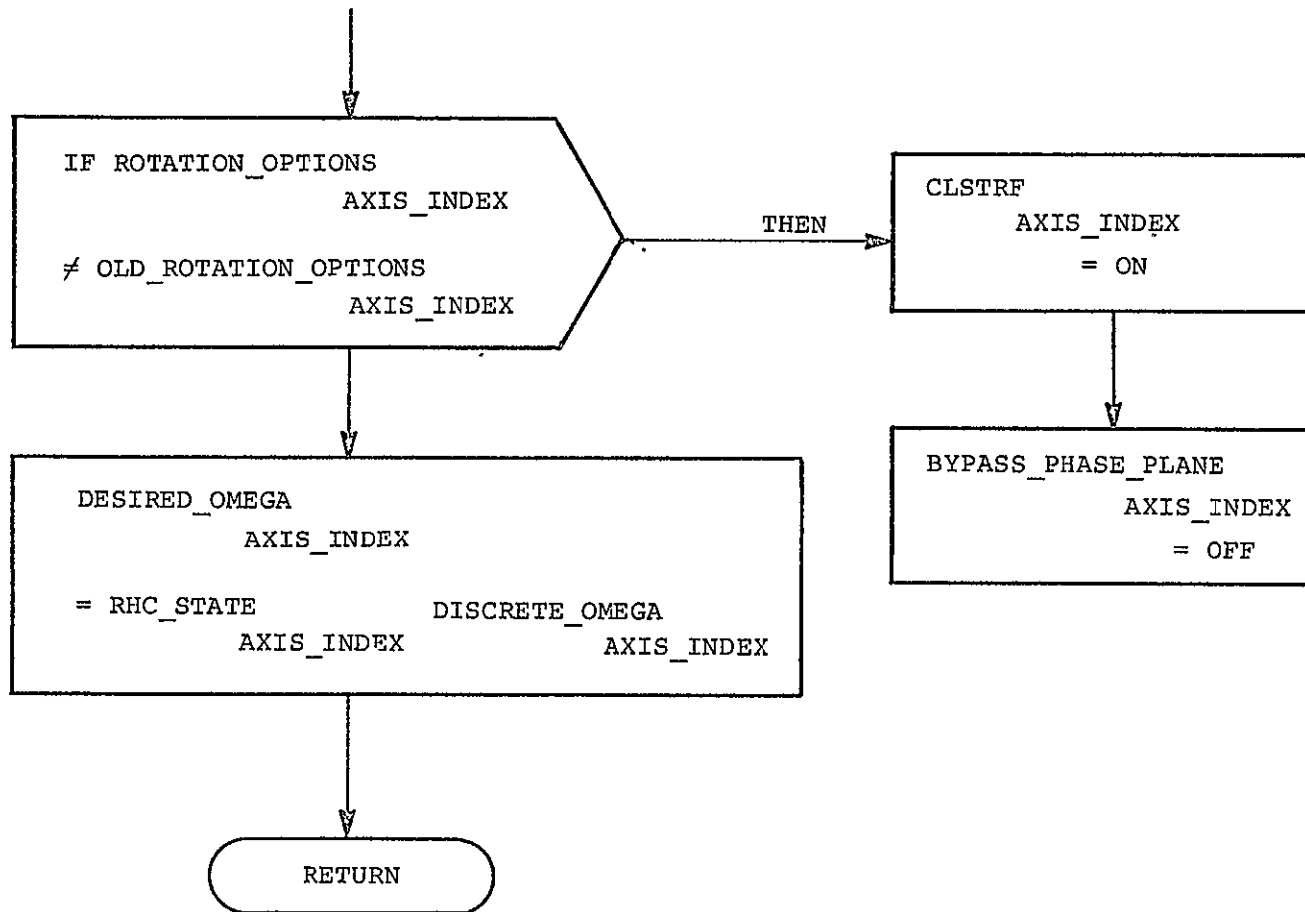


Figure 2.3.4.1.1.1-4. ROT_DISC: PROCEDURE.

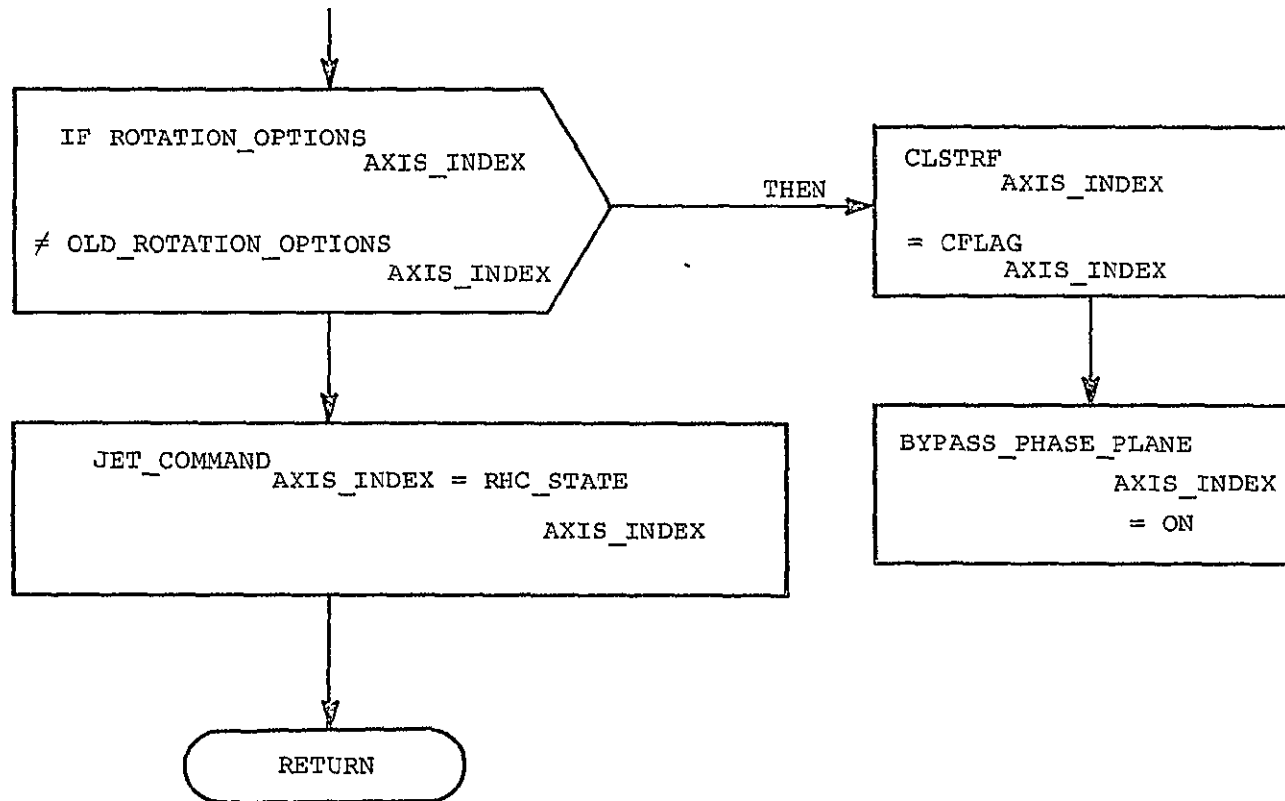


Figure 2.3.4.1.1.1-5. ROT_ACCEL: PROCEDURE.

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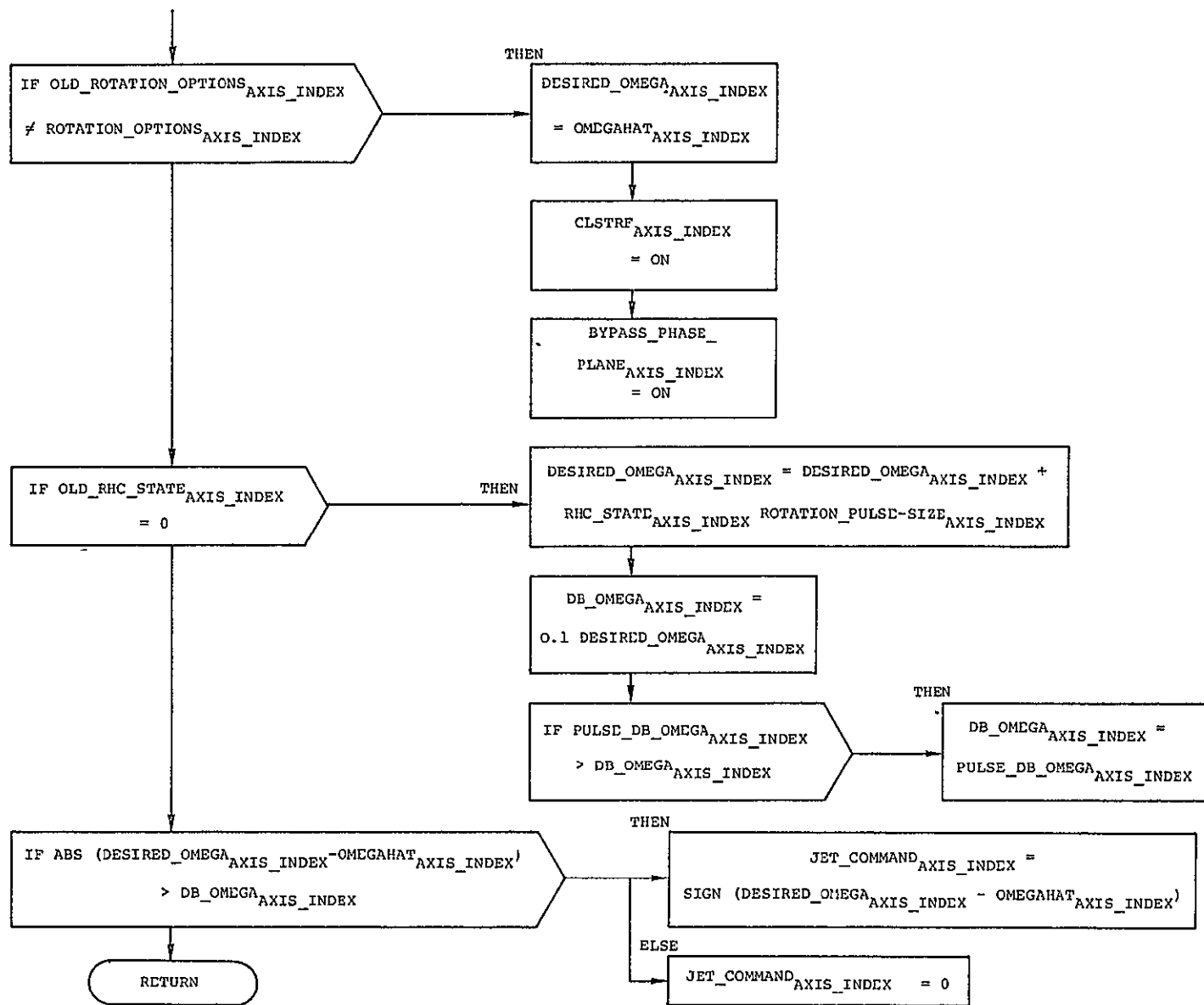


Figure 2.3.4.1.1.1-6. ROT_PULSE: PROCEDURE.

A deadband, equal to 0.1 times desired omega but not less than a preset minimum, is placed around the current estimated angular velocity. If the desired rate is outside this deadband, commands are sent to the Jet Selection Logic appropriate to drive the rate into the deadband. Otherwise, the jets are commanded OFF.

2.3.4.1.1.2 Translation

The procedure MAN_RCS_TRANS, flowcharted in Figure 2.3.4.1.1.2-1, checks the THC for detent. If the THC is out of detent, MAN_RCS_TRANS takes the translation submode selections to be the same as those of the previous pass, and commands the switches corresponding to those options to be illuminated, effecting inhibition of submode changes. If the THC is in detent, new submode selections are accepted, with the submodes of the previous pass as default selections.

MAN_RCS_TRANS then executes the selected submodes in each of the three translation axes.

2.3.4.1.1.2.1 Manual Direct Translation Acceleration Command Submode.

When the procedure TRANS_ACCEL, flowcharted in Figure 2.3.4.1.1.2-2, is selected for an axis, the component of CLSTRF in that axis is set ON or OFF in accordance with the translation high/low selections. The jet select rate change command in that axis is set equal to a nominal rate change with the sense of THC deflection. If the THC is in detent, the jets are commanded OFF.

2.3.4.1.1.2.2 Direct Translation Pulse Command Submode. - On the first

pass of the procedure TRANS_PULSE, flowcharted in Figure 2.3.4.1.1.2-3, the component of CLSTRF in the affected axis is set ON, and V_DESIRED and V_NOW are set to zero. If the THC was in detent on a previous FC pass, V_DESIRED is incremented by the selected translation pulse size with the same sense as the THC deflection. If the THC is in detent, V_DESIRED is not incremented. Should the difference between V_DESIRED and V_NOW be greater than a preset deadband, jets are commanded ON to drive this difference to zero. Otherwise, the jets are commanded OFF. V_NOW is incremented with the rate change predicted by the Jet Selection Logic.

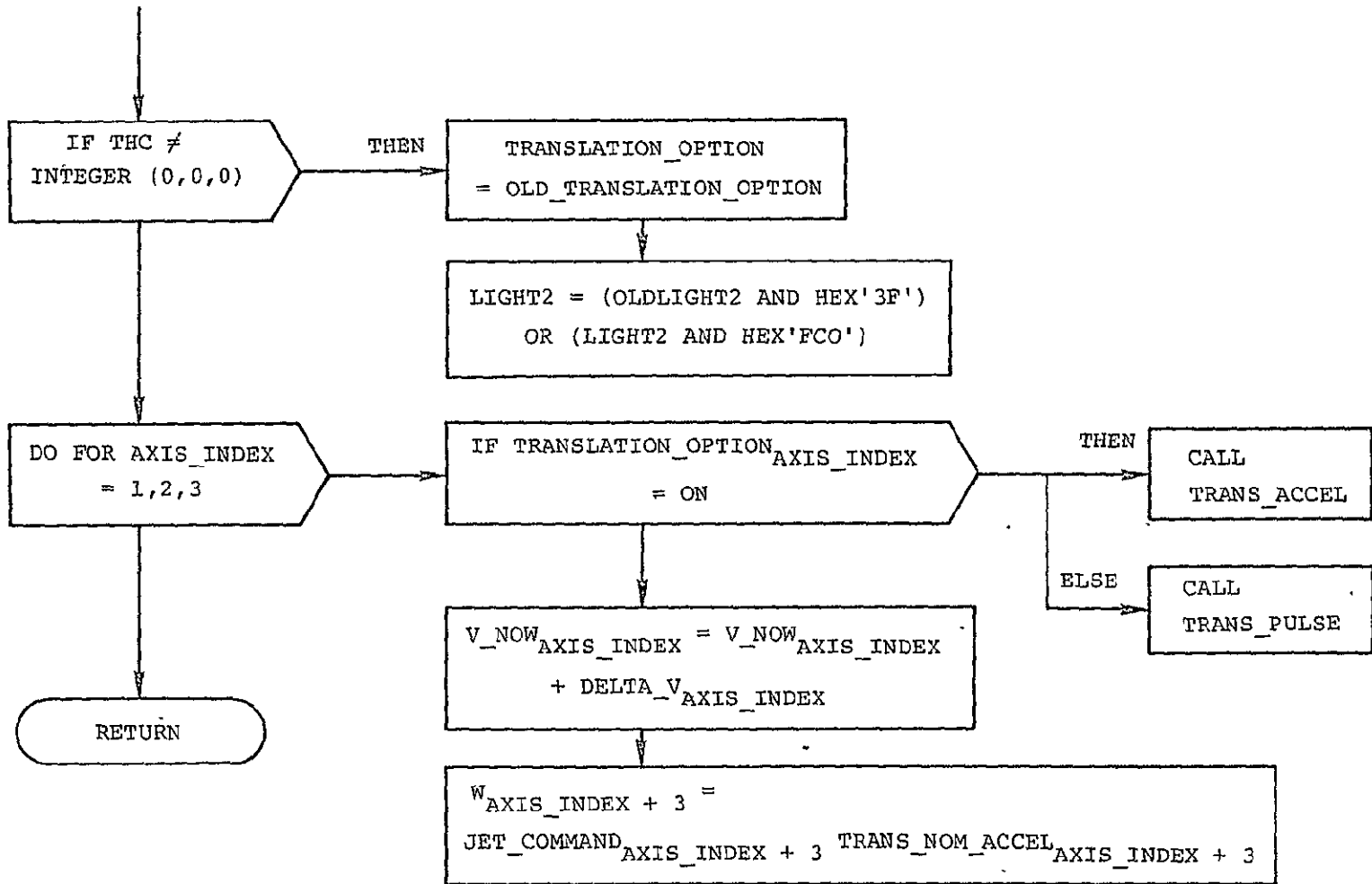


Figure 2.3.4.1.1.2-1. MAN_RCS_TRANS: PROCEDURE.

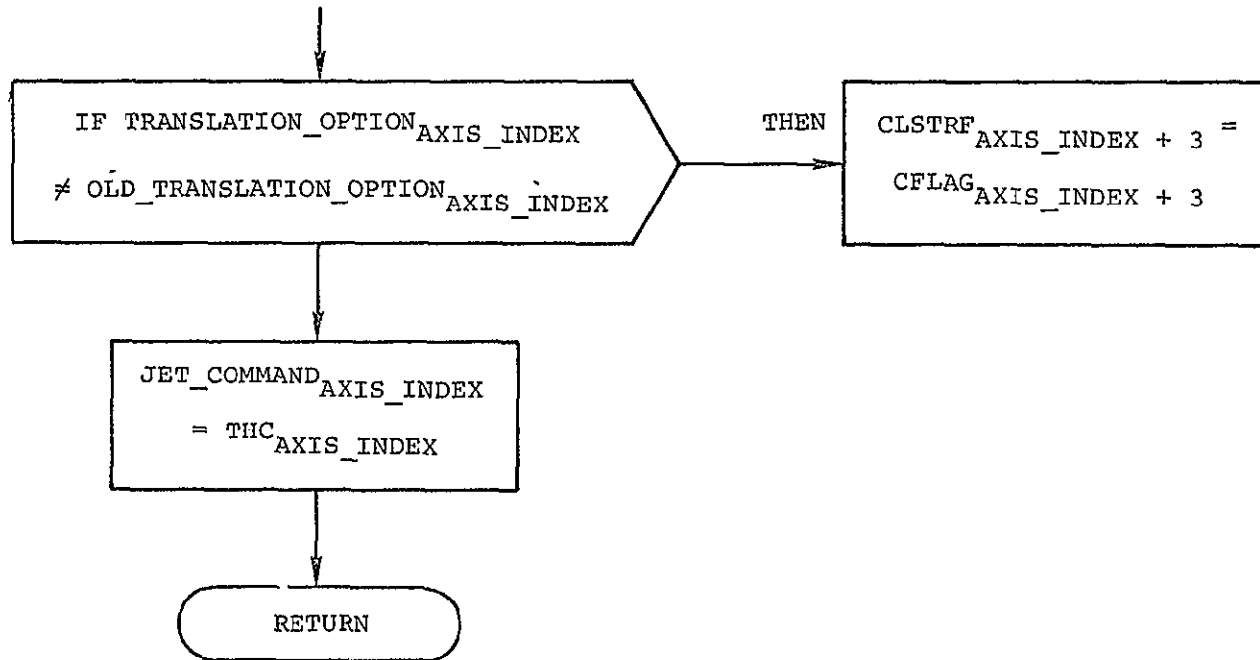


Figure 2.3.4.1.1.2-2. TRANS_ACCEL: PROCEDURE.

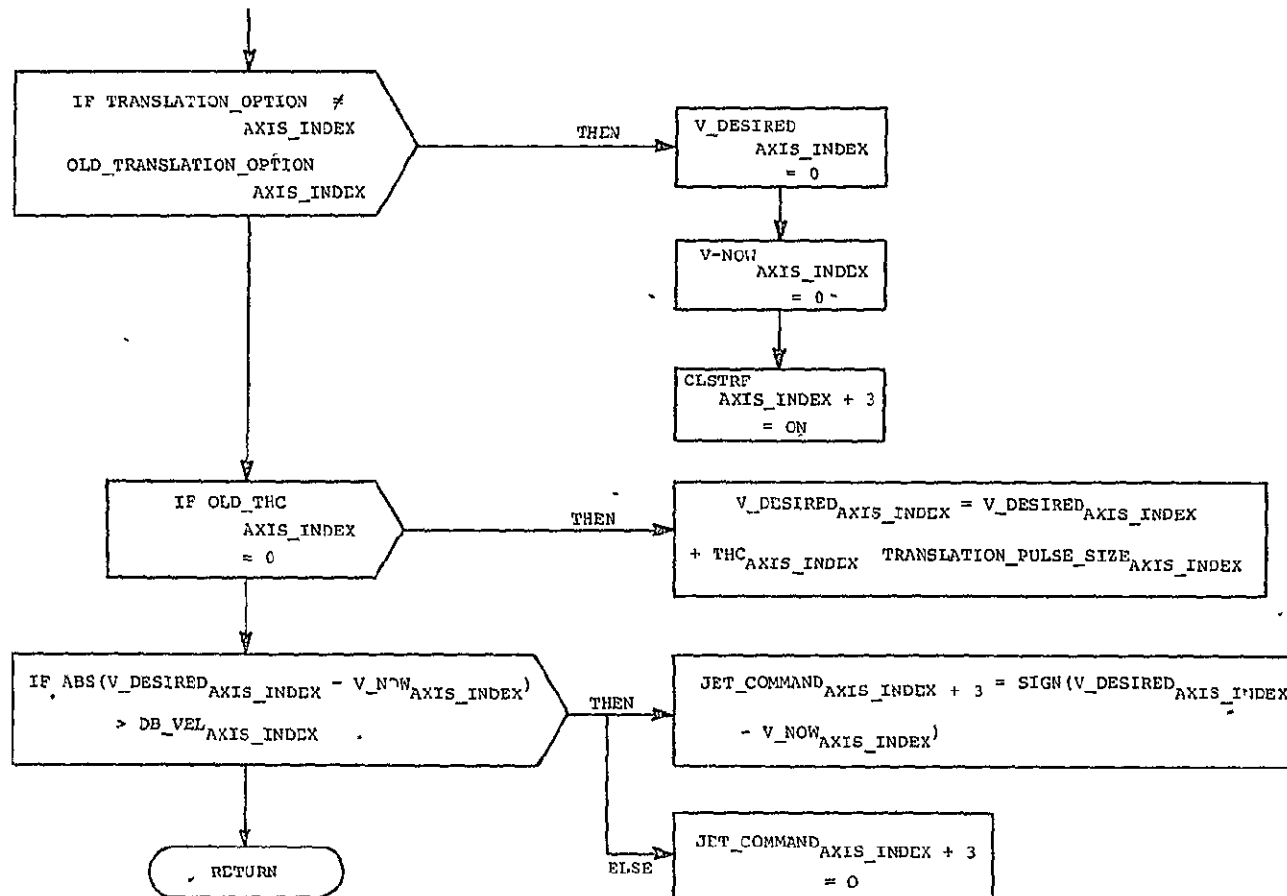


Figure 2.3.4.1.1.2-3. TRANS_PULSE: PROCEDURE.

2.3.4.1.2 Automatically Commanded RCS DAP Drivers

2.3.4.1.2.1 Rotation. - Figure 2.3.4.1.2.1-1 is a graphic summarization of the modular breakdown for automatic attitude maneuvers.

Table 2.3.4.1.2.1-1, the Module Dictionary for Attitude Maneuver, is a detailed summarization of the attitude maneuver modules and the flow of data into and out of these modules.

2.3.4.1.2.1.1 Three-Axis Automatic Attitude Maneuver. - An automatic attitude maneuver about all three axes is executed by calling the procedure ATTITUDE_MANEUVER. The structured flowchart for this procedure is found in Figure 2.3.4.1.2.1-2. The procedures STEERING, HOLD_ATTITUDE, and STOPRATE, set the values for $[\phi_D]$, $[\Delta\phi_D]$, β_{BIAS} and ω_D required for the RCS DAP. These procedures are flowcharted in Figures 2.3.4.1.2.1-3 through 2.3.4.1.2.1-5.

The service routines GIMBAL_ANGLE_READ, ANGLES_TO_DCM, DCM_TO_ANGLES and ROTATION_MATRIX are described in Subsection 2.3.4.1.2.1.4.

2.3.4.1.2.1.2 Two-Axis Automatic Attitude Maneuver. - A two-axis automatic attitude maneuver is executed by performing the procedure VECPOINT, followed by ATTITUDE_MANEUVER. The structured flowchart for VECPOINT appears in Figure 2.3.4.1.2.1-6. ATTITUDE_MANEUVER is described in Subsection 2.3.4.1.2.1.1. The service routines GIMBAL_ANGLE_READ, ANGLES_TO_DCM, DCM_TO_ANGLES, and ROTATION_MATRIX are described in Subsection 2.3.4.1.2.1.4.

2.3.4.1.2.1.3 OMS Prethrust Maneuver. - To be determined.

2.3.4.1.2.1.4 Automatic Attitude Maneuver Service Routines. - The procedures ANGLES_TO_DCM, DCM_TO_ANGLES, ROTATION_MATRIX, and GIMBAL_ANGLE_READ are flowcharted in Figures 2.3.4.1.2.1-7 through 2.3.4.1.2.1-10. These routines are called by a number of automatic attitude maneuver procedures.

2.3.4.1.2.1.5 Automatic Rate Drivers. - Automatic rate driving can be implemented by calling the procedure SM_RATE_ANGLE_DRIVE or BODY_RATE_ANGLE_DRIVE. Flowcharts of these procedures appear in Figures 2.3.4.1.2.1-11 and 2.3.4.1.2.1-12. The service routine COMPMPGA, which computes the transformation matrix from gimbal axes to body axes, is flowcharted in Figure 2.3.4.1.2.1-13. The service routine ANGLES_TO_DCM is described in the preceding subsection.

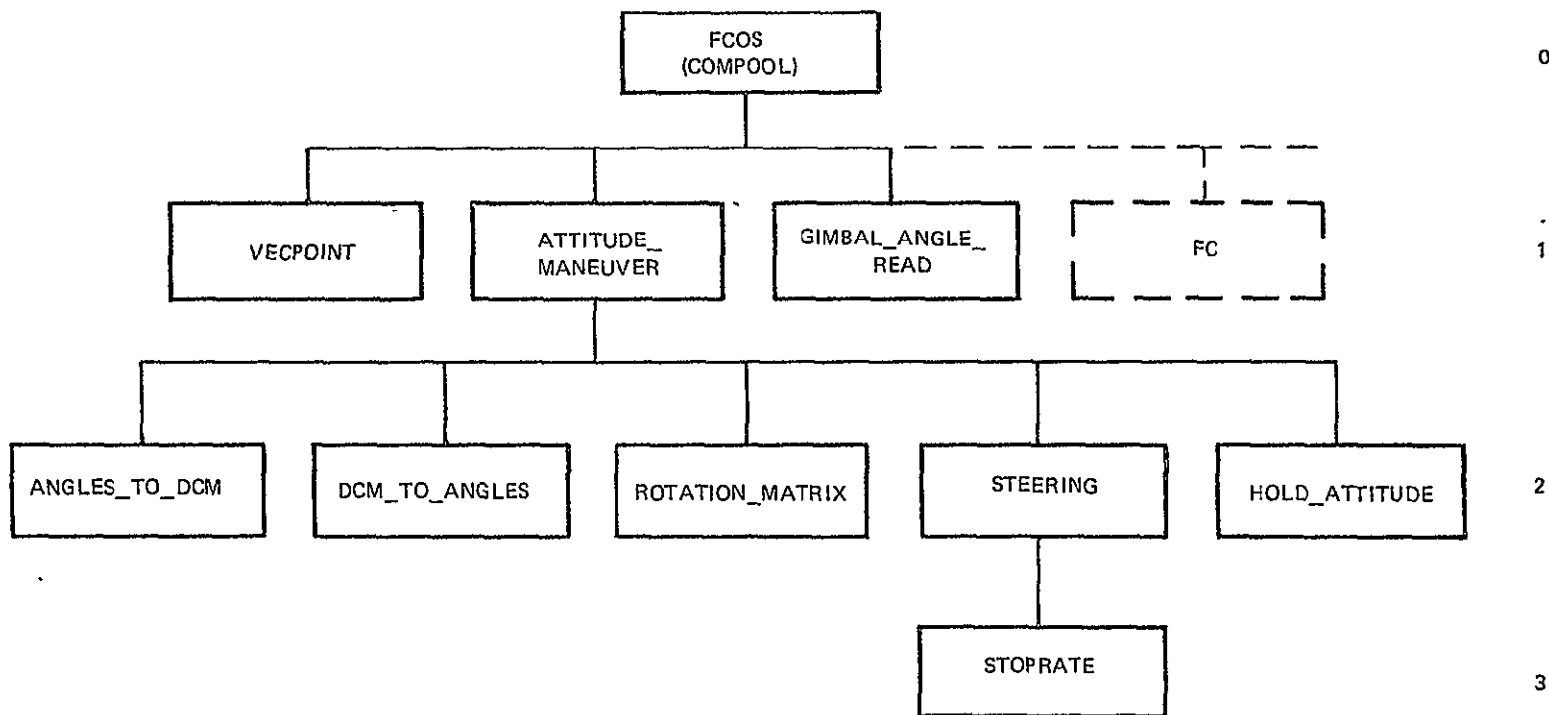


Figure 2.3.4.1.2.1-1. Structure of automatic attitude maneuvers.

Table 2.3.4.1.2.1-1. Attitude maneuver module dictionary.

MNEMONIC	DESCRIPTION	CLASS	DECLARED IN	ENTRY FORMAT	INPUTS REFERENCED	OUTPUTS ASSIGNED	LEVEL ²
ANGLES_TO_DCM	Converts an array of angles to a direction-cosine matrix	PROCEDURE	COMPOOL	ANGLES TO DCM PROCEDURE(ϕ) ASSIGN(C)	---	---	2
ATTITUDE_MANEUVER	Computes angle of rotation, A_M , and axis of single equivalent rotation, u_r , and calls STEERING	PROCEDURE	COMPOOL	ATTITUDE_MANEUVER PROCEDURE (ϕ_c, ω_r)	AUTO_MODE	---	1
DCM_TO_ANGLES	Converts direction-cosine matrix to an array of gimbal angles	PROCEDURE	COMPOOL	DCM_TO_ANGLES PROCEDURE(C) ASSIGN(ϕ)	π	---	2
GIMBAL_ANGLE_READ	Reads the gimbal angles	PROCEDURE	COMPOOL	GIMBAL_ANGLE_READ PROCEDURE ASSIGN (GA)	---	---	1
HOLD_ATTITUDE	Sends steering parameters to the autopilot to hold attitude at commanded gimbal angles	PROCEDURE	ATTITUDE_MANEUVER	HOLD_ATTITUDE PROCEDURE	ϕ_c	$\phi_D, [\Delta\phi_D],$ $[\beta_{BIAS}], \omega_D$	2
ROTATION_MATRIX	Computes rotation matrix R from u_r and A_M	PROCEDURE	ATTITUDE_MANEUVER	ROTATION_MATRIX PROCEDURE(u_r, A) ASSIGN (R)	{identity}	---	2
STEERING	Computes and send to autopilot the steering parameters every Δt_{cycle} seconds	PROCEDURE	ATTITUDE_MANEUVER	STEERING PROCEDURE	$A_M, u_r, \omega_r,$ $\omega_D, \phi_c, [\phi_B],$ 'fast' $\Delta t_{cycle}^{C_{BSM}}$ REALSEC, AUTO_ MODE	$\phi_D, [\Delta\phi_D], [\beta_{BIAS}]$ $\omega_d, [\phi_B], C_{BSM}$	2
STOPRATE	Sends steering parameters to the autopilot to hold attitude at present gimbal angles	PROCEDURE	ATTITUDE_MANEUVER	STOPRATE PROCEDURE	Present gimbal angles obtained from GIMBAL_ANGLE_ READ	$\phi_D, [\Delta\phi_D],$ $[\beta_{BIAS}], \omega_D$	3
VECPOINT	Computes ϕ_c from u_{ANB} and u_{DSM}	PROCEDURE	COMPOOL	VECPOINT PROCEDURE	$u_{ANB}, u_{DSM}, u_{XL}, \pi$	ϕ_c	1

²COMPOOL being on level 0

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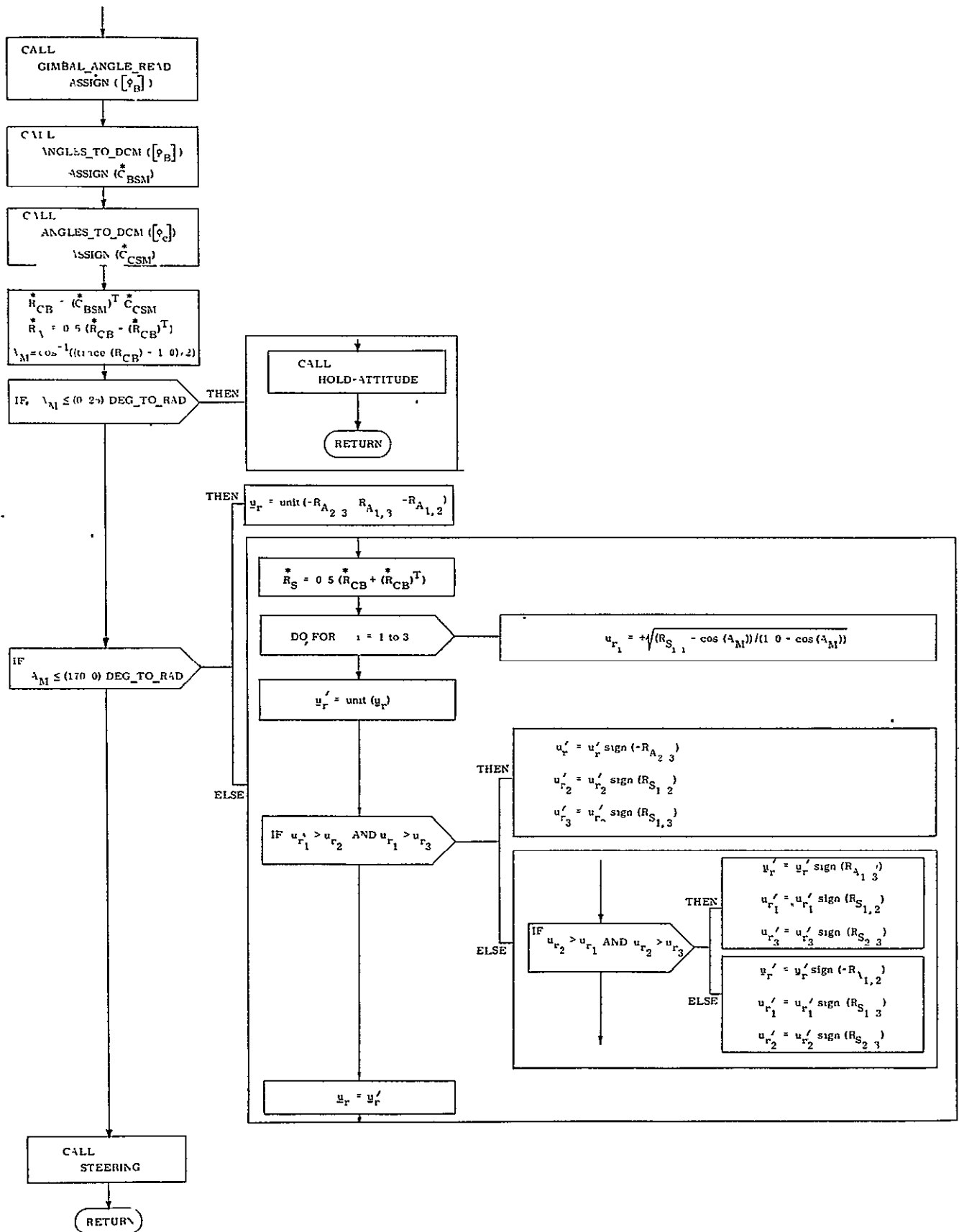


Figure 2.3.4.1.2.1-2. ATTITUDE_MANEUVER: PROCEDURE.

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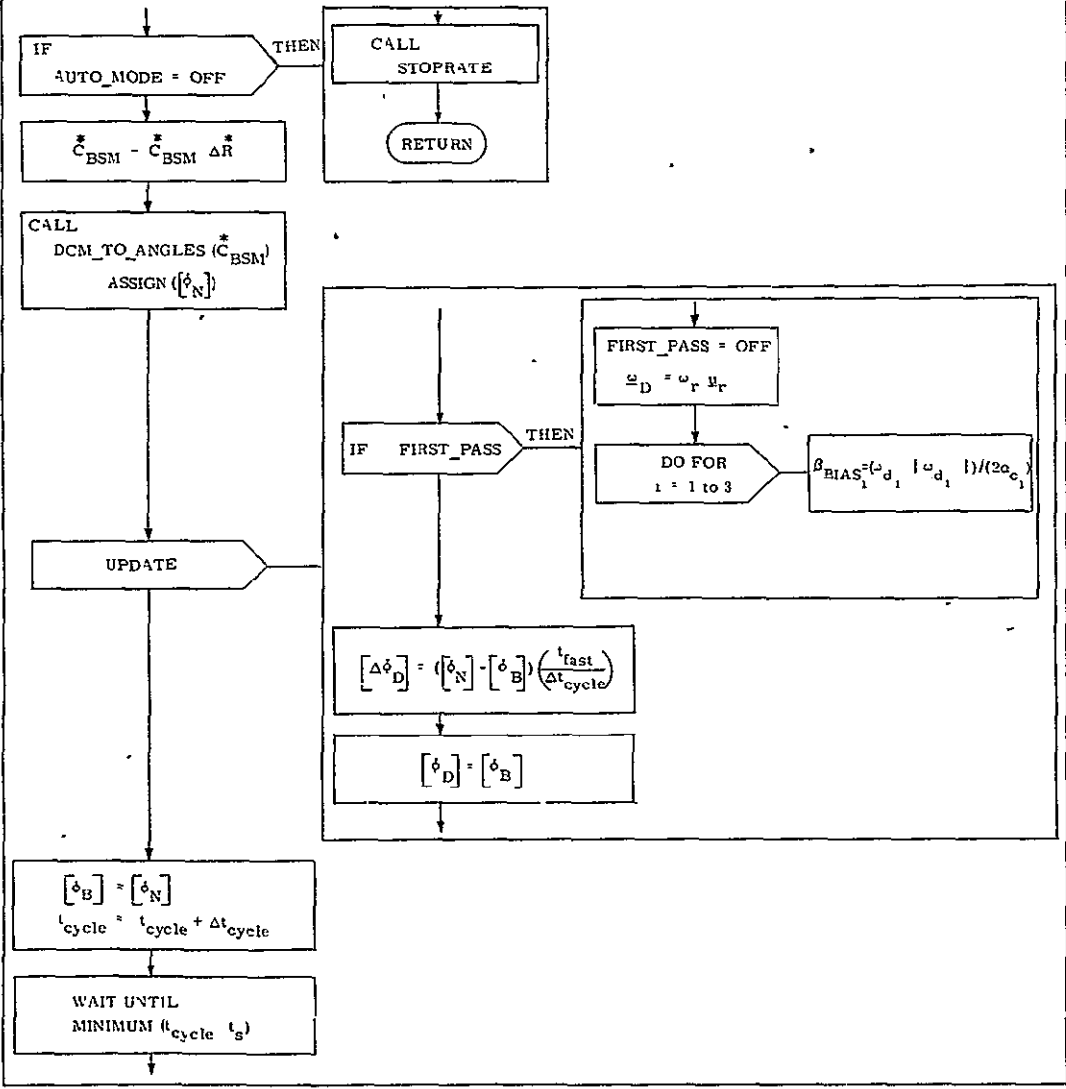
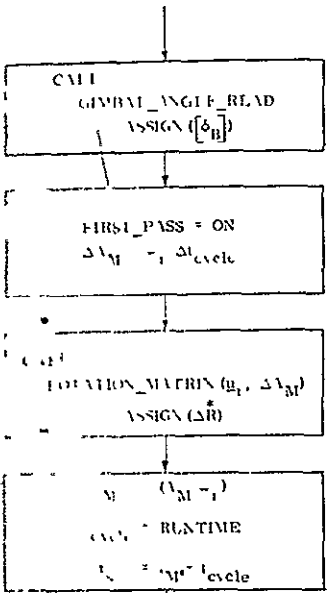


Figure 2.3.4.1.2.1-3. STEERING: PROCEDURE.

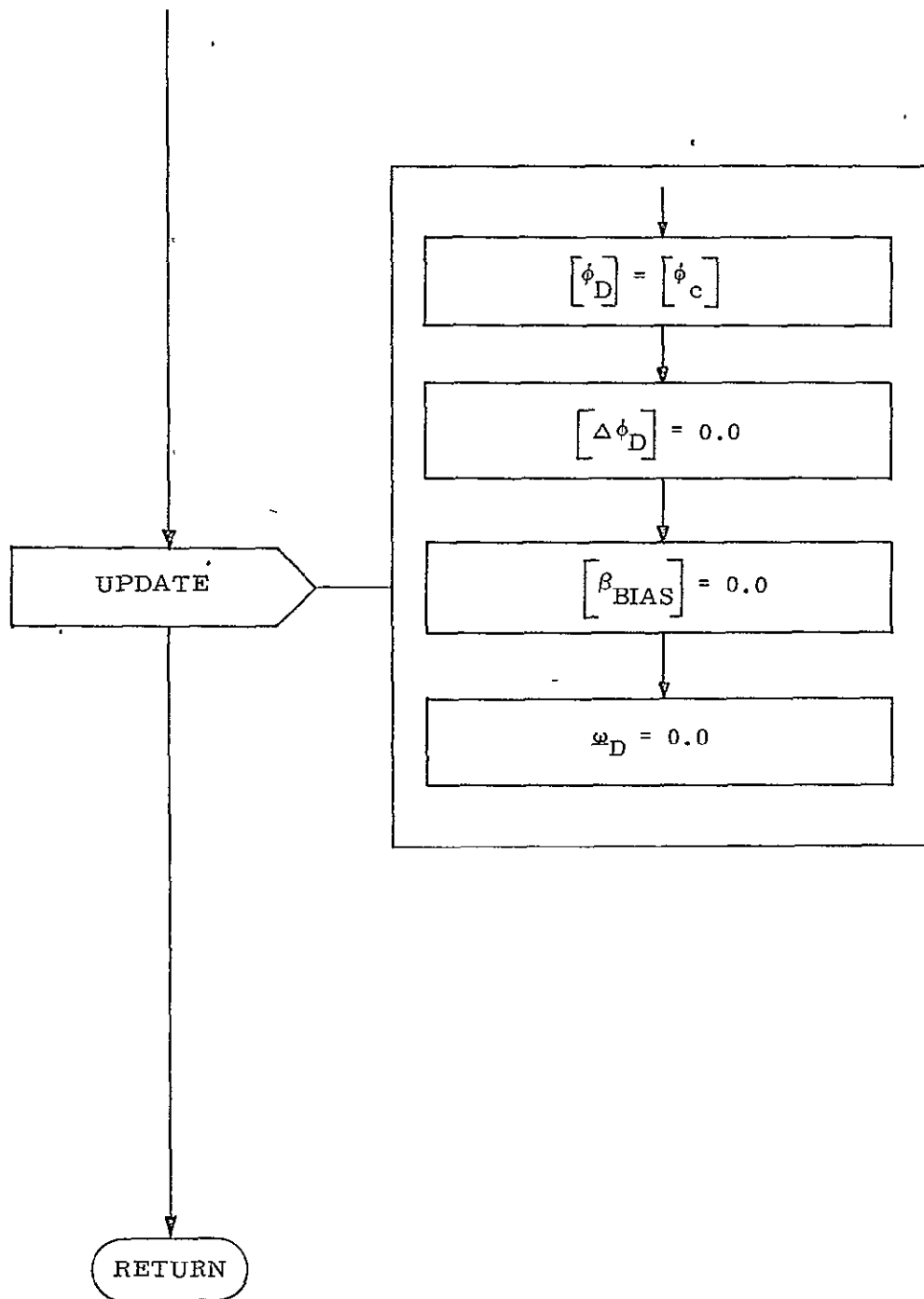


Figure 2.3.4.1.2.1-4. HOLD_ATTITUDE: PROCEDURE.

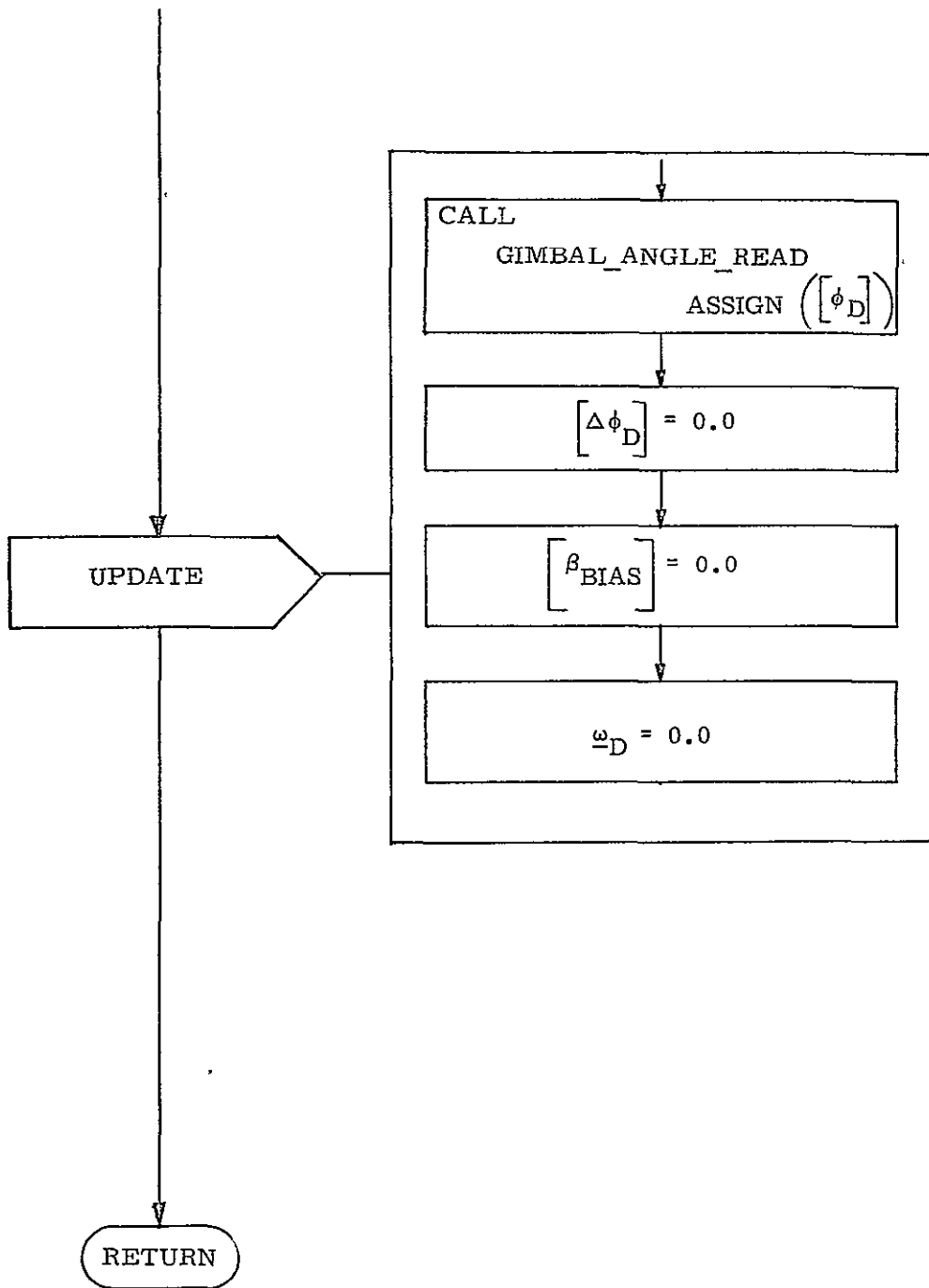
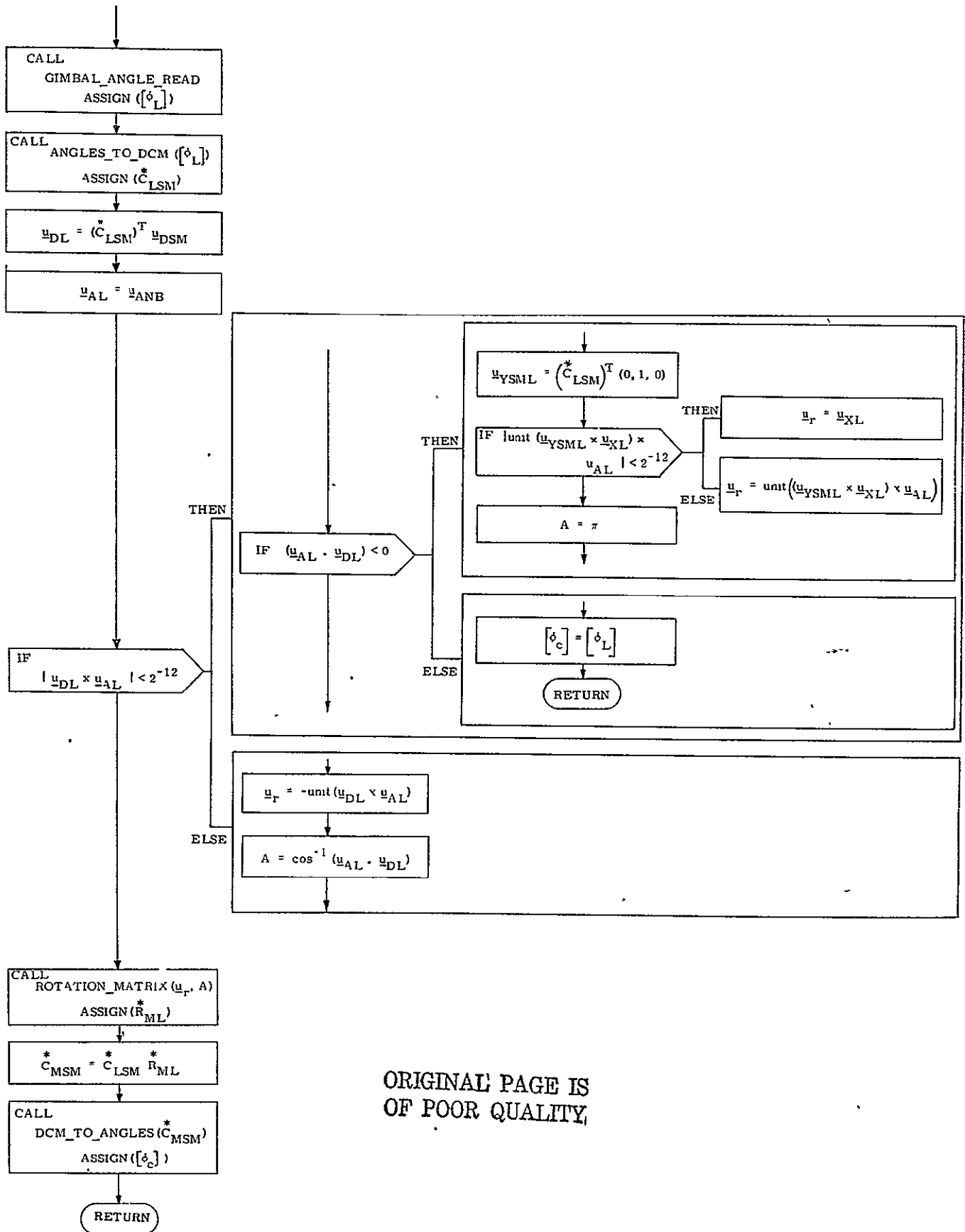


Figure 2.3.4.1.2.1-5. STOPRATE: PROCEDURE.



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Figure 2.3.4.1.2.1-6. VECPOINT: PROCEDURE.

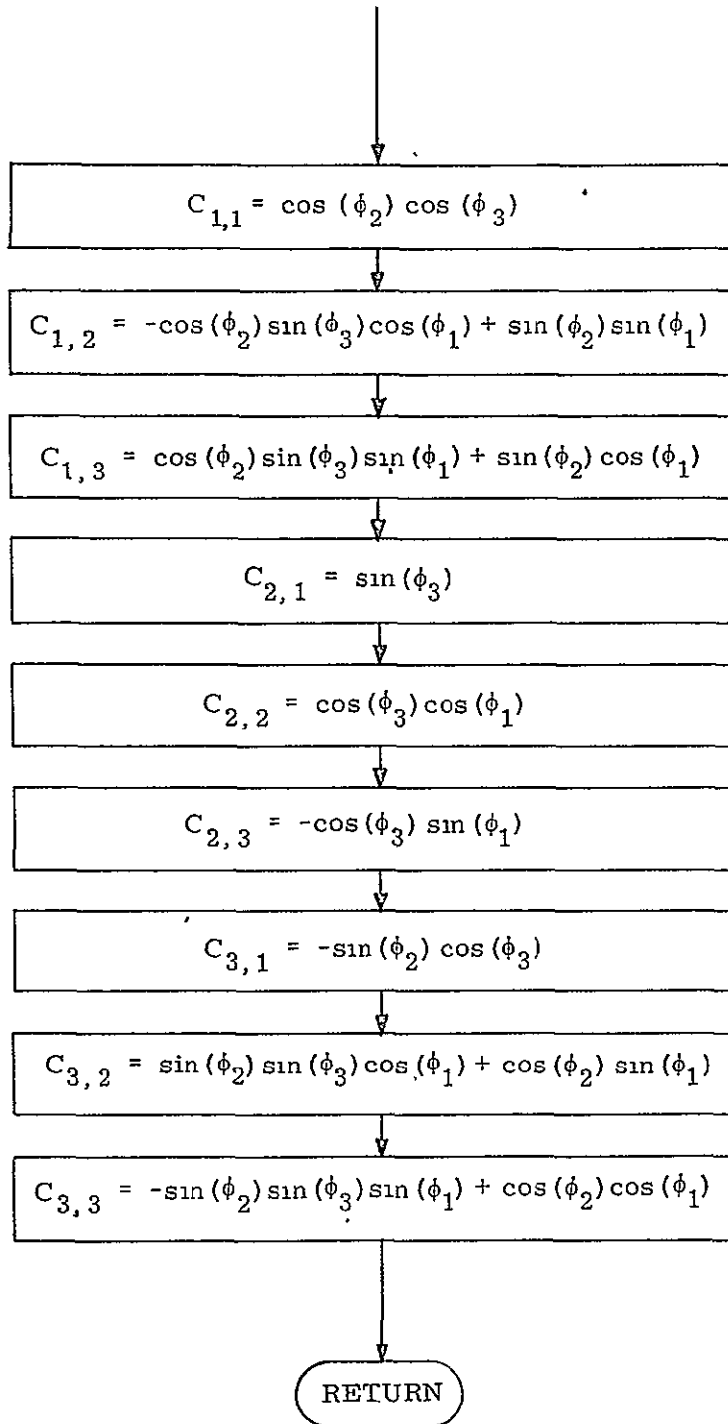
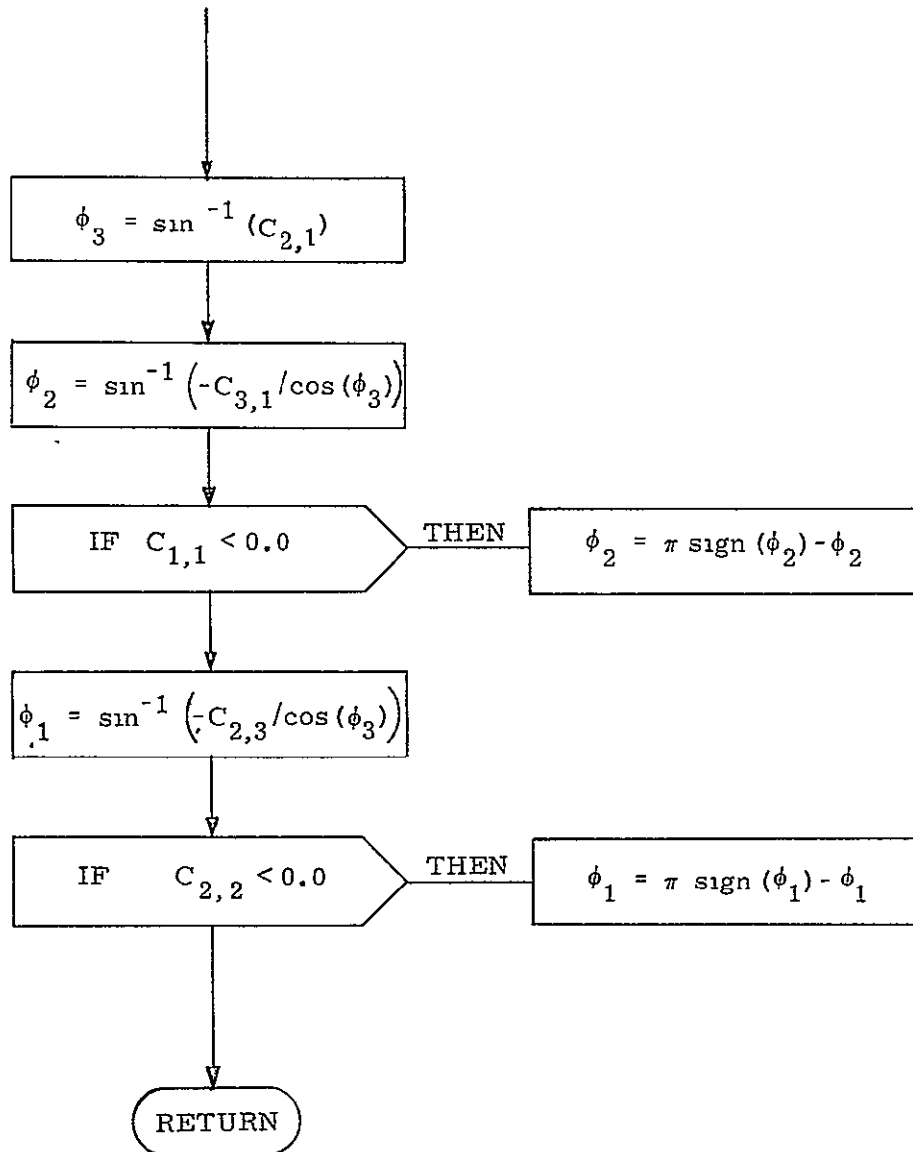


Figure 2.3.4.1.2.1-7. ANGLER_TO_DCM: PROCEDURE ([phi]) ASSIGN (C).



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Figure 2.3.4.1.2.1-8. DCM_TO_ANGLES: PROCEDURE (C) ASSIGN ([phi]).

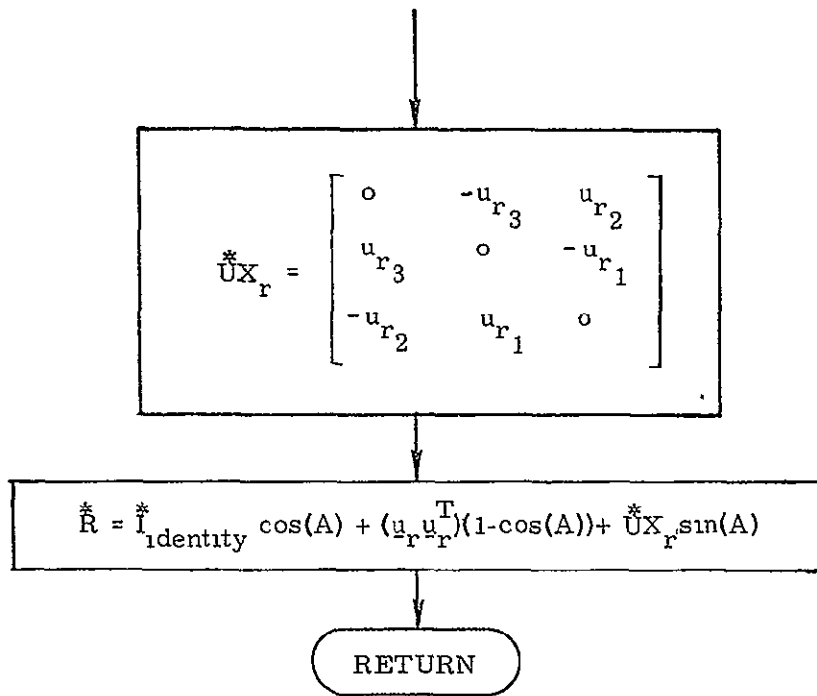


Figure 2.3.4.1.2.1-9. ROTATION_MATRIX: PROCEDURE (u_r, A) ASSIGN (*R).

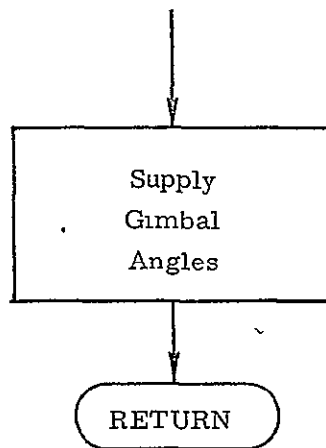


Figure 2.3.4.1.2.1-10. GIMBAL_ANGLE_READ: PROCEDURE ASSIGN ($[\phi]$).

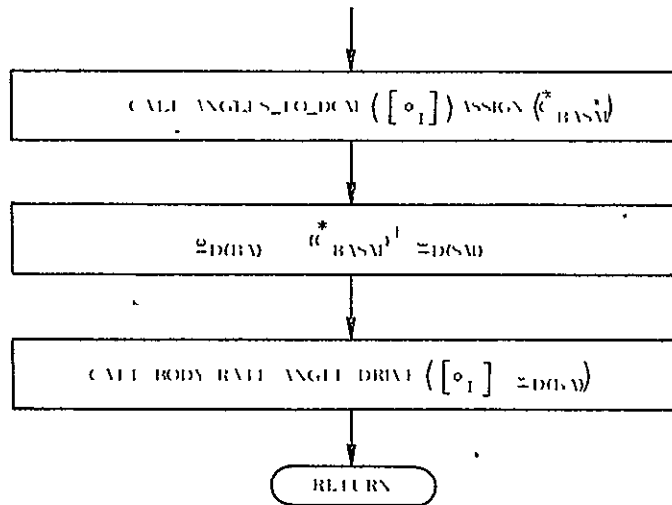


Figure 2.3.4.1.2.1-11. SM RATE ANGLE DRIVE:
PROCEDURE $([\phi_I], \omega_D(SM))$.

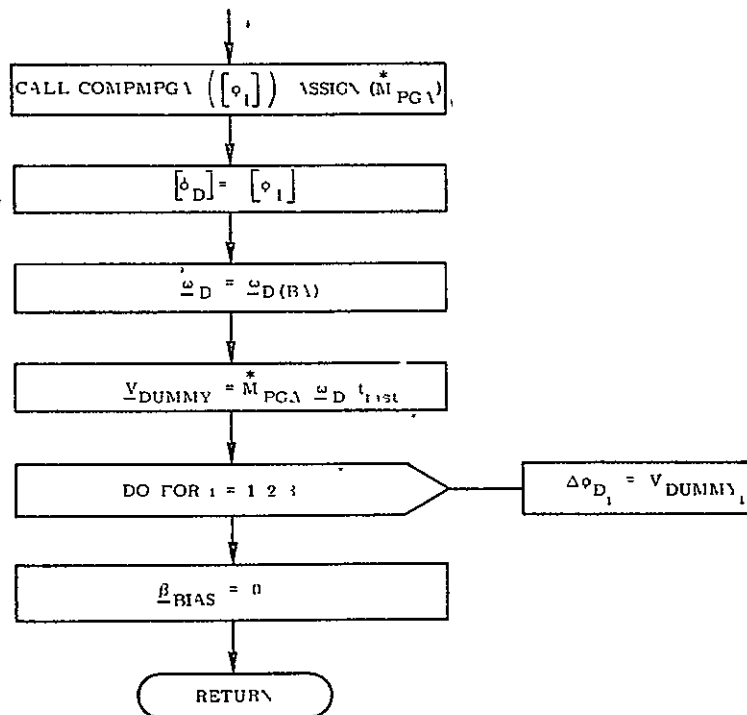


Figure 2.3.4.1.2.1-12. BODY RATE ANGLE DRIVE:
PROCEDURE $([\phi_I], \omega_D(BA))$.

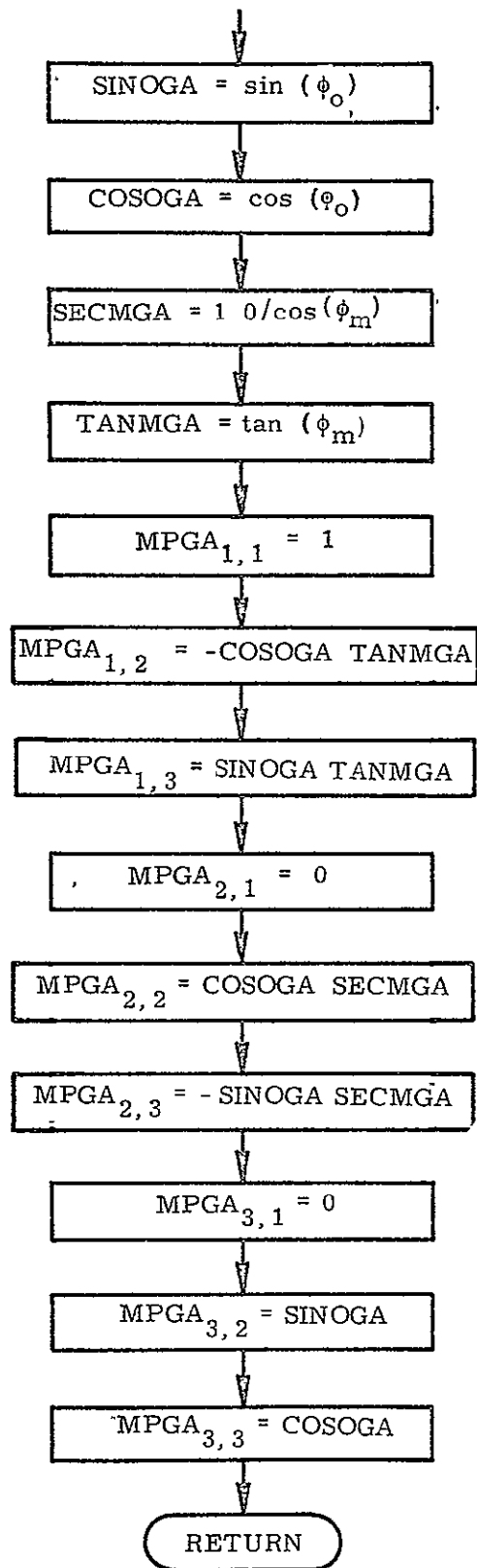


Figure 2.3.4.1.2.1-13. COMPMPGA: PROCEDURE $[(\phi)]$ ASSIGN $(MPGA)$.

- 2.3.4.1.2.1.6 Automatic Tracking. - To be determined.
- 2.3.4.1.2.1.7 Pointing. - To be determined.
- 2.3.4.1.2.1.8 Payload Supplied Commands. - To be determined.
- 2.3.4.1.2.2 Translation. - To be determined.
- 2.3.4.2 TVC DAP Drivers
 - 2.3.4.2.1 Manually Commanded TVC DAP Drivers. - To be determined.
 - 2.3.4.2.2 Automatically Commanded TVC DAP Drivers. - To be determined.
- 2.4 OMS/RCS Failure Detection and Identification
 - 2.4.1 OMS Engine FDI

The OMS engine failure detection and identification is performed by calling the procedure OMS_ENGINE_FDI once per second. The structured flowchart for this procedure is shown in Figure 2.4.1-1.

2.4.2 OMS Actuator FDI

The OMS actuator failure detection and identification is performed by calling the procedure OMS_ACTUATOR_FDI three times on successive 40 ms minor cycles, once per second. The structured flowchart for this procedure is shown in Figure 2.4.2-1.

2.4.3 RCS Jet FDI

Jet FDI is implemented in two main sections: Onfail Logic and Offail Logic. The Onfail Logic is again divided into new failure detection and recheck portions. The Onfail Logic is to be executed each major cycle, and Offail Logic each minor cycle. These routines are flowcharted in Figures 2.4.3-1 and 2.4.3-2.

The data used by the Jet FDI consists of jet commands from the jet selection routine, jet driver talkback combined with leak detector output, and pressure sensor output. Jet FDI issues fail flags and manifold shutdown commands.

The Onfail Logic first determines if a recheck is required due to the ON failure of any jet 3 major cycles before. If so, the recheck logic commands the appropriate manifold closed if the jet was failed ON at the last major cycle. Since this disables all jets on that manifold, fail flags for those jets are sent to the jet selection routine.

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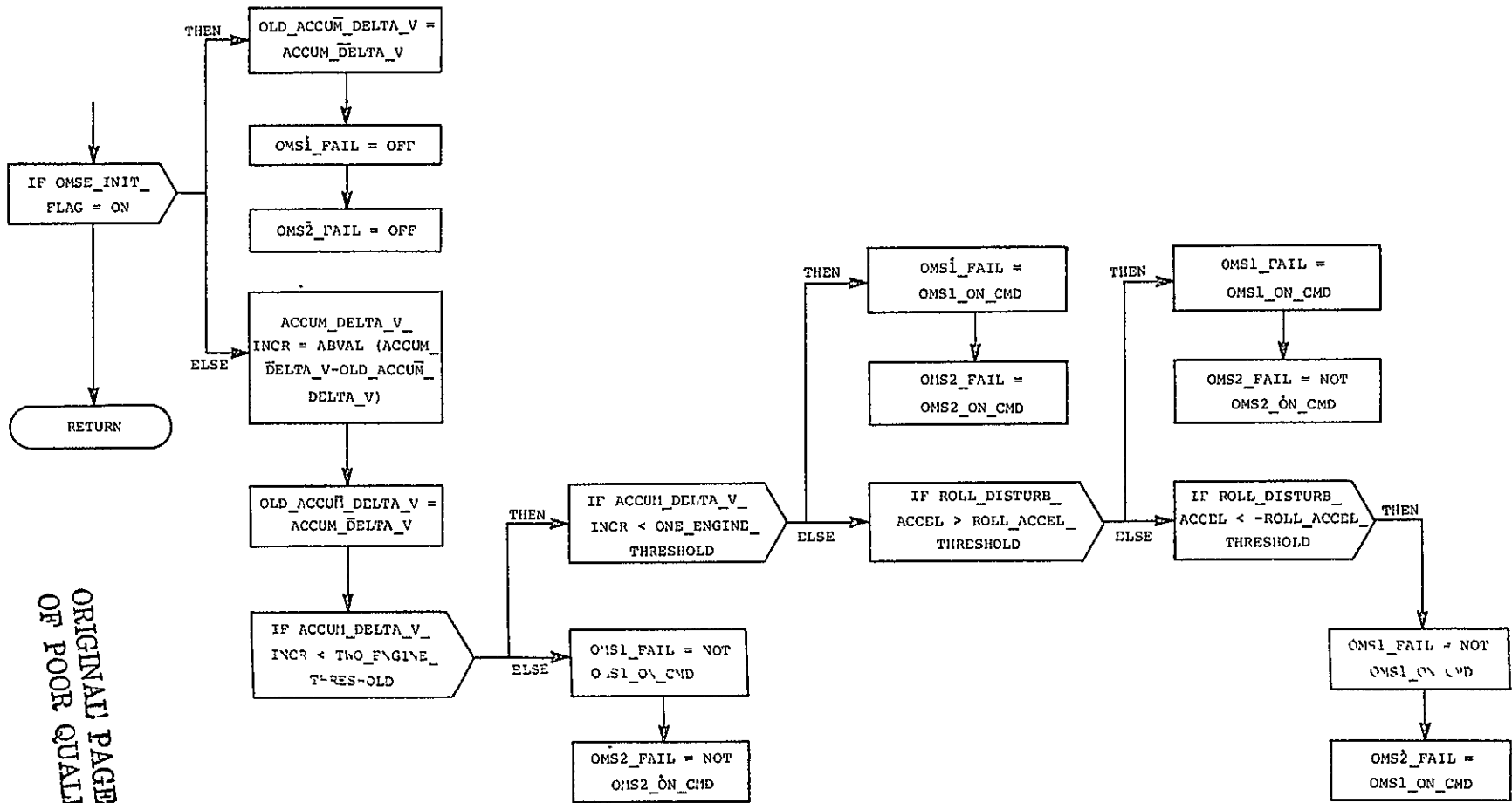


Figure 2.4.1-1. OMS_ENGINE_FDI: PROCEDURE.

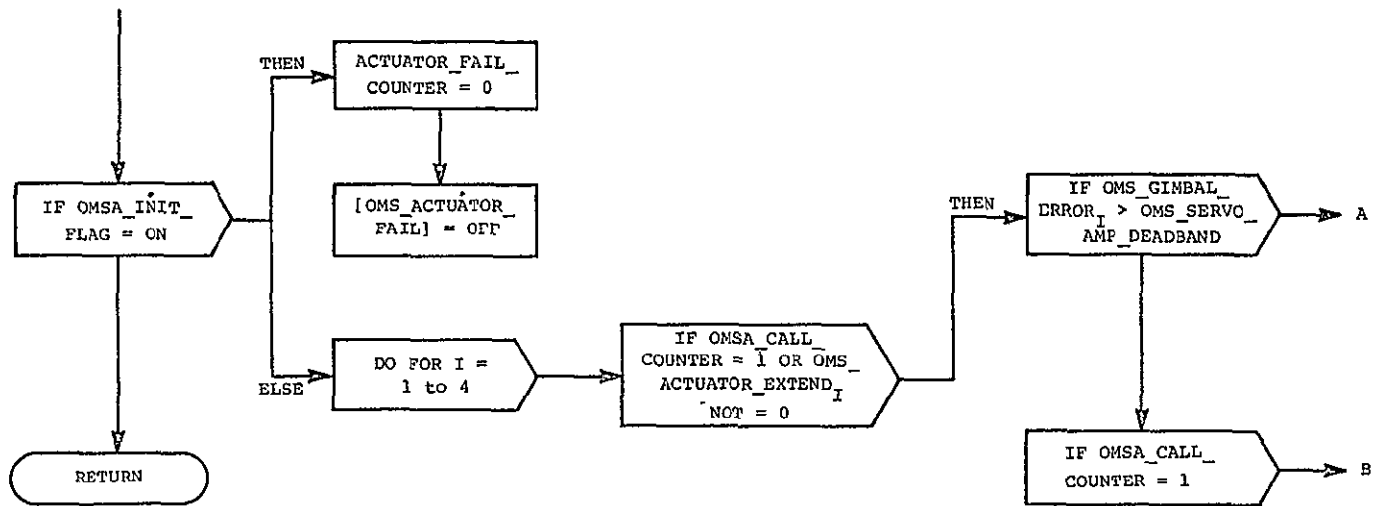
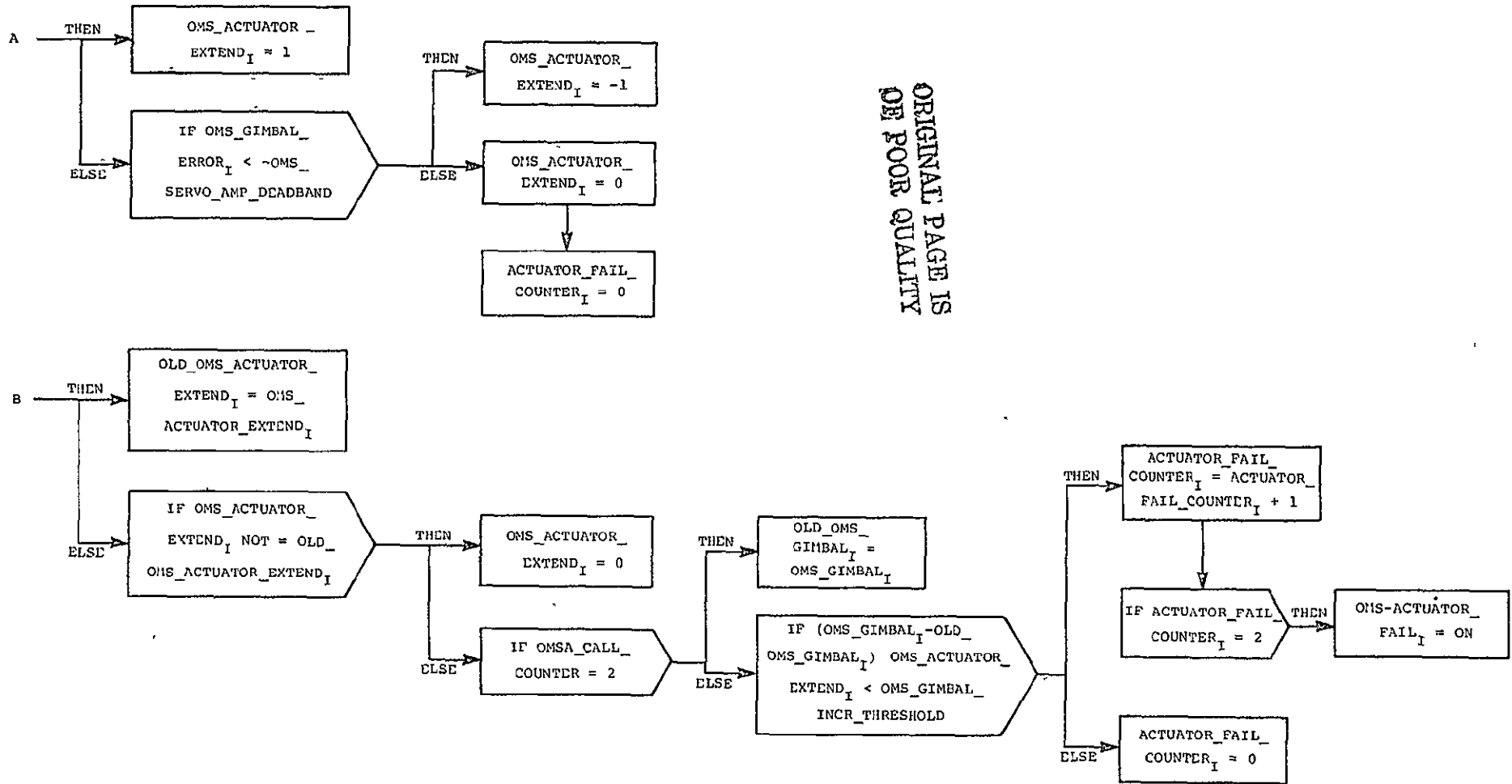


Figure 2.4.2-1. OMS_ACTUATOR_FDI: PROCEDURE.



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Figure 2.4.2-1. OMS_ACTUATOR_FDI: PROCEDURE (Cont.).

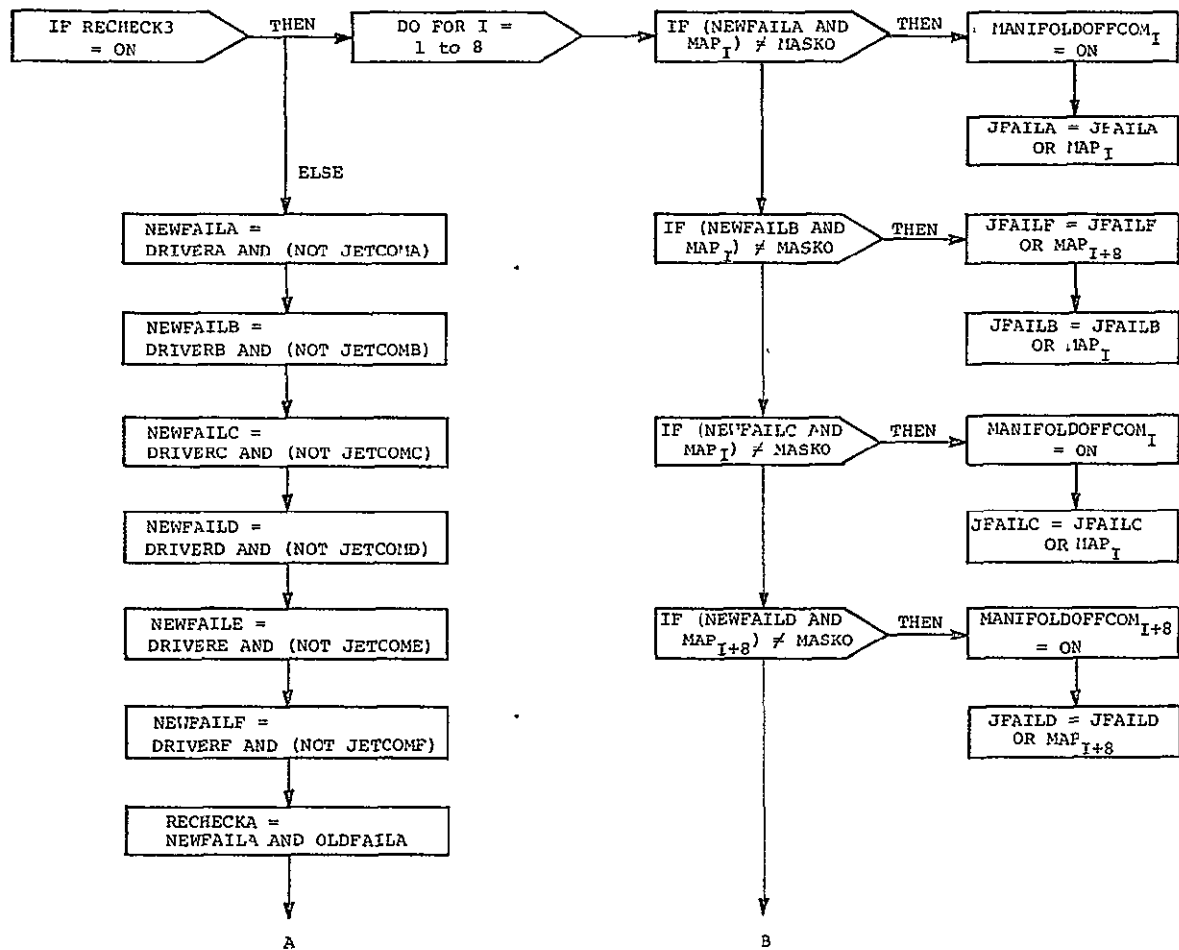


Figure 2.4.3-1. ONFAIL: PROCEDURE.

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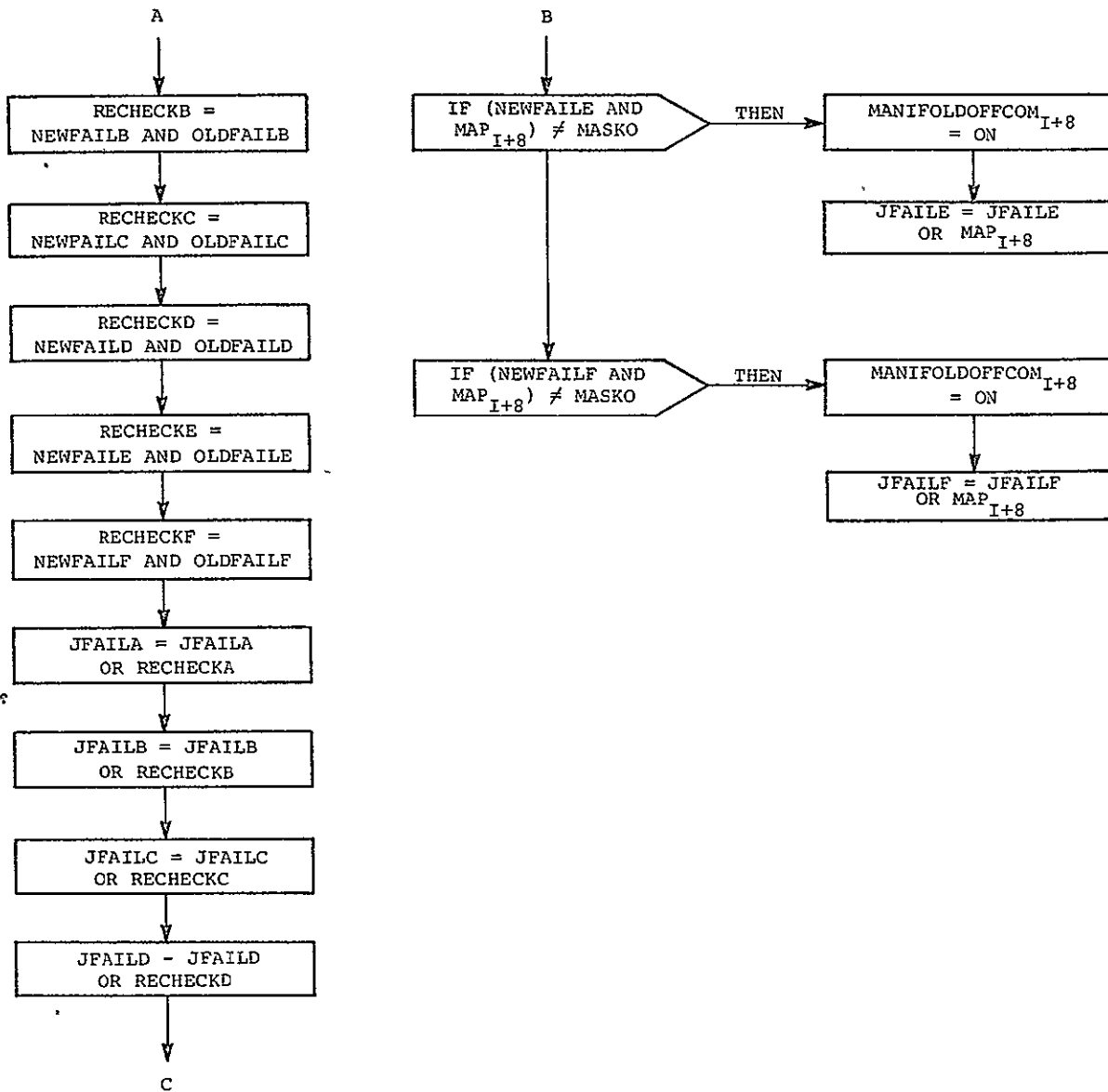


Figure 2.4.3-1. ONFAIL: PROCEDURE (Cont.).

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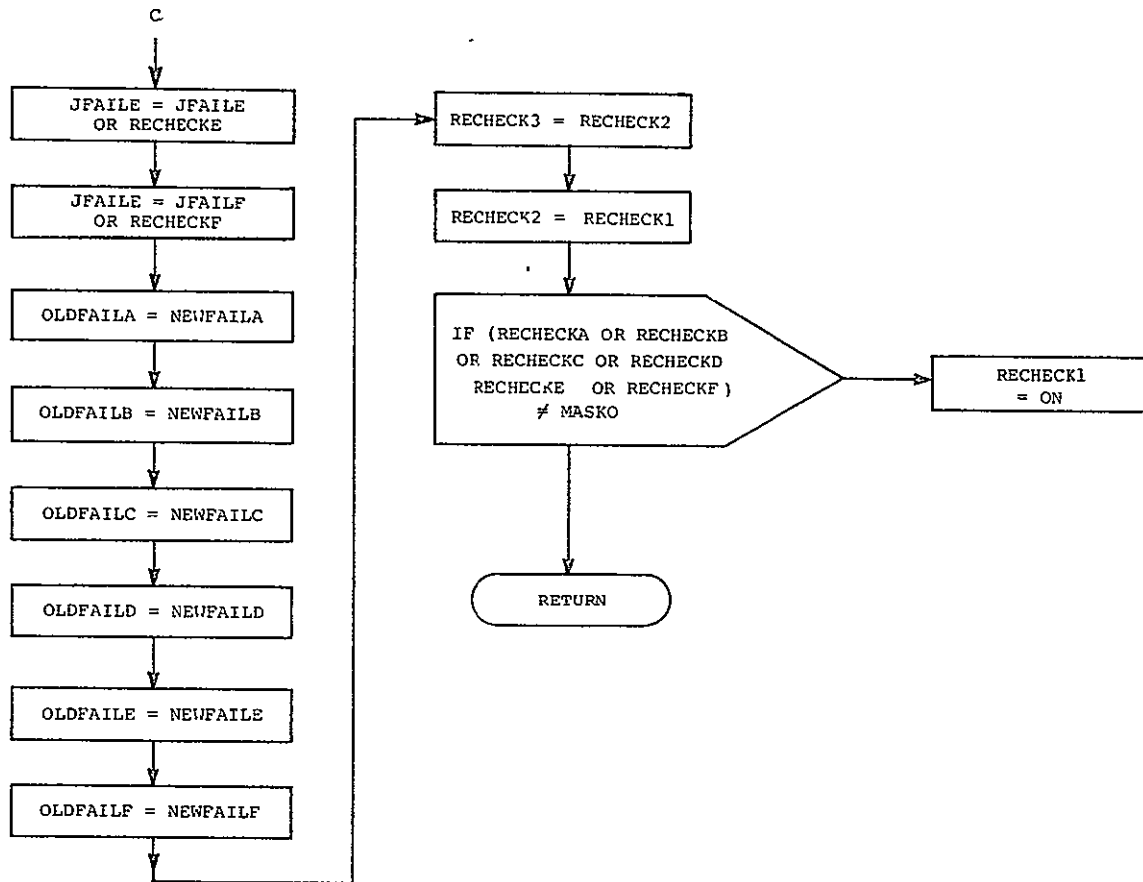


Figure 2.4.3-1. ONFAIL: PROCEDURE (Cont.).

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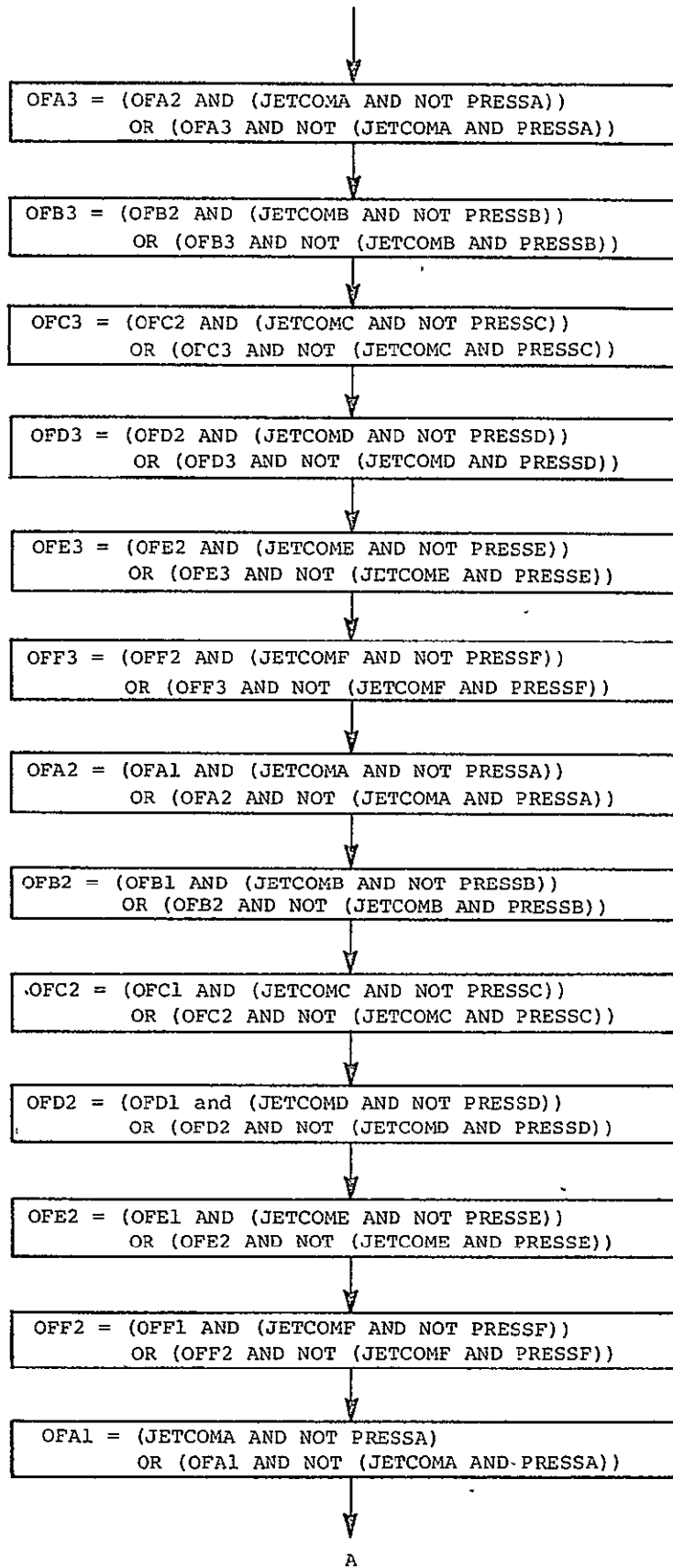


Figure 2.4.3-2. OFFAIL: PROCEDURE.

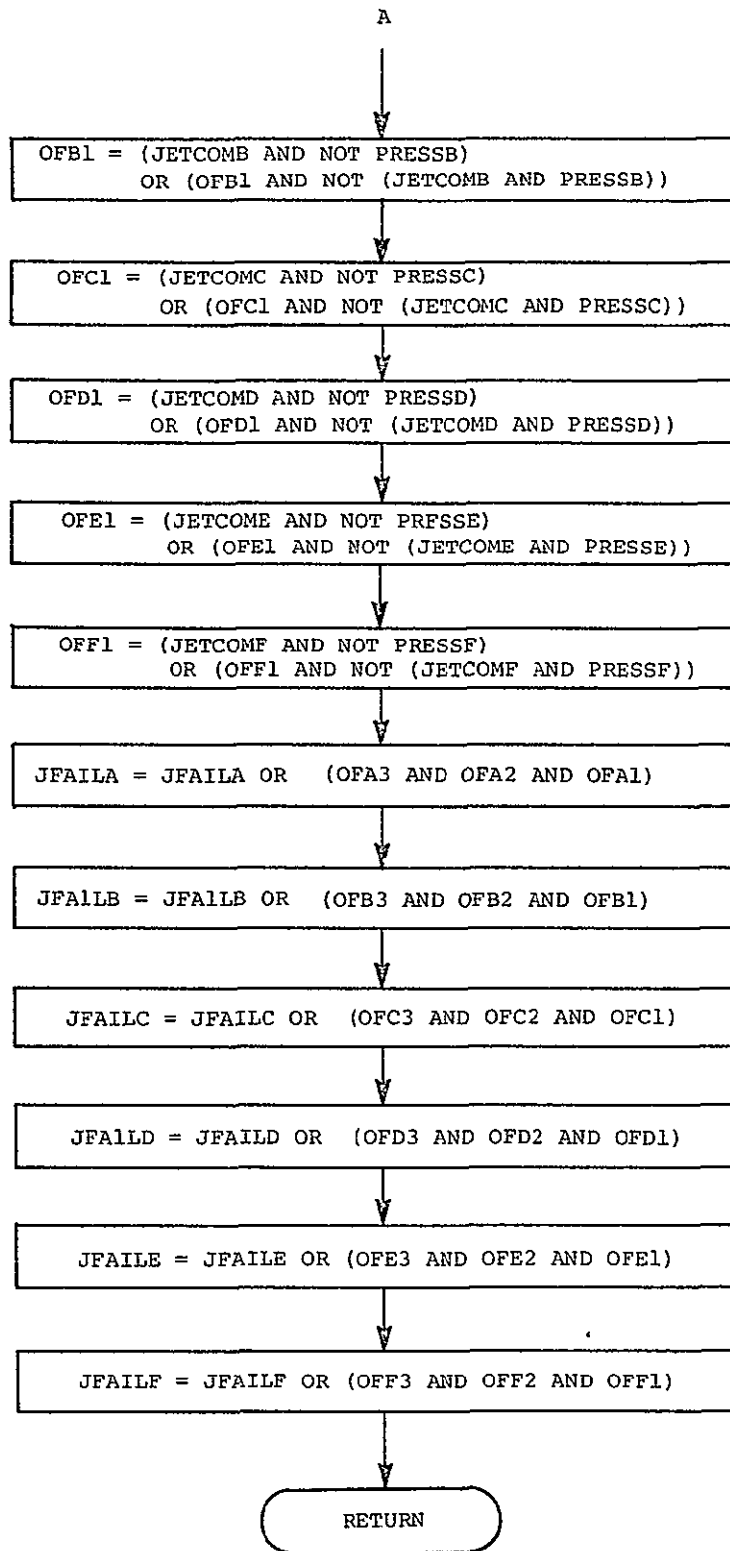


Figure 2.4.3-2. OFFAIL: PROCEDURE (Cont.).

On a pass with no recheck, jets which are not commanded ON, but which indicate either a leak or an ON command in the driver, are flagged as possible failures. A jet must be flagged on two successive Onfail passes before action is taken, as spurious signals in the hardware may give false indications on one pass. Those jets which are flagged for two successive passes are indicated as failures to the jet selection routine, and rechecked 3 passes later.

The Offail Logic flags as a potential failure any jet which is commanded ON and fails to indicate a normal operating pressure in its combustion chamber. Bubbles in the fuel line or chamber may delay the pressure buildup, so a jet must fail on 3 successive minor cycles before action is taken. When a jet is failed 3 times it is indicated as failed to the jet selection routine.

Data used by the jet FDI is to be packed in strings of 32 bits (1 word), with 8 to 10 jets represented in each string. Thus, for the 44 RCS jets, 6 such words are required for each item of data such as jet commands, driver talkback, etc. The structure of the jet FDI assumes that the structures of these bit string sets are all identical; i.e., that data pertaining to jet 1 will always be found in bit n of string m. Arranging the data in this manner allows processing to be done word by word, or 8 to 10 jets at a time. Also, since flags and commands are similarly arranged, most of the processing can be accomplished by simple AND and OR operations.

However, due to redundancy constraints on the hardware or the structure of the Jet Selection Logic, it is anticipated that some repacking of these bit strings may be necessary before data is used by the jet FDI or transmitted to either the hardware or the Jet Selection Logic. The Jet Selection Logic and jet FDI can be readily modified to assure conformity to the structure of these bit strings.

The data coming from the hardware will be packed in strings of 16 bits, which can be readily concatenated to 32-bit strings, and 32-bit words can readily be broken into 16-bit halfwords. The channelization of the Multiplexer/Demultiplexers is expected to be completed by September 1975 at which time this repacking can be more completely designed.

2.5 Remote Manipulator System

To be determined.

SECTION 3

GLOSSARY

This section contains an alphabetic list of all constants, variables, and symbols used in this document. It has been broken into units corresponding to the program modules described in earlier sections.

Table 3-1. Glossary of acronyms.

cg	center of gravity
DAP	Digital Autopilot
FC	Flight Control
FCOS	Flight Computer Operating System
FDI	Failure Detection and Identification
IMU	inertial measurement unit
OMS	Orbital Maneuvering System
RCS	Reaction Control System
RHC	rotational hand controller
SM	stable member
SOP	Subsystem Operating Program
TBD	to be determined
THC	translational hand controller
TMC	thrust misalignment correction
TVC	thrust vector control

Table 3-2. Notation conventions.

\oplus	Modular addition
\ominus ·	Modular subtraction
~	Measured quantity
^	Estimated quantity
∧	Extrapolated quantity
_ or -	Vector
*	Matrix
[]	Array
·	Boolean

Table 3.2.2-1. Panel switch interpretation glossary.

Name	Type/ Attribute	Description	Units	Value	Declared in	Assigned in	Referenced in
NEWORD1 NEWORD2 NEWORD3	B(16)/-	Panel switch discretetes	(None)	ON/OFF	COMPOOL	HARDWARE/ SOP	PANEL SWITCH INTERP
NORMAL VIEW_SW	B(1)/-	Flag for normal/view axes	(None)	ON/OFF	COMPOOL	PANEL SWITCH INTERP	MAN_RCS ROT, MAN RCS_TRANS
CFLAG	A(6),B(1)/-	Flag for high/low acceleration	(None)	ON/OFF	COMPOOL	PANEL SWITCH INTERP	MAN_RCS ROT, MAN RCS_TRANS
TRANSLATION_ OPTION	A(3),B(1)/-	Flag for translation submode by axis	(None)	ON/OFF	COMPOOL	PANEL SWITCH INTERP	MAN_RCS TRANS
ROTATION_ OPTIONS	A(3),I/-	Flag for rotation submode by axis	(None)	1,2,3	COMPOOL	PANEL SWITCH INTERP	MAN_RCS ROT
TRANSLATION_ PULSE_SIZE	A(3),Sc/-	Pulse ΔV by axis	ft/s	0.03 to 0.8	COMPOOL	PANEL SWITCH INTERP	TRANS PULSE
ROTATION_ PULSE_SIZE	A(3),Sc/-	Pulse $\Delta \omega$ by axis	rad/s	0.000873 to 0.00873	COMPOOL	PANEL SWITCH INTERP	ROT PULSE
DISCRETE_ OMEGA	A(3),Sc/-	Discrete ω by axis	rad/s	0.00105 to 0.0349	COMPOOL	PANEL SWITCH INTERP	ROT DISC

Table 3.2.2-1. Panel switch interpretation glossary (Cont.).

Name	Type/ Attribute	Description	Units	Value	Declared in	Assigned in	Referenced in
NOM_VERNIER_ SW	B(1)/-	Switch for nom/vernier RCS jets	(None)	ON/OFF	COMPOOL	PANEL SWITCH INTERP	RCS_DAP
TL	A(6),Sc/-	Threshold levels for off- axis compensation firings	m/s rad/s	TBD	COMPOOL	PANEL SWITCH INTERP	RCS_DAP
ATT_DB	A(3),Sc/-	Attitude deadbands for phase plane	rad	0.0087 to 0.087	COMPOOL	PANEL SWITCH INTERP	PHASE PLANE
INERTIAL_ LOCAL_SW	B(1)/-	Auto barbecue maneuver inertial/local vertical axis system selection	(None)	ON/OFF	COMPOOL	PANEL SWITCH INTERP	OODAP_ RECON
LIGHT1, LIGHT2, LIGHT3	B(16)/-	Lamp commands for panel switches	(None)	ON/OFF	COMPOOL	PANEL SWITCH INTERP	HARDWARE/ SOP
NOMVERN	I/-	Subscript denoting nominal/vernier RCS jets	(None)	1, 2	PANEL SWITCH INTERP	PANEL SWITCH INTERP	PANEL SWITCH INTERP
TRANSHILO	A(3),I/-	Subscript denoting trans- lation high/low options	(None)	1, 2	PANEL SWITCH INTERP	PANEL SWITCH INTERP	PANEL SWITCH INTERP
ROTHILO	A(3),I/-	Subscript denoting rota- tion high/low options	(None)	1, 2	PANEL SWITCH INTERP	PANEL SWITCH INTERP	PANEL SWITCH INTERP
OLDWORD1, OLDWORD2, OLDWORD3	B(16)	Values of NEWORD1, NEWORD2, NEWORD3 last FC cycle	(None)	ON/OFF	PANEL SWITCH INTERP	PANEL SWITCH INTERP	PANEL SWITCH INTERP

Table 3.2.2-1. Panel switch interpretation glossary (Cont.).

Name	Type/ Attribute	Description	Units	Value	Declared in	Assigned in	Referenced in
TRANSLATION_PULSE_ARRAY	A(2,3),Sc/-	Values of translation pulse size	m/s	TBD	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP
ROTATION_PULSE_ARRAY	A(2,3),Sc/-	Values of rotation pulse size	rad/s	TBD	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP
DISCRETE_OMEGA_ARRAY	A(2,2,3),Sc/-	Values of discrete ω	rad/s	TBD	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP
NEWVAL	B(1)/-	Flag indicating new parameters are selected	(None)	ON/OFF	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP
TLNARROW	A(6),Sc/-	Narrow threshold for off-axis compensation firings	m/s rad/s	TBD	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP
TLWIDE	A(6),Sc/-	Wide threshold for off-axis compensation firings	m/s rad/s	TBD	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP
AXIS	I/-	Subscript	(None)	1,2,3	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP	PANEL_SWITCH_INTERP

Table 3.3.2-1. RCS DAP glossary.

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
ALPHADBAR	$\hat{\alpha}_d$	V(3)/SP	Extrapolated estimate of disturbance acceleration	rad/s ²	TBD	COMPOOL	PART2_FILTER	PART1_FILTER
ALPHADHAT	$\hat{\alpha}_d$	V(3)/SP	Updated estimate of disturbance acceleration	rad/s ²	TBD	COMPOOL	PART1_FILTER	RCS_ERRORS, PART2_FILTER
ALPHADM	α_{dm}	V(3)/SP, A	Sum of estimated disturbance and bias accelerations	rad/s ²	TBD	FC	RCS_ERRORS	RCS_DAP, PART2_FILTER
ANGULAR_ERROR	ℓ_e	V(3)/SP, A	Body angle errors	rad	TBD	RCS_DAP	VERNIER, RCS_ERRORS	RCS_DAP
ANGULAR_ERROR	θ_e	Sc/SP, A	Formal parameter for body angle error	rad	TBD	PHASE_PLANE	(See Note 1)	PHASE_PLANE
B_SIGN	B_SIGN	Sc/SP	Sign of estimate disturbance acceleration	(none)	-1.0 or +1.0	BOUNDARY	BOUNDARY	BOUNDARY
BIAS_ACCELERATION	a_m	V(3)/SP	Bias acceleration used to better estimate switch curves of phase plane	rad/s ²	TBD	COMPOOL	PART2_FILTER	RCS_ERRORS
BIAS_BETA	β_{BIAS}	V(3)/SP	Bias body angles to prevent overshoot when starting or stopping a maneuver	rad	TBD	COMPOOL	autopilot driver	RCS_ERRORS

Note 1 PHASE_PLANE
LARGE_ERROR_CONTROL_LOGIC
SMALL_ERROR_CONTROL_LOGIC
REGION_II_TARGETTING

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Table 3.3.2-1 RCS DAP glossary (Cont.)

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
BOUNDARY_I_TO_COAST BOUNDARY_I_TO_II BOUNDARY_II_TO_COAST BOUNDARY_III_TO_COAST BOUNDARY_IV_TO_COAST BOUNDARY_IV_TO_III		Sc/SP, A	Switch curves in small error control region of the phase plane	rad	TBD	SMALL_ERROR_CONTROL_LOGIC	SMALL_ERROR_CONTROL_LOGIC	SMALL_ERROR_CONTROL_LOGIC
CD	CD	Sc/SP, C	Phase plane switch curve design parameter.	(none)	0.8	COMPOOL	COMPOOL	PHASE_PLANE, SMALL_ERROR_CONTROL_LOGIC
CD	CD	Sc/SP	Formal parameter for phase plane switch curve designs	(none)	0.0 to 1.0	BOUNDARY	BOUNDARY	BOUNDARY
COAST_I_BOUNDARY		Sc/SP, A	Switch curve in large error control region of the phase plane	rad/s	TBD	PHASE_PLANE	PHASE_PLANE	(See Note 2)
COAST_IV_BOUNDARY		Sc/SP, A	Switch curve in large error control region of the phase plane	rad/s	TBD	PHASE_PLANE	PHASE_PLANE	LARGE_ERROR_CONTROL_LOGIC
CONTROL_ACCELERATION_MAGNITUDE	$[\alpha_c]$	A(3), Sc/SP	Nominal magnitudes of roll, pitch, and yaw control accelerations	rad/s ²	TBD	COMPOOL	TBD	RCS_DAP
COSMGA	COSMGA	Sc/SP, A	Cosine of middle gumbal angle	(none)	-1.0 to +1.0	INPUT_INTERFACE	INPUT_INTERFACE	INPUT_INTERFACE
COSOGA	COSOGA	Sc/SP, A	Cosine of outer gumbal angle	(none)	-1.0 to +1.0	INPUT_INTERFACE	INPUT_INTERFACE	INPUT_INTERFACE

Note 2: LARGE_ERROR_CONTROL_LOGIC REGION_II_TARGETTING

Table 3.3.2-1. RCS DAP glossary (Cont.).

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
DEG_TO_RAD	DEG_TO_RAD	Sc/DP, C	Conversion factor for degrees to radians	rad/deg	$\pi/180$	COMPOOL	COMPOOL	PHASE_PLANE
DELTA	Δ_{DB}	Sc/SP, A	Width of "shelf" to prevent excess firings in phase plane logic	rad	$0.2 X_{DB}$	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE
DELTA_BODY_ANGLE	$\Delta\theta$	V(3)/SP, A	Incremental body angle	rad	TBD	PART1_FILTER	PART1_FILTER	PART1_FILTER
[DELTA_GA]	$[\Delta\phi_D]$	A(3), Sc/SP	Incremental gimbals angles	rad	$-\pi$ to $+\pi$	COMPOOL	driver routine	RCS_ERRORS
DELTA_POSITION	θ'_e	Sc/SP	Formal parameter for angular error	rad	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE
DELTA_RATE	$\Delta\omega$	V(3)/SP, St	Desired change in vehicle angular rate	rad/s	TBD	RCS_DAP	RCS_DAP, VERNIER	RCS_DAP, VERNIER
DELTA_RATE	ω'_e	Sc/SP	Formal parameter for angular rate error	rad/s	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE
DESIRED_BODY_RATE	ω_D	V(3)/SP	Desired angular velocity vector	rad/s	TBD	COMPOOL	driver routine	RCS_ERRORS
DFCS_FLAG1	DFCS_FLAG1	I/SP	External FC restart flag	(none)	0,1	COMPOOL	driver routine	FC
DFCS_FLAG2	DFCS_FLAG2	I/SP	External FC phase flag	(none)	1 to 8 (6 for ACPS orbital)	COMPOOL	driver routine	FC
DFCS_FLAG3	DFCS_FLAG3	I/SP	Control mode flag	(none)	TBD	COMPOOL	driver routine	FC
DFCS_FLAG4	DFCS_FLAG4	I/SP	Manual control mode flag	(none)	TBD	COMPOOL	driver routine	FC

Table 3.3.2-1. RCS DAP glossary (Cont.).

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
[DFCS_GA]	$[\phi]$	A(3), Sc/SP, A	Copy of the measured gimbal angles inside the DFCS	rad	TBD	FC	INPUT_INTERFACE	INPUT_INTERFACE, PART1_FILTER, RCS_ERRORS, PART2_FILTER
DFCS_MODE	DFCS_MODE	I/SP	Internal DFCS mode flag	(none)	TBD	FC	PHASE_START	FC
PHASE	PHASE	I/SP	Internal DFCS phase flag	(none)	1 to 8 (6 for ACPS orbital)	FC	PHASE_START	FC
DL	DL	Sc/SP, A	θ_e intercept for BOUNDARY_III_TO_COAST	rad	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE, SMALL_ERROR_CONTROL_LOGIC
DL_PRIME1	DL'	Sc/SP, A	θ_e intercept for BOUNDARY_IV_TO_COAST	rad	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE, SMALL_ERROR_CONTROL_LOGIC
DR	DR	Sc/SP, A	θ_e intercept for BOUNDARY_II_TO_COAST	rad	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE, SMALL_ERROR_CONTROL_LOGIC
DR	DR	Sc/SP	Formal parameter for θ_e intercept	rad	TBD	BOUNDARY	BOUNDARY	BOUNDARY

Table 3.3.2-1 RCS DAP glossary (Cont.).

Name of Variable or Constant		Type/ Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
DR_PRIME1	DR'	Sc/SP, A	θ_e intercept for BOUNDARY_I_TO_COAST	rad	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE, SMALL_ERROR_CONTROL LOGIC
DR_PRIME2	DR''	Sc/SP, A	θ_e intercept for BOUNDARY_I_TO_II	rad	TBD	PHASE_PLANE	PHASE_PLANE	(See Note 3)
[DUMMY_DELTA] _GA	(none)	A(3), Sc/SP, A	Temporary variable for DELTA_GA	rad	TBD	RCS_ERRORS	RCS_ERRORS	RCS_ERRORS
[DUMMY_GA] _DESIRED	(none)	A(3), Sc/SP, A	Temporary variable for GA_DESIRED	rad	TBD	RCS_ERRORS	RCS_ERRORS	RCS_ERRORS
[FAST]	[FAST]	A(8), Sc/SP,	List of FC cycle times for each mission phase	s	TBD	COMPOOL	COMPOOL	PHASE_START
[GA_DESIRED]	$[\phi_D]$	A(3), Sc/SP	Set of desired gumbal angles	rad	$-\pi$ to $+\pi$	COMPOOL	driver routine, RCS_ERRORS	RCS_ERRORS
[GA_ERROR]	$[\phi_e]$	A(3), Sc/SP, A	Error in gumbal angles	rad	$-\pi$ to $+\pi$	RCS_ERRORS	RCS_ERRORS	RCS_ERRORS
[GA_INCREMENT]	$[\Delta\phi]$	A(3), Sc/SP, A	Amount of change in gumbal angles after 1 FC pass	rad	TBD	PART1_FILTER	PART1_FILTER	PART1_FILTER
[GA_OLD]	$[\phi_{old}]$	A(3), Sc/SP	Set of measured gumbal angles on the previous FC pass	rad	$-\pi$ to $+\pi$	COMPOOL	PART2_FILTER	PART1_FILTER
IM	IM	I/SP, St	Medium pass counter	(none)	TBD	FC	PHASE_START	FC
IS	IS	I/SP, St	Slow pass counter	(none)	TBD	FC	PHASE_START	FC

Note 3: PHASE_PLANE
SMALL_ERROR_CONTROL_LOGIC

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Table 3.3.2-1. RCS DAP glossary (Cont.).

Name of Variable or Constant		Type/ Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
ISTART	ISTART	I/SP, St	Internal restart flag	(none)	0,1	FC	PHASE_ START	FC
ITM	ITM	I/SP, St	Number of fast passes per medium pass	(none)	TBD	FC	PHASE_ START	FC
ITS	ITS	I/SP, St	Number of fast passes per slow pass	(none)	TBD	FC	PHASE_ START	FC
K	K	I/SP, A	Counter	(none)	1,2,3	PART1_ FILTER	PART1_ FILTER	PART1_ FILTER
K	K	Sc/SP, A	Sign of estimated disturbance acceleration	(none)	-1 0,+1 0	PHASE_ PLANE	PHASE_ PLANE	PHASE_ PLANE, LARGE_ ERROR_ CONTROL_ LOGIC, SMALL_ ERROR_ CONTROL_ LOGIC
K	K	I/SP, A	Counter	(none)	1,2,3	RCS_ ERRORS	RCS_ ERRORS	RCS_ ERRORS
J	J	I/SP, A	Counter	(none)	1,2,3	PART2_ FILTER	PART2_ FILTER	PART2_ FILTER
[JT]	[JT]	A(44), I/B, St	On or off commands, one for each RCS jet	(none)	0,1	FC	NOMINAL, VERNIER	PART2_ FILTER
KALPHA	K α	Sc/SP, C	Gain in filtering angular disturbance acceleration	(none)	0 02147	COMPOOL	COMPOOL	PART1_ FILTER

Table 3.3.2-1. RCS DAP glossary (Cont.).

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
KOMEGA	K_{ω}	Sc/SP, C	Gain in filtering angular rate	(none)	0.3018	COMPOOL	COMPOOL	PART1_FILTER
KTHETA	K_{θ}	Sc/SP, C	Gain in filtering body angles	(none)	0.6294	COMPOOL	COMPOOL	PART1_FILTER
MAG_U_C	$ U_C $	Sc/SP, A	Formal parameter for magnitude of control acceleration	rad/s ²	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE, SMALL_ERROR_CONTROL_LOGIC, REGION_II_TARGETTING
MAG_U_D	$ U_D $	Sc/SP, A	Magnitude of disturbance acceleration	rad/s ²	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE, SMALL_ERROR_CONTROL_LOGIC, REGION_II_TARGETTING
NO_CHANGE	$X_{D_{old}}$	Sc/SP	Angular rate change computed on last FC pass	rad/s	TBD	PHASE_PLANE	PHASE_PLANE	LARGE_ERROR_CONTROL_LOGIC, SMALL_ERROR_CONTROL_LOGIC
NUMBER_OF_JETS	n	I/SP	Number of RCS jets	(none)	TBD	COMPOOL	COMPOOL	COMPOOL, PART2_FILTER
OMEGABAR	$\hat{\omega}$	V(3)/SP	Extrapolated estimate of angular rate	rad/s	TBD	COMPOOL	PART2_FILTER	PART1_FILTER

Table 3.3.2-1. RCS DAP glossary (Cont.).

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
OMEGAHAT	$\hat{\omega}$	V(3)/SP	Updated estimate of angular rate	rad/s	TBD	COMPOOL	PART1_FILTER	RCS_ERRORS, PART2_FILTER, VERNIER
P_CEPT	P_CEPT	Sc/SP,A	θ intercept of BOUNDARY_I_TO_II	rad	TBD	SMALL_ERROR_CONTROL_LOGIC	SMALL_ERROR_CONTROL_LOGIC, REGION_II_TARGETTING	SMALL_ERROR_CONTROL_LOGIC, REGION_II_TARGETTING
PLL	PLL	Sc/SP,A	Left position limit of large error control region	rad	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE, LARGE_ERROR_CONTROL_LOGIC
PLR	PLR	Sc/SP,A	Right position limit of large control region	rad	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE, LARGE_ERROR_CONTROL_LOGIC
POSITION	θ	Sc/SP,A	Formal parameter for angular position error	rad	TBD	BOUNDARY	BOUNDARY	BOUNDARY
POSITION_ERROR	θ_e	Sc/SP	Formal parameter for angular error	rad	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE
RATE	ω	Sc/SP,A	Formal parameter for angular rate error	rad/s	TBD	BOUNDARY	BOUNDARY	BOUNDARY
RATE_ERROR	ω_e	V(3)/SP,A	Three components of angular rate error	rad/s	TBD	RCS_DAP	RCS_ERRORS	RCS_DAP

Table 3.3.2-1. RCS DAP glossary (Cont.).

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
RATE_ERROR	ω_e	Sc/SP, A	Formal parameter for angular rate error	rad/s	TBD	PHASE_PLANE	PHASE_PLANE	LARGE_ERROR_CONTROL_LOGIC, SMALL_ERROR_CONTROL_LOGIC
RATE_INTEGRAL	$\tilde{\theta}$	V(3)/SP, St	Sum of incremental body angle changes	rad	$-\pi$ to $+\pi$	PART1_FILTER	PART1_FILTER	PART1_FILTER
RL	RL	Sc/SP, A	Rate limits of large error control region of the phase plane	rad/s	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE, LARGE_ERROR_CONTROL_LOGIC
SINMGA	SINMGA	Sc/SP, A	Sine of middle gimbale angle	(none)	-1.0 to +1.0	INPUT_INTERFACE	INPUT_INTERFACE	INPUT_INTERFACE
SINOGA	SINOGA	Sc/SP, A	Sine of outer gimbale angle	(none)	-1.0 to +1.0	INPUT_INTERFACE	INPUT_INTERFACE	INPUT_INTERFACE
TARGET_ARL	TARGET_ARL	Sc/SP, A	Possible target curve in SMALL_ERROR_CONTROL_LOGIC	rad/s	TBD	SMALL_ERROR_CONTROL_LOGIC	REGION_II_TARGETING	REGION_II_TARGETING
TARGET_DISTURB	TARGET_DISTURB	Sc/SP, A	Possible target curve in SMALL_ERROR_CONTROL_LOGIC	rad	TBD	SMALL_ERROR_CONTROL_LOGIC	SMALL_ERROR_CONTROL_LOGIC	SMALL_ERROR_CONTROL_LOGIC
TEMP1	TEMP1	Sc/SP, A	Change in body angle since the last FC pass	rad	TBD	PART1_FILTER	PART1_FILTER	PART1_FILTER

Table 3.3.2-1. RCS DAP glossary (Cont.).

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
TEMP_DÉLTA_ANGLE	$\Delta\theta$	V(3)/SP, A	Angular change due to RCS jets	rad	TBD	PART2_FILTER	PART2_FILTER	PART2_FILTER
TEMP_DÉLTA_RATE	$\Delta\omega$	V(3)/SP, A	Rate change due to RCS jets	rad/s	TBD	PART2_FILTER	PART2_FILTER	PART2_FILTER
TF	t_{fast}	Sc/SP, St	Internal copy of FC cycle time	s	TBD	FC	PHASE_START	(See Note 4)
THETĀBAR	$\hat{\theta}'$	V(3)/SP	Extrapolated estimate of body angles	rad	TBD	COMPOOL	PART2_FILTER	PART1_FILTER
THETĀHAT	$\hat{\theta}$	V(3)/SP	Updated estimate of body angles	rad	TBD	COMPOOL	PART1_FILTER	PART2_FILTER
TICK_TO_SEC	TICK_TO_SEC	Sc/SP, C	Conversion factor to synchronize program to computer	s/computer tick	1 0	COMPOOL	COMPOOL	INPUT_INTERFACE
[TLAST]	$[t_{\theta}]$	A(3), Sc/SP, St	Times of last measurement incorporation	s	TBD	PART1_FILTER	PART1_FILTER	PART1_FILTER
TNOW	t_n	Sc/SP, A	Time of immediate gumbal angle reading	s	TBD	FC	INPUT_INTERFACE	PART1_FILTER
[TRAPSIZE]	$[\theta_T]$	A(3), Sc/SP, C	Size of the "trap" to filter quantization noise	rad	TBD	COMPOOL	COMPOOL	PART1_FILTER
U_D	U_D	Sc/SP, A	Formal parameter for disturbance acceleration	rad/s ²	TBD	PHASE_PLANE	PHASE_PLANE	PHASE_PLANE, SMALL_ERROR_CONTROL_LOGIC

Note 4: PHASE_START, PART2_FILTER_ACPS

Table 3.3.2-1. RCS DAP glossary (Cont.).

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
UC	UC	Sc/SP	Formal parameter for magnitude of control acceleration	rad/s ²	TBD	BOUNDARY	BOUNDARY	BOUNDARY
UD	UD	Sc/SP	Formal parameter for magnitude of disturbance acceleration	rad/s ²	TBD	BOUNDARY	BOUNDARY	BOUNDARY
VERNIER _ACCEL	[ACC]	A(2), Sc/SP	Single vernier jet acceleration for roll and pitch	rad/s ²	TBD	COMPOOL	COMPOOL	VERNIER
λ _BAR	$\bar{\lambda}$	Sc/SP, A	Displacement of the centroid of a limit cycle	rad	TBD	PHASE_ PLANE	PHASE_ PLANE	SMALL_ ERROR_ CONTROL_ LOGIC, REGION_II_ TARGET- TING
X_D	λ_D	Sc/SP, A	Desired change in angular rate	rad/s	TBD	PHASE_ PLANE	PHASE_ PLANE, LARGE_ ERROR_ CONTROL_ LOGIC, SMALL_ ERROR_ CONTROL_ LOGIC, REGION_II_ TARGET- TING	PHASE_ PLANE, LARGE_ ERROR_ CONTROL_ LOGIC, SMALL_ ERROR_ CONTROL_ LOGIC, REGION_II_ TARGET- TING
X_DB	λ_{DB}	Sc/SP	Limit cycle deadband width	rad	0.087, 0.0087	COMPOOL	COMPOOL	PHASE_ PLANE

Table 3.3.2.4.1-1. Main RCS jet selection glossary.

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
TBD	THCX	INTEGER	Translational command in the X axis (includes acceleration level)	(none)	-2 to 2	TBD	TBD	TBD
TBD	THCY	INTEGER	Translational command in the Y axis (includes acceleration level)	(none)	-2 to 2	TBD	TBD	TBD
TBD	THCZ	INTEGER	Translational command in the Z axis (includes acceleration level)	(none)	-2 to 2	TBD	TBD	TBD
TBD	ROLL	INTEGER	Rotational command in the X axis (includes acceleration level)	(none)	-2 to 2	TBD	TBD	TBD
TBD	PITCH	INTEGER	Rotational command in the Y axis (includes acceleration level)	(none)	-2 to 2	TBD	TBD	TBD
TBD	YAW	INTEGER	Rotational command in the Z axis (includes acceleration level)	(none)	-2 to 2	TBD	TBD	TBD
TBD	A	FL PT	A 40 x 6 array of translational and rotational accelerations for each jet	m/s ² rad/s ²	{ -0.0484 to 0.0484 -0.0133 to 0.0133	TBD	TBD	TBD
TBD	FL	LOGICAL	A logical array where TRUE indicates a jet is failed	(none)	TRUE/FALSE	TBD	TBD	TBD
TBD	TONM	FL PT	Minimum on-time for compensation firings	s	0.04	TBD	TBD	TBD
TBD	XLEV	FL PT	X-translational disturbance counter threshold	(none)	0.096	TBD	TBD	TBD
TBD	YLEV	FL PT	Y-translational disturbance counter threshold	(none)	0.096	TBD	TBD	TBD
TBD	ZLEV	FL PT	Z-translational disturbance counter threshold	(none)	0.192	TBD	TBD	TBD
TBD	RLEV	FL PT	Roll disturbance counter threshold	(none)	0.026	TBD	TBD	TBD
TBD	TL	FL PT	Threshold levels for off-axis compensation firings	m/s rad/s	TBD	TBD	TBD	TBD

Table 3.3.2.4.1-1. Main RCS jet selection glossary (Cont.).

Name of Variable or Constant		Type/ Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
TBD	PLEV	FL PT	Pitch disturbance counter threshold	(none)	0 031	TBD	TBD	TBD
TBD	YAWLEV	FL PT	Yaw disturbance counter threshold	(none)	0 015	TBD	TBD	TBD
TBD	ONDELAY	FL PT	The amount of on-delay occurring when a jet is turned on	s	0.016	TBD	TBD	TBD
TBD	JT	LOGICAL	Array indicating desired state of each jet each cycle (TRUE indicates ON)	(none)	TRUE/FALSE	TBD	TBD	TBD
TBD	TJET	FL PT	Array containing the on-times for each jet each cycle	s	0 to 0 04	TBD	TBD	TBD

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Table 3.3.3-1. TVC DAP glossary.

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
TBD	K_D	Sc/SP,St	Pitch or yaw TVC digital compensation filter gain	(None)	2 states	TBD	TBD	TBD
TBD	K_M	Sc/SP,St	Pitch or yaw manual TVC gain	rad/s/rad	TBD	TBD	TBD	TBD
TBD	K_{steer}	Sc/SP,St	Guidance loop gain	(None)	TBD	TBD	TBD	TBD
TBD	K_r	Sc/SP,St	Roll TVC gain	(None)	TBD	TBD	TBD	TBD
TBD	T	Sc/SP,St	DAP sampling period	s	0.04	TBD	TBD	TBD
TBD	δ	Sc/SP,St	Actual OMS engine deflection	rad	TBD	TBD	TBD	TBD
TBD	δ_{c_n}	Sc/SP,St	Commanded OMS engine deflection	rad	TBD	TBD	TBD	TBD
TBD	δ_e	Sc/SP,St	OMS engine deflection error	rad	TBD	TBD	TBD	TBD
TBD	θ	Sc/SP,St	Measured vehicle pitch or yaw attitude	rad	TBD	TBD	TBD	TBD
TBD	θ_c	Sc/SP,St	Commanded vehicle pitch or yaw attitude	rad	TBD	TBD	TBD	TBD
TBD	θ_e	Sc/SP,St	Vehicle pitch or yaw attitude error	rad	TBD	TBD	TBD	TBD
TBD	DAP1	Sc/SP,St	Output of first filter section	rad	TBD	TBD	TBD	TBD
TBD	sum1	Sc/SP,St	First filter section update for next FC pass	rad	TBD	TBD	TBD	TBD
TBD	sum2	Sc/SP,St	Second filter section update for next FC pass	rad	TBD	TBD	TBD	TBD

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Table 3.3.3-1. TVC DAP glossary (Cont.).

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
TBD	sum3	Sc/SP,St	Second filter section update for two FC passes from now	rad	TBD	TBD	TBD	TBD
TBD	DAPOUT	Sc/SP,St	Filter output	rad	TBD	TBD	TBD	TBD
TBD	δ'_c	Sc/SP,St	Output of 1st section of the TMC filter	rad	TBD	TBD	TBD	TBD
TBD	LAST1	Sc/SP,St	TMC filter update for next FC pass	rad	TBD	TBD	TBD	TBD
TBD	LAST2	Sc/SP,St	TMC filter update for next FC pass	rad	TBD	TBD	TBD	TBD
TBD	ω_c	Sc/SP,St	Manual or automatic rate command to TVC	rad/s	TBD	TBD	TBD	TBD

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Table 3.3.4.1.1.1-1. Manual RCS rotation glossary.

Name	Type/ Attribute	Description	Units	Value	Declared in	Assigned in	Referenced in							
DESIRED_OMEGA	V(3)/-	Desired rotational velocities	rad/s	TBD	MAN_RCS_ROT	MAN_RCS_ROT	BODY_RATE_ANGLE_DRIVE							
AXIS_INDEX	I/-	Subscript by axis	(None)	1,2,3	MAN_RCS_ROT, MAN_RCS_TRANS	MAN_RCS_ROT, MAN_RCS_TRANS	MAN_RCS_ROT, MAN_RCS_TRANS							
OLDLIGHT1	B(16)/-	Value of LIGHT1 from last pass	(None)	ON/OFF	MAN-RCS_ROT	MAN_RCS_ROT	MAN_RCS_ROT							
OLD_ROTATION_OPTIONS	A(3),I/-	Value of ROTATION_OPTIONS from last pass	(None)	1,2,3	MAN_RCS_ROT	MAN_RCS_ROT	MAN_RCS_ROT							
OLD_RHC	A(3),TBD/-	Value of RHC from last pass	TBD	TBD	MAN_RCS_ROT	MAN_RCS_ROT	MAN_RCS_ROT							
OLD_RHC_STATE	A(3),I/-	Value of RHC_STATE from last pass	(None)	-1,0,1	MAN_RCS_ROT	RHC_READ	MAN_RCS_ROT							
RHC_STATE	A(3), I/-	Out-of detent flag with sense of deflection	(None)	-1,0,1	MAN_RCS_ROT	RHC_READ	ROT_DISC, ROT_ACCEL, ROT_PULSE							
SRA SLA SRB SLB	TBD	Deadband limits for RHC hysteresis	TBD	TBD	RHC_READ	RHC_READ	RHC_READ							
PULSE_DB_OMEGA								A(3),Sc/-	Lower limit of rate deadband in pulse submode	rad/s	0.00087266	ROT_PULSE	ROT_PULSE	ROT_PULSE
DB_OMEGA_2								A(3),Sc/-	Rate deadband in pulse submode	rad/s	TBD	ROT_PULSE	ROT_PULSE	ROT_PULSE
RHC								A(3),TBD/-	Values of RHC deflection	TBD	TBD	COMPOOL	Hardware/SOP	MAN_RCS_ROT, RHC_READ

Table 3.3.4.1.1.1-1. Manual RCS rotation glossary (Cont.).

Name	Type/ Attribute	Description	Units	Value	Declared in	Assigned in	Referenced in
INIT_MAN_ROT FLAG	B(1)/-	Flag for initialization of MAN_RCS_ROT	(None)	ON/OFF	COMPOOL	OODAP_ RECON	MAN_RCS_ ROT
LIGHT1	B(16)/-	Commands for panel switch lamps	(None)	ON/OFF	COMPOOL	MAN_RCS_ ROT	Hardware/ SOP
ROTATION_ OPTIONS	A(3),I/-	Rotation submode selections by axis	(None)	1,2,3	COMPOOL	PANEL_ SWITCH_ INTERP	MAN_RCS_ ROT
BYPASS_ PHASE_PLANE	A(3),B(1)/-	Flag for direct control of jet select	(None)	ON/OFF	COMPOOL	ROT_DISC, ROT_PULSE, ROT_ACCEL	RCS_DAP
CLSTRF	A(6),B(1)/-	Flags for high/low acceleration option by axis	(None)	ON/OFF	COMPOOL	ROT_DISC, ROT_PULSE, ROT_ACCEL	RCS_DAP
CFLAG	A(6),B(1)/-	Flag for high/low acceleration selection	(None)	ON/OFF	COMPOOL	PANEL_ SWITCH_ INTERP	ROT_ACCEL
OMEGA_HAT	V(3)/-	Current angular rate estimate	rad/s	TBD	COMPOOL	PART1_ FILTER	ROT_PULSE
ROTATION_ PULSE_SIZE	A(3),Sc/-	Selected pulse $\Delta\omega$	rad/s	0.000873 to 0.00873	COMPOOL	PANEL_ SWITCH_ INTERP	ROT_PULSE
DB_OMEGA	A(3),Sc/-	Angular rate deadband	rad/s	TBD	ROT_PULSE	ROT_PULSE	ROT_PULSE
JET_COMMAND	A(6),I/-	Jet firing commands by axis	(None)	-1,0,1	COMPOOL	ROT_PULSE, ROT_ACCEL	RCS_DAP
DISCRETE_ OMEGA	A(3),Sc/-	Discrete ω_D by axis	rad/s	0.00105 to 0.0349	COMPOOL	PANEL_ SWITCH_ INTERP	ROT_DISC

Table 3.3.4.1.1.2-1. Manual RCS translation glossary.

Name	Type/ Attribute	Description	Units	Value	Declared in	Assigned in	Referenced in
TRANS_NOM_ ACCEL	A(3),Sc/-	Nominal acceleration levels by axis	ft/s ²	TBD	MAN_RCS_ TRANS	MAN_RCS_ TRANS	MAN_RCS_ TRANS
AXIS_INDEX	I/-	Subscript denoting axis	(None)	1,2,3	MAN_RCS_ TRANS	MAN_RCS_ TRANS	MAN_RCS_ TRANS
OLDLIGHT2	B(16)	Value of LIGHT2 from last pass	(None)	ON/OFF	MAN_RCS_ TRANS	MAN_RCS_ TRANS	MAN_RCS_ TRANS
OLD_THC	A(3),I/-	Value of THC from last pass	(None)	-1,0,1	MAN_RCS_ TRANS	MAN_RCS_ TRANS	MAN_RCS_ TRANS
V_NOW	A(3),Sc/-	Current reference velocity	ft/s	TBD	TRANS_ PULSE	TRANS_ PULSE	TRANS_PULSE
OLD_ TRANSLATION_ OPTION	A(3),B(1)/-	Value of TRANSLATION_OPTION from last pass	(None)	ON/OFF	MAN_RCS_ TRANS	MAN_RCS_ TRANS	MAN_RCS_ TRANS
THC	A(3),I/-	Flag for THC deflection containing sense	(None)	-1,0,1	COMPOOL	Hardware/ SOP	MAN_RCS_ TRANS, TRANS_PULSE, TRANS_ACCEL
TRANSLATION_ OPTION	A(3),B(1)/-	Flag for translation submode selections by axis	(None)	ON/OFF	COMPOOL	PANEL_ SWITCH_ INTERP	MAN_RCS_ TRANS
LIGHT2	B(16)/-	Commands to panel switch lamps	(None)	ON/OFF	COMPOOL	PANEL_ SWITCH_ INTERP, MAN_RCS_ TRANS	Hardware/ SOP
DELTA_V	V(3)/-	Estimated translational rate changes	ft/s	TBD	COMPOOL	PART1_ FILTER	MAN_RCS_ TRANS

Table 3.3.4.1.1.2-1. Manual RCS translation glossary (Cont.)

Name	Type/ Attribute	Description	Units	Value	Declared in	Assigned in	Referenced in
W	A(6),Sc/-	Rate change commands to jet select	rad/s ft/s	TBD	COMPOOL	RCS_DAP, MAN_RCS_ TRANS	RCS_DAP
JET_COMMAND	A(6),I/-	Jet firing commands by axis	(None)	-1,0,1	COMPOOL	TRANS_ ACCEL, TRANS_ PULSE	RCS_DAP
DB_VEL	A(3),Sc/-	Translation rate deadbands for TRANS_PULSE	ft/s	TBD	TRANS_ PULSE	TRANS_ PULSE	TRANS_ PULSE
V_DESIRED	A(3),Sc/-	Desired translation rates	ft/s	TBD	TRANS_ PULSE	TRANS_ PULSE	TRANS_ PULSE
CLSTRF	A(6),B(1)/-	Flag for high/low acceleration by axis	(None)	ON/OFF	COMPOOL	TRANS_ ACCEL, TRANS_ PULSE	RCS_DAP
TRANSLATION_PULSE_SIZE	A(3),Sc/-	Selected rate change per pulse	ft/s	0.03 to 0.8	COMPOOL	PANEL_ SWITCH_ INTERP	TRANS_ PULSE
CFLAG	A(6),B(1)/-	Flag for high/low acceleration selection	(None)	ON/OFF	COMPOOL	PANEL_ SWITCH_ INTERP	TRANS_ ACCEL

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Table 3.3.4.1.2.1-1. Attitude maneuver glossary.

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
A	A	Sc/SP, St	Formal parameter Angle of rotation about u_r	rad	$0 \leq x \leq \pi$	VECPPOINT	VECPPOINT	VECPPOINT
A	A	Sc/SP, St	Formal parameter. Angle of rotation about u_r .	rad	$0 \leq x \leq \pi$	ROTATION_MATRIX	ROTATION_MATRIX	ROTATION_MATRIX
A_M	A_M	Sc/SP, St	Angle of rotation about u_r	rad	$0 \leq x \leq \pi$	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER
AUTO_MODE	AUTO_MODE	B(1)/-	Automatic mode switch.	(none)	TBD	COMPOOL	COMPOOL	STEERING
BIAS_BETA	ℓ_{BIAS}	V(3)/SP, St, L	Bias body angles	rad	TBD	COMPOOL	STEERING, STOPRATE, HOLD_ATTITUDE	RCS_DAP
*C	*C	M(3, 3)/SP, St	Formal parameter Direction cosine matrix	(none)	TBD	ANGLES_TO_DCM	ANGLES_TO_DCM	(none)
*C	*C	M(3, 3)/SP, St	Formal parameter. Direction cosine matrix	(none)	TBD	DCM_TO_ANGLES	(none)	DCM_TO_ANGLES
*C_BSM	*C _{BSM}	M(3, 3)/SP, St	Direction cosine matrix between present vehicle axes and stable member axes	(none)	TBD	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER, STEERING	ATTITUDE_MANEUVER, STEERING
*C_CSM	*C _{CSM}	M(3, 3)/SP, St	Direction cosine matrix between commanded vehicle axes and stable member axes	(none)	TBD	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER
*C_LSM	*C _{LSM}	M(3, 3)/SP, St	Direct cosine matrix between L-coordinate frame and stable member axes	(none)	TBD	VECPPOINT	VECPPOINT	VECPPOINT

Table 3.3.4.1.2.1-1. Attitude maneuver glossary (Cont.)

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
\hat{C}_{MSM}	\hat{C}_{MSM}	M(3, 3)/SP, St	Direction cosine matrix between M-coordinate frame and stable member axes	(none)	TBD	VEC POINT	VEC POINT	VEC POINT
[CONTROL_ACCELERATION_MAGNITUDE]	$[a_c]$	A(3), Sc/DP, St	Magnitudes of the U, V, W control accelerations.	rad/s ²	TBD	COMPOOL	autopilot	STEERING
DEG_TO_RAD	DEG_TO_RAD	Sc/SP, St, C	Conversion factor	rad/deg	$\pi/180$	COMPOOL	COMPOOL	ATTITUDE_MANEUVER
[DELTA_GA]	$[\Delta\phi_D]$	A(3), Sc/SP, St, L	Incremental gimbals angles.	rad	TBD	COMPOOL	STEERING, STOPRATE, HOLD_ATTITUDE	RCS_DAP
DELTAAM	Δa_M	Sc/SP, St, L	Incremental rotation angle	rad	TBD	STEERING	STEERING	STEERING
DELTA [*] R	ΔR^*	M(3, 3)/SP, St, L	Incremental rotation matrix.	(none)	TBD	STEERING	STEERING	STEERING
DELTA [*] T_C	Δt_{cycle}	Sc/SP, St, C	Period of the cycle of STEERING	s	1.2	COMPOOL	COMPOOL	STEERING
DESIRED_BODY_RATE	ω_D	V(3)/SP, St, L	Desired angular velocity vector in navigation-based coordinate	rad/s	TBD	COMPOOL	STEERING, STOPRATE, HOLD_ATTITUDE	STEERING, RCS_DAP
DESIRED_MAGNITUDE_OF_BODY_RATE	ω_r	Sc/DP, St	Requested magnitude of angular velocity.	rad/s	TBD	ATTITUDE_MANEUVER	calling program	STEERING
FAST_DFCS_FLAG2	t_{fast}	Sc/SP, St	Period of the RCS DAP cycle	s	0.04	COMPOOL	autopilot	STEERING
FIRST_PASS	FIRST_PASS	B(1)/-	First pass switch	(none)	TBD	STEERING	STEERING	STEERING
[GA]	$[\phi]$	A(3), Sc/DP, St	Gimbal angles read from sensors.	rad	TBD	GIMBAL_ANGLE_READ	GIMBAL_ANGLE_READ	GIMBAL_ANGLE_READ
[GA]	$[\phi]$	A(3), Sc/SP, St	Formal parameter, gimbal angles	rad	$-\pi \leq x \leq \pi$	DCM_TO_ANGLES	DCM_TO_ANGLES	DCM_TO_ANGLES

Table 3.3.4.1.2.1-1. Attitude maneuver glossary (Cont.)

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
[GA]	$[\phi]$	A(3), Sc/SP, St	Formal parameter Gimbal angles	rad	$-\pi \leq x \leq \pi$	ANGLES_ TO_DCM	(none)	ANGLES_ TO_DCM
[GA_B]	$[\phi_B]$	A(3), Sc/SP, St	Gimbal angles at the start of ATTITUDE_MANEUVER.	rad	$-\pi \leq x \leq \pi$	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER, STEERING	ATTITUDE_MANEUVER, STEERING
[GA_COMMANDED]	$[\phi_C]$	A(3), Sc/SP, St	Commanded terminal gimbal angles	rad	$-\pi \leq x \leq \pi$	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER, VECPOINT	ATTITUDE_MANEUVER, HOLD_ATTITUDE
[GA_DESIRED]	$[\phi_D]$	A(3), Sc/SP, St, L	Intermediate desired gimbal angles	rad	$-\pi \leq x \leq \pi$	COMPOOL	STEERING, STOPRATE, HOLD_ATTITUDE	RCS_DAP
[GA_L]	$[\phi_L]$	A(3), Sc/SP, St	Gimbal angles at the start of VECPOINT.	rad	$-\pi \leq x \leq \pi$	VECPOINT	VECPOINT	VECPOINT
[GA_N]	$[\phi_N]$	A(3), Sc/SP, St	Gimbal angles predicted Δt_c in advance.	rad	$-\pi < x < \pi$	STEERING	STEERING	STEERING
*ID_MATRIX	* $I_{identity}$	M(3, 3)/DP, St, C	Identity matrix.	(none)	TBD	COMPOOL	COMPOOL	ROTATION_MATRIX
PI	π	Sc/ DP, St	P1	rad	TBD	COMPOOL	COMPOOL	VECPOINT, DCM_TO_ANGLES
*R	*R	M(3, 3)/SP, St	Formal parameter, rotation matrix	(none)	TBD	ROTATION_MATRIX	ROTATION_MATRIX	ROTATION_MATRIX
*R_A	* \hat{R}_A	M(3, 3)/SP, St	Antisymmetric component of R_{CP} .	(none)	TBD	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER
R_CB	* \hat{R}_{CB}	M(3, 3)/SP, St	Rotation matrix between commanded and initial attitudes	(none)	TBD	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER
*R_ML	* \hat{R}_{ML}	M(3, 3)/SP, St	Rotation matrix between the M and L coordinate frames	(none)	TBD	VECPOINT	VECPOINT	VECPOINT

Table 3.3.4.1.2.1-1. Attitude maneuver glossary (Cont.),

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
\bar{R}_S	\bar{R}_S	M(3, 3)/SP, St	Symmetric component of R_{CB}	(none)	TBD	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER
REALSEC	REALSEC	Sc/SP, St, C	Scale factor to synchronize with computer clock.	computer ticks/s	TBD	COMPOOL	COMPOOL	STEERING
RUNTIME	RUNTIME	Sc/SP	FCOS runtime.	s	TBD	COMPOOL	COMPOOL	STEERING
T_CYCLE	t_{cycle}	Sc/SP, St	Time at which each new pass of STEERING begins	s	TBD	STEERING	STEERING	STEERING
T_M	t_M	Sc/SP, St	Time of maneuver duration.	s	TBD	STEERING	STEERING	STEERING
T_S	t_s	Sc/SP, St	Time of maneuver completion	s	TBD	STEERING	STEERING	STEERING
\bar{u}_{AL}	\bar{u}_{AL}	V(3), SP, St	Prescribed unit vector \bar{u}_A in the L-coordinate frame.	ft	TBD	VECPOINT	VECPOINT	VECPOINT
\bar{u}_{ANB}	\bar{u}_{ANB}	V(3)/SP, St	Prescribed unit vector \bar{u}_A in navigation-base coordinates	ft	TBD	VECPOINT	VECPOINT	VECPOINT
\bar{u}_{DL}	\bar{u}_{DL}	V(3)/DP, St	Desired unit vector in the L-coordinate frame	ft	TBD	VECPOINT	VECPOINT	VECPOINT
\bar{u}_{DSM}	\bar{u}_{DSM}	V(3)/DP, St	Desired unit vector in the stable-member coordinate frame.	ft	TBD	VECPOINT	VECPOINT	VECPOINT
\bar{u}_R	\bar{u}_R	V(3)/SP, St	Single equivelant rotation vector. Rotation through the angle A	ft	TBD	VECPOINT	VECPOINT	VECPOINT

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Table 3.3.4.1.2.1-1. Attitude maneuver glossary (Cont.).

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
$U_{\bar{R}}$	u_r	V(3)/SP, St	Formal parameter. Single equivalent rotation vector	ft	TBD	ROTATION_MATRIX	ROTATION_MATRIX	ROTATION_MATRIX
$U_{\bar{R}}$	u_r	V(3)/SP, St	Single equivalent rotation vector. Rotation through the angle A_M	ft	TBD	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER, STEERING
U_{RPRIME}	u_r'	V(3)/SP, St	Intermediate rotation vector used in determining proper signs of u_r .	ft	TBD	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER	ATTITUDE_MANEUVER
$U_{\bar{X}L}$	u_{XL}	V(3)/SP, St	Unit vector along the navigation-based x-axis (1,0,0)	ft	1, 0, 0	COMPOOL	COMPOOL	VECPPOINT
$U_{\bar{Y}SML}$	u_{YSML}	V(3)/SP, St, C	Unit vector along the y-axis of the stable-member frame projected into the L-frame	ft	TBD	VECPPOINT	VECPPOINT	VECPPOINT
* U_{X_R}	* U_{X_r}	M(3, 3)/SP, St	Antisymmetric matrix whose components are taken from u_r	it	TBD	ROTATION_MATRIX	ROTATION_MATRIX	ROTATION_MATRIX

Table 3.3.4.1.2.1-2 Automatic rate driver glossary.

Name of Variable or Constant		Type/ Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
BIAS_BLTA	β_{BIAS}	V(3)/SP	Bias body angles to prevent overshoot when starting or stopping a maneuver	rad	TBD	COMPOOL	BODY_RATE_ANGLE_DRIVE	RCS_DAP
BODY_RATE	$\omega_{D(BA)}$	V(3)/SP	Specified body rate to BODY RATE ANGLE DRIVE	rad/s	TBD	BODY_RATE_ANGLE_DRIVE	BODY_RATE_ANGLE_DRIVE	BODY_RATE_ANGLE_DRIVE
BODY_RATE	$\omega_{D(BA)}$	V(3)/SP, A	Specified body rate to SM RATE ANGLE DRIVE	rad/s	TBD	SM_RATE_ANGLE_DRIVE	SM_RATE_ANGLE_DRIVE	SM_RATE_ANGLE_DRIVE
BODY_TO_SM	C_{BASM}^*	M(3, 3)/SP, A	Direction cosine matrix from body to stable member axes	(none)	TBD	SM_RATE_ANGLE_DRIVE	SM_RATE_ANGLE_DRIVE	SM_RATE_ANGLE_DRIVE
COSOGA	COSOGA	Sc/SP, A	Cosine of outer gimbal angle	(none)	TBD	COMPMPGA	COMPMPGA	COMPMPGA
[DELTA_GA]	$[\Delta\phi_D]$	A(3), Sc/SP	Incremental gimbal angle	rad	TBD	COMPOOL	BODY_RATE_ANGLE_DRIVE	RCS_DAP
DESIRED_BODY_RATE	ω_D	V(3)/SP	Desired angular velocity vector	rad/s	TBD	COMPOOL	BODY_RATE_ANGLE_DRIVE	RCS_DAP
DUMMY_VECTOR	V_{DUMMY}	V(3)/SP, A	Temporary location for $[\Delta\phi_D]$	rad/s	TBD	BODY_RATE_ANGLE_DRIVE	BODY_RATE_ANGLE_DRIVE	BODY_RATE_ANGLE_DRIVE
^{FAST} DFCS_FLAG2	t_{fast}	$\left\{ \begin{array}{l} \text{FAST} \\ \text{A(8), Sc/SP} \\ \text{DFCS_FLAG2} \\ \text{1/SP} \end{array} \right\}$	RCS DAP cycle time	s	TBD	COMPOOL	COMPOOL	BODY_RATE_ANGLE_DRIVE

Table 3.3.4.1.2.1-2. Automatic rate driver glossary (Cont.).

Name of Variable or Constant		Type/Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
[GA]	$[\phi]$	A(3), Sc/SP	Gimbal angles	rad	TBD	COMPMPGA	COMPMPGA	COMPMPGA
[GA_DESIRED]	$[\phi_D]$	A(3), Sc/SP	Desired gimbal angles	rad	TBD	COMPOOL	BODY_ RATE_ ANGLE_ DRIVE	RCS_DAP
[GA_INITIAL]	$[\phi_I]$	A(3), Sc/SP	Initial gimbal angles	rad	TBD	BODY_ RATE_ ANGLE_ DRIVE	BODY_ RATE_ ANGLE_ DRIVE	BODY_ RATE_ ANGLE_ DRIVE
[GA_INITIAL]	$[\phi_I]$	A(3), Sc/SP	Initial gimbal angles	rad	TBD	SM_RATE_ ANGLE_ DRIVE	SM_RATE_ ANGLE_ DRIVE	SM_RATE_ ANGLE_ DRIVE
*MPGA	*M _{PGA}	M(3, 3)/SP	Pilot to gimbal axes transformation matrix	(none)	TBD	BODY_ RATE_ ANGLE_ DRIVE	BODY_ RATE_ ANGLE_ DRIVE	BODY_ RATE_ ANGLE_ DRIVE
*MPGA	*M _{PGA}	M(3, 3)/SP	Pilot to gimbal axes transformation matrix	(none)	TBD	COMPMPGA	COMPMPGA	COMPMPGA
SECMGA	SECMGA	Sc/SP, A	Secant of middle gimbal angle	(none)	TBD	COMPMPGA	COMPMPGA	COMPMPGA
SINOGA	SINOGA	Sc/SP, A	Sine of outer gimbal angle	(none)	TBD	COMPMPGA	COMPMPGA	COMPMPGA
SM_RATE	$\omega_{D(SM)}$	V(3)/SP	Angular velocity in stable member coordinates	rad	TBD	SM_RATE_ ANGLE_ DRIVE	SM_RATE_ ANGLE_ DRIVE	SM_RATE_ ANGLE_ DRIVE
TANMGA	TANMGA	Sc/SP, A	Tangent of middle gimbal angle	(none)	TBD	COMPMPGA	COMPMPGA	COMPMPGA

Table 3.4.1-1. OMS engine FDI glossary.

Name of Variable or Constant		Type/ Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
ROLL_DISTURB_ ACCEL	$\hat{\alpha}_r$	Sc/SP	Roll angular disturbance acceleration estimate	rad/s ²	TBD	COMPOOL	PART1_FILTER	OMS_ENGINE_FDI
ROLL_ACCEL_ THRESHOLD	ROLL_ACCEL_ THRESHOLD	Sc/SP,C	Yaw acceleration threshold	rad/s ²	TBD	OMS_ENGINE_FDI	OMS_ENGINE_FDI	OMS_ENGINE_FDI
OMS1_ON_CMD	OMS1_ON_CMD	B(1)/-	OMS engine #1 ON/OFF command	(None)	ON/OFF	COMPOOL	TBD	OMS_ENGINE_FDI
OMS2_ON_CMD	OMS2_ON-CMD	B(1)/-	OMS engine #2 ON/OFF command	(None)	ON/OFF	COMPOOL	TBD	OMS_ENGINE_FDI
ACCUM_DELTA_ V_INCR	ACCUM_DELTA_ V_INCR	Sc/SP,A	Increment in the accumulated velocity change	ft/s	TBD	OMS_ENGINE_FDI	OMS_ENGINE_FDI	OMS_ENGINE_FDI
ONE_ENGINE_ THRESHOLD	ONE_ENGINE_ THRESHOLD	Sc/SP,C	One-engine velocity increment threshold	ft/s	TBD	OMS_ENGINE_FDI	OMS_ENGINE_FDI	OMS_ENGINE_FDI
TWO_ENGINE_ THRESHOLD	TWO_ENGINE_ THRESHOLD	Sc/SP,C	Two-engine velocity increment threshold	ft/s	TBD	OMS_ENGINE_FDI	OMS_ENGINE_FDI	OMS_ENGINE_FDI
OMS1_FAIL	OMS1_FAIL	B(1)/-	OMS engine #1 failure flag	(None)	ON/OFF	COMPOOL	OMS_ENGINE_FDI	FDI executive
OMS2_FAIL	OMS2_FAIL	B(1)/-	OMS engine #2 failure flag	(None)	ON/OFF	COMPOOL	OMS_ENGINE_FDI	FDI executive
OMSE_INIT_ FLAG	OMSE_INIT_ FLAG	B(1)/-	Initialization flag	(None)	ON/OFF	COMPOOL	FDI executive	OMS_ENGINE_FDI
ACCUM_ DELTA_V	Δv_n	V(3)/SP	Accumulated vehicle velocity change	ft/s	TBD	COMPOOL	Hardware/SOP	OMS_ENGINE_FDI
OLD_ACCUM_ DELTA_V	Δv_{n-1}	V(3)/SP	Last value of accumulated velocity	ft/s	TBD	OMS_ENGINE_FDI	OMS_ENGINE_FDI	OMS_ENGINE_FDI

Table 3.4.2-1. OMS actuator FDI glossary.

Name of Variable or Constant		Type/ Attribute	Description	Units	Value or Range	Declared in	Assigned in	Referenced in
Computer Notation	Mathematical Notation							
[OMS_GIMBAL]	$[\delta]$	A(4),Sc/SP	Measured OMS gimbal deflections	rad	-0.123 < x < 0.123	COMPOOL	Hardware/SOP	OMS_ACTUATOR_FDI
[OLD_OMS_GIMBAL]	$[\delta_{old}]$	A(4),Sc/SP,St	Last values of measured OMS gimbal deflections	rad	TBD	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI
[OMS_GIMBAL_ERROR]	$[\delta_e]$	A(4),Sc/SP	OMS gimbal deflection errors	rad	TBD	COMPOOL	TVC_DAP	OMS_ACTUATOR_FDI
[OMS_ACTUATOR_EXTEND]	[OMS_ACTUATOR_EXTEND]	A(4),I/SP	Actuator extension indicators	(None)	-1,0,1	COMPOOL	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI, FDI executive
[OLD_OMS_ACTUATOR_EXTEND]	[OLD_OMS_ACTUATOR_EXTEND]	A(4),I/SP,St	First-pass values of actuator extension indicators	(None)	-1,0,1	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI
[OMS_SERVO_AMP_DEADBAND]	e_d	Sc/SP,C	OMS servo amplifier deadtone	rad	0.07	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI
[OMS_ACTUATOR_FAIL]	[OMS_ACTUATOR_FAIL]	A(4)/B	OMS actuator failure flags	(None)	ON/OFF	COMPOOL	OMS_ACTUATOR_FDI	FDI executive
I	I	I/SP,A	Index variable and counter	(None)	1,2,3,4	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI
OMSA_INIT_FLAG	OMSA_INIT_FLAG	B(1)/-	Initialization flag	(None)	ON/OFF	COMPOOL	FDI executive	OMS_ACTUATOR_FDI
[ACTUATOR_FAIL_COUNTER]	[ACTUATOR_FAIL_COUNTER]	A(4),I/SP	Actuator failure counters	(None)	0,1,2	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI
OMSA_CALL_COUNTER	OMSA_CALL_COUNTER	I/SP	Procedure call counter	(None)	1,2,3	COMPOOL	FDI executive	OMS_ACTUATOR_FDI, FDI executive
OMS_GIMBAL_INCR_THRESHOLD	OMS_GIMBAL_INCR_THRESHOLD	Sc/SP,C	Gimbal deflection threshold level	rad	TBD	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI	OMS_ACTUATOR_FDI

Table 3.4.3-1. RCS jet FDI glossary.

Name (Computer Notation)	Type/ Attribute	Description	Units	Value	Declared in	Assigned in	Referenced in
RECHECK1 RECHECK2 RECHECK3	B(1)/-	Recheck delay flags	(None)	ON/OFF	ONFAIL	ONFAIL	ONFAIL
MANIFOLD_ OFF_COM	A(15),B(1)/-	Manifold shutdown commands	(None)	ON/OFF	ONFAIL	ONFAIL	Hardware/ SOP
DRIVERA DRIVERB DRIVERC DRIVERD DRIVERE DRIVERF	B(32)/-	Driver talkback words	(None)	ON/OFF	ONFAIL	Hardware/ SOP	ONFAIL
JETCOMA JETCOMB JETCOMC JETCOMD JETCOME JETCOMF	B(32)/-	Jet ON/OFF command words	(None)	ON/OFF	COMPOOL	JET SELECT	ONFAIL, OFFAIL
NEWFAILA NEWFAILB NEWFAILC NEWFAILD NEWFAILE NEWFAILF	B(32)/-	Current ONFAIL status	(None)	ON/OFF	ONFAIL	ONFAIL	ONFAIL
OLDFAILA OLDFAILB OLDFAILC OLDFAILD OLDFAILE OLDFAILF	B(32)/-	ONFAIL status from last pass	(None)	ON/OFF	ONFAIL	ONFAIL	ONFAIL

Table 3.4.3-1. RCS jet FDI glossary (Cont.).

Name (Computer Notation)	Type/ Attribute	Description	Units	Value	Declared in	Assigned in	Referenced in
JFAILA JFAILB JFAILC JFAILD JFAILE JFAILF	B(32)/-	Jet fail flags	(None)	ON/OFF	COMPOOL	ONFAIL, OFFAIL	JET SELECT
RECHECKA RECHECKB RECHECKC RECHECKD RECHECKE RECHECKF	B(32)/-	Map of jets to be rechecked	(None)	ON/OFF	ONFAIL	ONFAIL	ONFAIL
MAP	A(16),B(32)/-	Map of jets by manifold	(None)	ON/OFF	ONFAIL	ONFAIL	ONFAIL
OFA3 OFB3 OFC3 OFD3 OFE3 OFF3 OFA2 OFB2 OFC2 OFD2 OFE2 OFF2 OFA1 OFB1 OFC1 OFD1 OFE1 OFF1	B(32)/-	OFFAIL pushdown lists	(None)	ON/OFF	OFFAIL	OFFAIL	OFFAIL

Table 3.4.3-1. RCS jet FDI glossary (Cont.).

Name (Computer Notation)	Type/ Attribute	Description	Units	Value	Declared in	Assigned in	Referenced in
PRESSA PRESSB PRESSC PRESSD PRESSE PRESSF	B(32)/-	Pressure sensor discrete	(None)	ON/OFF	COMPOOL	Hardware/ SOP	OFFAIL

CODES FOR TYPE/ATTRIBUTE COLUMN

Key for Type

- E - Event
- P - Process Event
- St - Structure
- A(1) - Array (i)
- M(i,j) - Matrix (i,j)
- V(1) - Vector (1)
- Sc - Scalar
- I - Integer
- B(1) - Bit (1)
- Ch - Character

Key for Attributes

- SP - Single Precision
- DP - Double Precision
- A - Automatic
- C - Constant
- St - Static
- B - Boolean
- L - Locked

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SECTION 4

APPENDIX

This appendix contains derivations and other material supportive to the designs presented in Sections 1 and 2. The numbering scheme follows that of the earlier sections, but the numbering is not necessarily consecutive.

4.3.2.3 Appendix to Phase Plane Switching Logic

In this subsection, two idealized limit cycles are presented. One limit cycle is in the presence of positive disturbing accelerations while the other is in the presence of zero disturbing accelerations. For each limit cycle the average attitude error will be derived.

An idealized limit cycle for a positive disturbing acceleration is illustrated in Figure 4.3.2.3-1. The coordinates θ_e and ω_e are chosen to be the state, where θ_e represents the angular position error and ω_e represents the angular rate error. X_{DB} is the attitude variation in the course of limit cycling. In the presence of a positive disturbance acceleration, U_D , the state is driven along the trajectory from A to B. At point B a negative control acceleration, $-U_C$, is applied to return the state to point A.

The time average attitude error, \bar{X} , of the limit cycle in Figure 4.3.2.3-1 is found by determining the average attitude error for each of the trajectories OB and BO' (called \bar{X}_1 and \bar{X}_2) and then "weighting" them according to time to calculate the net average, \bar{X} .

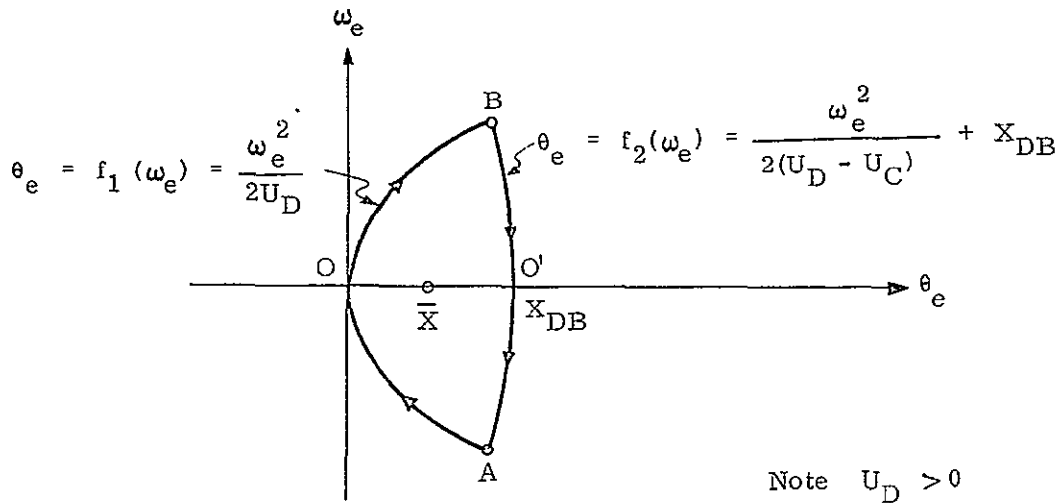


Figure 4.3.2.3-1. Idealized limit cycle for a positive disturbing acceleration.

Determination of \bar{X}_1 :

\bar{X}_1 is, by definition,

$$\bar{X}_1 = \frac{1}{t_1} \int_0^{t_1} \frac{1}{2} U_D t^2 dt \quad (4.3.2.3-1)$$

t_1 , the time to travel from point O to point B, can be calculated from the value of the θ_e abscissa of point B, B_{θ_e} , since

$$B_{\theta_e} = \frac{1}{2} U_D t_1^2 \quad (4.3.2.3-2)$$

B_{θ_e} is found by first rearranging $\theta_e = f_1(\omega_e)$ and $\theta_e = f_2(\omega_e)$ such that

$$\omega_e = g_1(\theta_e), \quad \omega_e = g_2(\theta_e) \quad (4.3.2.3-3)$$

Then, at point B, $g_1(\theta_e) = g_2(\theta_e)$, and

$$B_{\theta_e} = X_{DB} \left(\frac{U_C - U_D}{U_C} \right) \quad (4.3.2.3-4)$$

and from Eq. (4.3.2.3-2)

$$t_1 = + \sqrt{\frac{2X_{DB}(U_C - U_D)}{U_C U_D}} \quad (4.3.2.3-5)$$

Using t_1 in Eq. (4.3.2.3-1)

$$\bar{X}_1 = \frac{1}{3} X_{DB} \left(\frac{U_C - U_D}{U_C} \right) \quad (4.3.2.3-6)$$

Determination of \bar{X}_2 :

The time average attitude error for the trajectory segment BO' can be found by setting $t = 0$, at point B. Then,

$$\bar{X}_2 = \frac{1}{t_2} \int_0^{t_2} \left[X_0 + \dot{X}_0 t + \frac{1}{2} (U_D - U_C) t^2 \right] dt$$

or,

$$\bar{X}_2 = X_0 + \frac{\dot{X}_0 t_2}{2} + \frac{1}{6} (U_D - U_C) t_2^2 \quad (4.3.2.3-7)$$

X_0 is defined in Eq. (4.3.2.3-4) and \dot{X}_0 can be determined from

$$\dot{X}_0 = U_D t_1 = + \sqrt{\frac{2X_{DB} U_D (U_C - U_D)}{U_C}} \quad (4.3.2.3-8)$$

To find t_2 one can use the following relation,

$$\dot{X}_0 + (U_D - U_C) t_2 = 0$$

from which it follows,

$$t_2 = \sqrt{\frac{2X_{DB} U_D}{U_C (U_C - U_D)}} \quad (4.3.2.3-9)$$

Substituting the results of Eqs. (4.3.2.3-4), (4.3.2.3-8), and (4.3.2.3-9) into Eq. (4.3.2.3-7) yields:

$$\bar{X}_2 = X_{DB} \left(1 - \frac{U_D}{3U_C} \right) \quad (4.3.2.3-10)$$

Determination of \bar{X} :

Finally, the total average attitude error, \bar{X} , can be found from,

$$\bar{X} = \frac{\bar{X}_1 t_1 + \bar{X}_2 t_2}{t_1 + t_2} \quad (4.3.2.3-11)$$

Substituting the results of Eqs. (4.3.2.3-5), (4.3.2.3-6), (4.3.2.3-9) and (4.3.2.3-10) into Eq. (4.3.2.3-11) yields:

$$\bar{X} = \frac{X_{DB}}{3} \left(1 + \frac{U_D}{U_C} \right) \quad (4.3.2.3-12)$$

This is the average attitude error for the limit cycle in Figure 4.3.2.3-1. Thus, the average attitude error would be zero if the intercept of the curve on the right, which is the trajectory along which the control is applied, were shifted from point O' to have an abscissa of

$$DR = X_{DB} - \bar{X} \quad (4.2.3.2-13)$$

A similar result can be obtained for the case of a negative disturbance acceleration. Equations (4.3.2.3-12) and (4.3.2.3-13) are used in FC in order to minimize the time average attitude error.

The attitude variation, X_{DB} , could be chosen as follows:

- (1) To achieve the cycle period, T :

$$\text{Set } X_{DB} = \left[1 - \frac{|U_D|}{|U_C|} \right] \frac{|U_D|}{8} T^2 \quad (4.3.2.3-14)$$

- (2) To achieve the limit cycle maximum rate, \dot{X}_{\max} :

$$\text{Set } X_{DB} = \frac{|U_C| (\dot{X}_{\max})^2}{2|U_D| (|U_C| - |U_D|)} \quad (4.3.2.3-15)$$

- (3) By simply setting X_{DB} to the allowable attitude variation.

Currently, the final option is employed in the FC.

An idealized limit cycle in the presence of no disturbing accelerations is illustrated in Figure 4.3.2.3-2. From point A the state is allowed to drift to point B where a negative control acceleration, $-U_C$, (in the form of a minimum impulse jet firing) is applied to drive the state to point C. From point C the state is then allowed to drift to

point D. At point D a positive control acceleration, $+U_c$, is applied to return the state to point A. By choosing $DL = DR$, the state limit cycles with zero average attitude error. The generalized limit cycle for positive disturbing acceleration is made to reduce to the limit cycle for zero disturbing accelerations by selecting

$$DL = \bar{X} + \frac{1}{3} X_{DB} \quad (4.3.2.3-16)$$

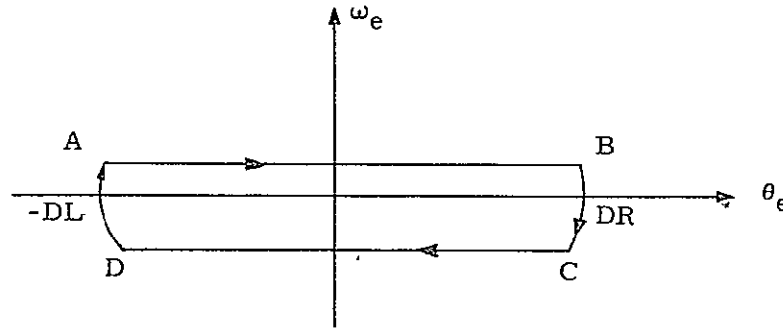


Figure 4.3.2.3-2. Limit cycle in presence of no disturbing accelerations.

4.3.2.4 Appendix to Jet Selection

Jet Numbering

The system for numerical identification of the RCS jets has changed from an "old" configuration (as found in this report), which uses the consecutive numbers 1 to 38 for the main jets, to a "new" configuration which uses a three-digit number for each main and vernier jet. For a jet numbered ABC,

- (1) A identifies the RCS module containing the jet (see Figure 4.3.2.4-1) as follows:
 - (a) A = 1 if the jet is in the forward module.
 - (b) A = 2 if the jet is in the left aft module.
 - (c) A = 3 if the jet is in the right aft module.
- (2) B identifies the fuel and oxidizer manifolds feeding the jet (see Figure 4.3.2.4-2).

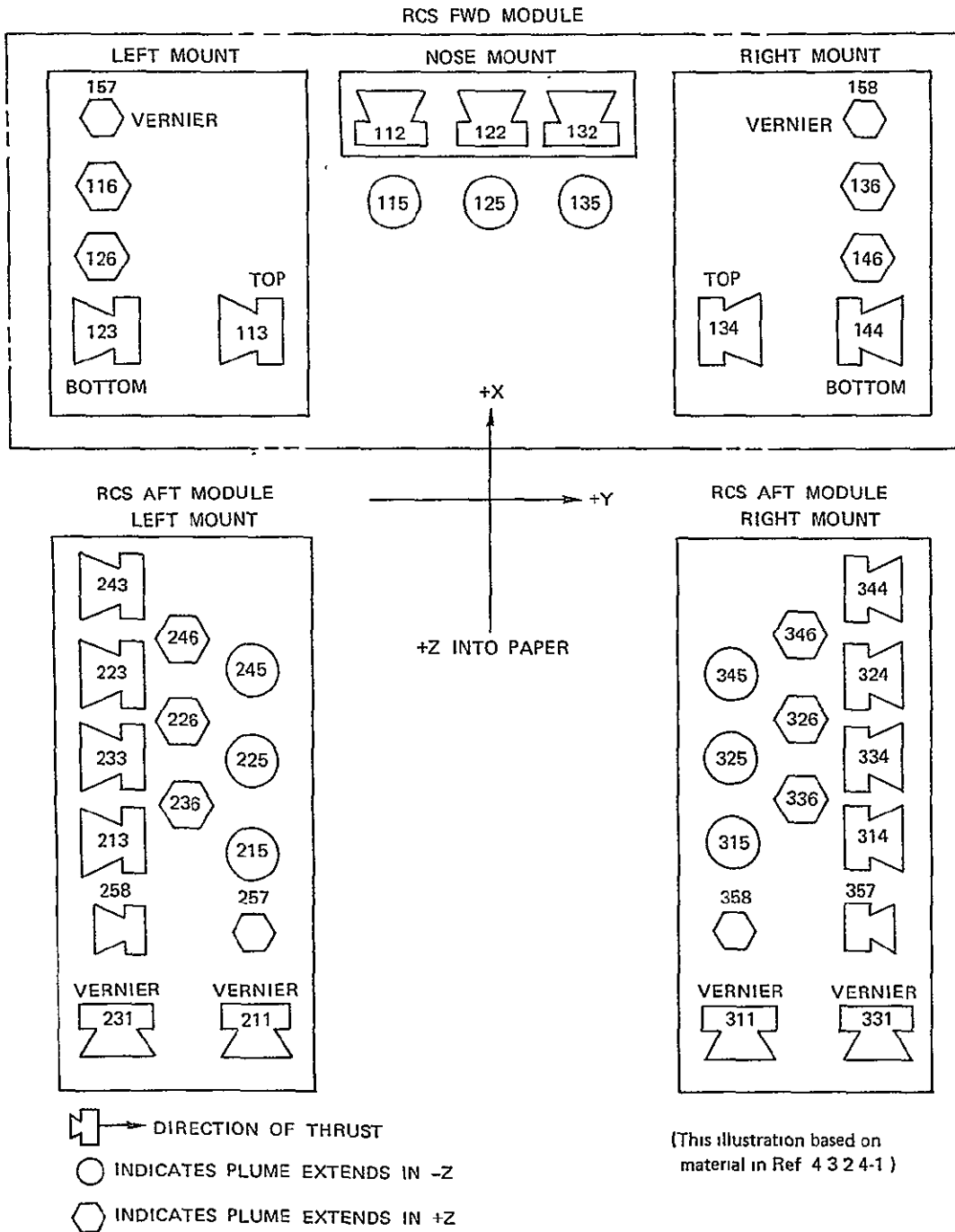
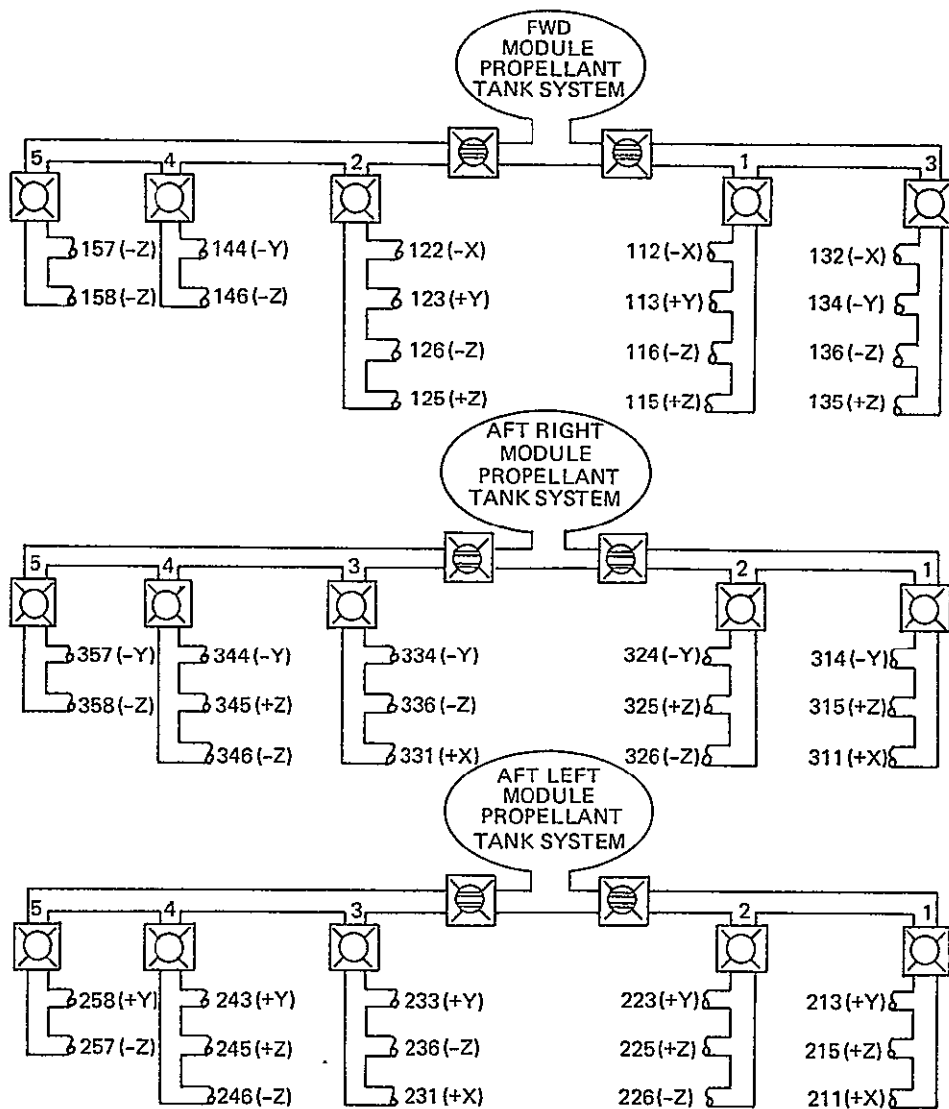


Figure 4.3.2.4-1. RCS jet location, by module.



NOTE

THIS DIAGRAM PERTAINS TO ONE PROPELLANT ONLY (FUEL OR OXIDIZER) THE OTHER PROPELLANT SYSTEM IS IDENTICAL.

LEGEND

- VALVE (OPERATED BY CREW ONLY)
- VALVE (AUTOMATIC OR CREW CONTROL)

(This illustration based on material in Ref 4 3 2 4-1)

Figure 4.3.2.4-2. RCS jet location, by manifold.

- (3) C identifies the thrust direction of the jet as follows:
- (a) C = 1 for a main jet thrusting in +X.
 - (b) C = 2 for a main jet thrusting in -X.
 - (c) C = 3 for a main jet thrusting in +Y.
 - (d) C = 4 for a main jet thrusting in -Y.
 - (e) C = 5 for a main jet thrusting in +Z.
 - (f) C = 6 for a main jet thrusting in -Z.
 - (g) C = 7 for a vernier jet effecting +roll.
 - (h) C = 8 for a vernier jet effecting -roll.

Table 4.3.2.4-1 relates the old and new jet numbering systems for the main jets, and additionally provides information on main-jet grouping, mnemonic names and locations.

Thrust History Correction

Due to the difference between the actual response of an RCS thruster and its modelled response, a thrust history of the RCS jets is required in the estimate of ΔV . A typical thrust history for an RCS jet is given in Figure 4.3.2.4-3 with thrust on the vertical axis and time on the horizontal. The time of the jet "on" command is represented as t_{on} , and the time of the jet "off" command is represented by t_{off} .

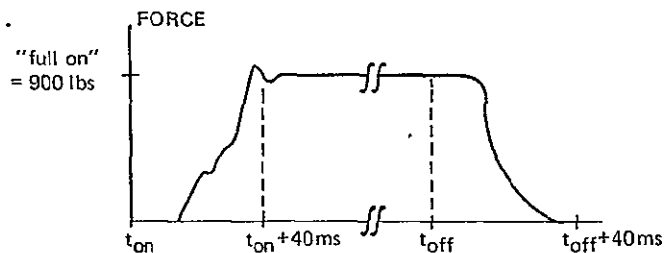


Figure 4.3.2.4-3. Typical thrust history.

A simplified model of this response is given in Figure 4.3.2.4-4 with the same coordinates. During the pass when the "on" command is received, the response can be modelled as a constant equal to f_1 times the "full-on" value. During the pass when the "off" command is received, the response can be modelled as a constant thrust equal to f_2 times the

Table 4.3.2.4-1. RCS main jet data.

New Jet Number	Jet Group	Old Jet Number (FD-2)	Mnemonic Name	Thrust Direction	Location (in)		
					X	Y	Z
112	*	1	FLF	-X	332.0	-14.0	389.31
122	*	2	FCF	-X	332.0	0.0	391.0
132	*	3	FRF	-X	332.0	14.0	389.31
123	2	4	FLS	+Y	360.0	-47.0	367.5
113	2	5	FLS	+Y	360.0	-47.0	353.5
115	**	6	FLU	+Z	350.0	-13.0	394.7
125	**	7	FCU	+Z	350.0	0.0	394.7
135	**	8	FRU	+Z	350.0	13.0	394.7
116	4	9	FLD	-Z	333.0	-40.5	381.0
126	4	10	FLD	-Z	347.0	-44.68	385.5
144	6	11	FRS	-Y	361.75	47.0	367.5
134	6	12	FRS	-Y	361.75	47.0	353.5
136	8	13	FRD	-Z	333.0	40.5	381.0
146	8	14	FRD	-Z	347.0	44.68	385.5
211	9	15	ALA	+X	1557.46	-119.0	473.44
231	9	16	ALA	+X	1557.46	-132.0	473.44
243	10	17	ALS	+Y	1516.0	-122.5	459.0
223	10	18	ALS	+Y	1529.0	-122.5	459.0
233	10	19	ALS	+Y	1542.0	-122.5	459.0
213	10	20	ALS	+Y	1555.0	-122.5	459.0
245	11	21	ALU	+Z	1516.0	-132.0	480.5
225	11	22	ALU	+Z	1529.0	-132.0	480.5
215	11	23	ALU	+Z	1542.0	-132.0	480.5
246	12	24	ALD	-Z	1516.0	-112.0	437.24
226	12	25	ALD	-Z	1529.0	-111.0	440.0
236	12	26	ALD	-Z	1542.0	-110.0	442.76
311	13	27	ARA	+X	1557.46	119.0	473.44
331	13	28	ARA	+X	1557.46	132.0	473.44
344	14	29	ARS	-Y	1516.0	122.5	459.0
324	14	30	ARS	-Y	1529.0	122.5	459.0
334	14	31	ARS	-Y	1542.0	122.5	459.0
314	14	32	ARS	-Y	1555.0	122.5	459.0
345	15	33	ARU	+Z	1516.0	132.0	480.5
325	15	34	ARU	+Z	1529.0	132.0	480.5
315	15	35	ARU	+Z	1542.0	132.0	480.5
346	16	36	ARD	-Z	1516.0	112.0	437.24
326	16	37	ARD	-Z	1529.0	111.0	440.0
336	16	38	ARD	-Z	1542.0	110.0	442.76

(This table is based in part on material from Ref. 4.3.2.4-2.)

"full-on" thrust. During intermediate passes, the thrust is set equal to the "full-on" value. This model is based on the total impulse obtained during a pass.

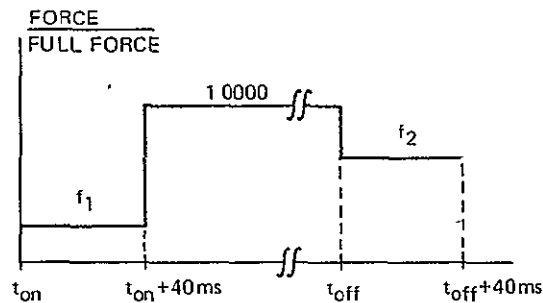


Figure 4.3.2.4-4. Modelled thrust history.

The flowchart required for the estimate of ΔV is presented in Figure 4.3.2.4-5. On the first pass with JTLST equal to one, the expected rates are incremented by f_1 times the "full-on" increments for all jets turned on. When the jets receive subsequent "on" commands, the expected rates are incremented by the "full-on" increments for all jets which have been turned on in previous passes. When the jets first receive the "off" command, the rate is incremented by f_2 times the "full-on" increment, after which the increment is zero until the next "on" command.

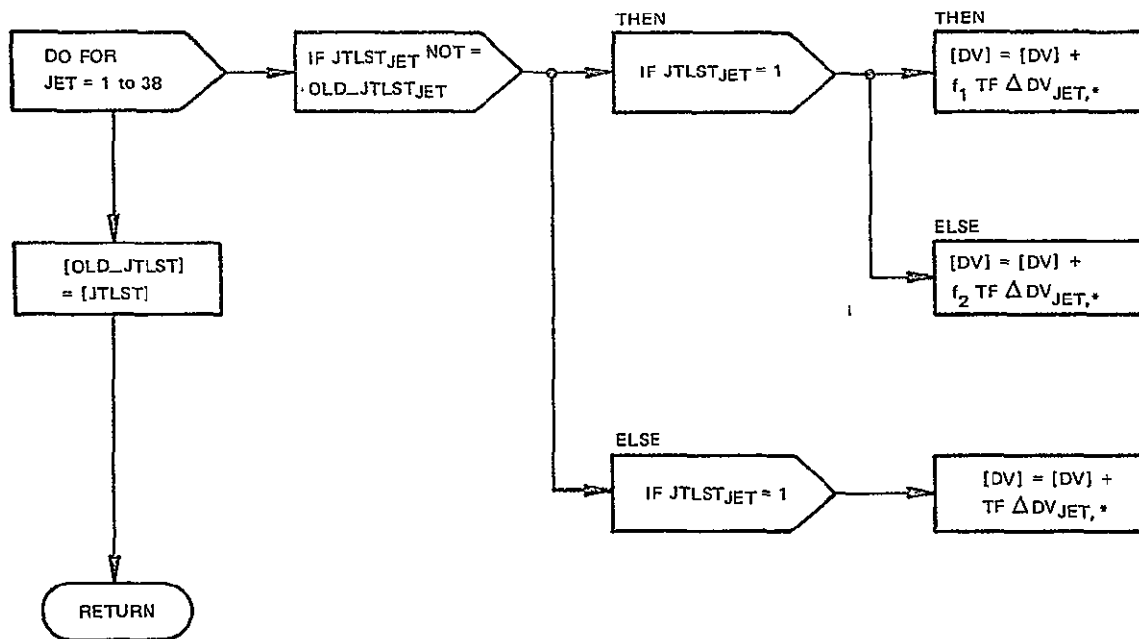


Figure 4.3.2.4-5. Modelled RCS thrust history correction.

4.3.2.4.1 Vernier Jet Selection

The vernier jet configuration is sketched in Figure 4.3.2.4.1-1. The jet numbers shown are only for the purposes of this discussion.

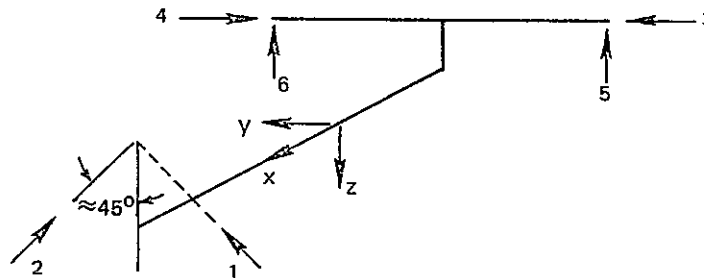


Figure 4.3.2.4.1-1. Vernier jet configuration.

It can be seen that +pitch may be obtained by firing jets 1 and 2, and -pitch results from firing jets 5 and 6. However, for other commands, the jet(s) which must be chosen produce considerable cross coupling. Although this cross coupling is unavoidable, it may be used to advantage by attempting to select jet(s) whose coupling into the off-axis is favorable. To perform this task, one must compute a three-axis command vector which contains not only the original phase plane command, but also preferences for the direction of coupling into the off-axis. Although the logic for the three-axis command with cross-coupling computations has not yet been finalized, nonetheless, the following will illustrate how such a logic is formulated.

Consider a line in the coast region of the small error control logic to determine whether positive or negative cross coupling is desirable. This is shown as a dashed line in Figure 4.3.2.4.1-2.

If the operation is above the dashed line in an uncommanded axis, then it would be preferable that the cross coupling provide a negative acceleration. However, for operation below the dashed line, it is best if the cross coupling is positive. The off-axis command component can then be completely defined by specifying its sign as the desired coupling direction, and its magnitude as a TBD weighting of how strongly we prefer that direction. Combining each of the off-axis command component(s) with the original phase plane command(s) yields the 3-axis command vector to be sent to the vernier logic.

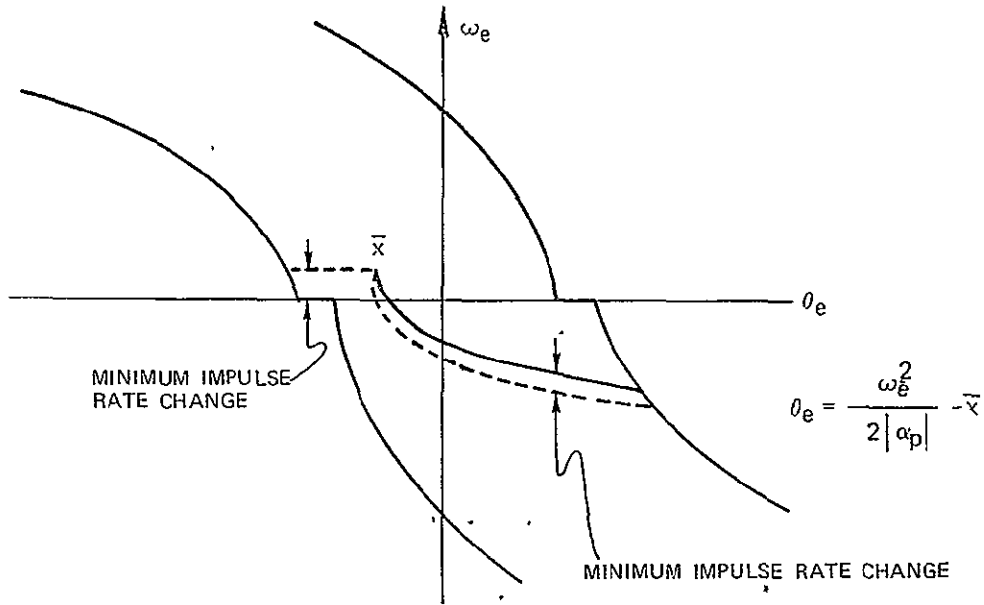


Figure 4.3.2.4.1-2. Cross-coupling preference.

4.3.3 Appendix to TVC DAP

Thrust Vector Control of the OMS Engines

This subsection presents the TVC design goals, the design procedure, and the analytical tools used for achieving these goals. In addition to vehicle dynamics, an important part of the TVC loop is the engine gimbal servo. The discussion uses as an example a now outdated engine gimbal servo model operating in its linear range. However, the current model of the engine gimbal servo uses a bang-bang amplifier and has other nonlinearities as well. Therefore, a linearization procedure is needed and is outlined in the latter part of this subsection. The impact of these changes in servo characteristics on the present autopilot design is also presented.

The performance and stability objectives used for the TVC law are stated in terms of either the open- or closed-loop frequency response:

- (1) Open-loop frequency response
 - crossover frequency ≥ 1 rad/s
 - gain margin ≥ 8 dB
 - phase margin $\geq 50^\circ$
 - rigid body attenuation of bending mode frequencies ≥ 50 dB
- (2) Closed-loop frequency response
 - closed-loop resonant peak (below crossover frequency) ≤ 2.5 dB

The objective of attenuating the bending mode frequencies by at least 50 dB is determined by the rationalization that if the peak of the bending mode is 20 dB above the rigid body response, then the bending mode peak is still attenuated by 30 dB. For design purposes, the attenuation is measured at a frequency which is 70 percent of the first bending mode frequency.

The dynamic effects acting on the vehicle which were considered in this design are: rigid body effects, effects of propellant slosh, bending effects, and the "tail-wags-dog" effect in which the vehicle is subjected to the dynamic effects of an actuator physically moving a large rocket engine. The "dog-wags-tail" effect, in which a vibrating structure subjects the engine to large initial loads which cause the engine to move about its gimbal, is not considered.

The first step in the approach used for the TVC design was to obtain the necessary data concerning the vehicle and engine dynamics. For the rigid body effects, the information needed was the vehicle mass and moment of inertia, the thrust magnitude, and the distance from the cg of the vehicle to the engine hinge point. The necessary data for slosh effects included the slosh mode frequencies, the slosh mass, the slosh damping ratio, and the slosh mass moment arm. For bending effects, the bending mode frequencies, the generalized bending masses, the bending damping ratio, the bending deflections and slopes at the engine hinge point, and the slopes at the IMU station were needed. The tail-wags-dog effect is defined by the engine mass and moment of inertia, the distance from the cg of the engine to the engine hinge point, the engine exhaust jet damping constant, and the hose stiffness constant. Finally, the engine gimbal servo characteristics are needed for the effects of engine dynamics.

All of the above data except that concerning the engine gimbal servo characteristics were used as input to a matrix program which models the vehicle dynamics according to a set of differential equations and which yields as output the s-transfer function relating the actual vehicle attitude θ to the actual engine deflection δ (see Figure 1.3.3.1-1). By adding the transfer function determined from the engine gimbal servo characteristics, the transfer function relating the actual vehicle attitude θ to the commanded engine deflection δ_c was obtained (see Figure 1.3.3.1-1). This function is called $G(s)$. The engine-gimbal-servo transfer function used was:

$$\frac{\delta}{\delta_c} = \frac{625}{s^2 + 25s + 625}$$

Due to the digital nature of the system, the design of the TVC autopilot must be carried out in terms of either the z- or w-transfer functions. The w-transfer function is preferred because the relationship between the s- and w-planes and their frequencies (ω and u , respectively) is clearer. Therefore, the next step in the design approach was to find the z- and w-transforms of $G(s)$ (to which has been added a zero-order hold). $G(s)$ and $G(z)$ are related by the transformation

$$z = e^{sT}$$

where T is the sampling period, and $G(z)$ and $G(w)$ are related by the bilinear transformation

$$z = \frac{1 + w}{1 - w}$$

The left half of the s-plane transforms into the left half of the w-plane, and the frequencies of the two transforms are related by

$$u = \tan \frac{\omega T}{2}$$

At low frequencies, the u frequency is simply a scaled ω frequency.

Next, the frequency response of $G(w)$ was found to determine what the uncompensated values were for phase and gain margins, crossover frequency, bending mode attenuation, and closed-loop resonant peak. The digital compensation filter $D(w)$ (see Figure 4.3.3-1) was then designed to adjust these values to satisfy the performance and stability objectives. The open-loop transfer function is then $D(w) G(w)$. Finally, the thrust misalignment correction loop $M(w)$ (see Figure 4.3.3-1) was added and the frequency response of $D(w) M(w) G(w)$ is checked. A modification of $D(w)$ may be necessary at this point. The effects of the TMC loop are predominantly low-frequency effects and should not alter the frequency response characteristics near and above the crossover frequency.

Figure 4.3.3-2 shows a magnitude (decibels) versus phase (degrees) plot for $G(w)$ generated by a computer program. The large loop is due to the slosh mode and appears to be superimposed upon the rigid body curve. The reason for this appearance is that the complex pole and zero pairs which the slosh mode adds to the transfer function occur

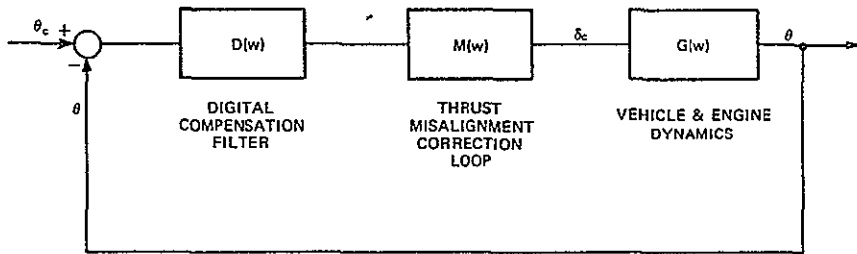


Figure 4.3.3-1. w-plane representation of the TVC digital autopilot loop.

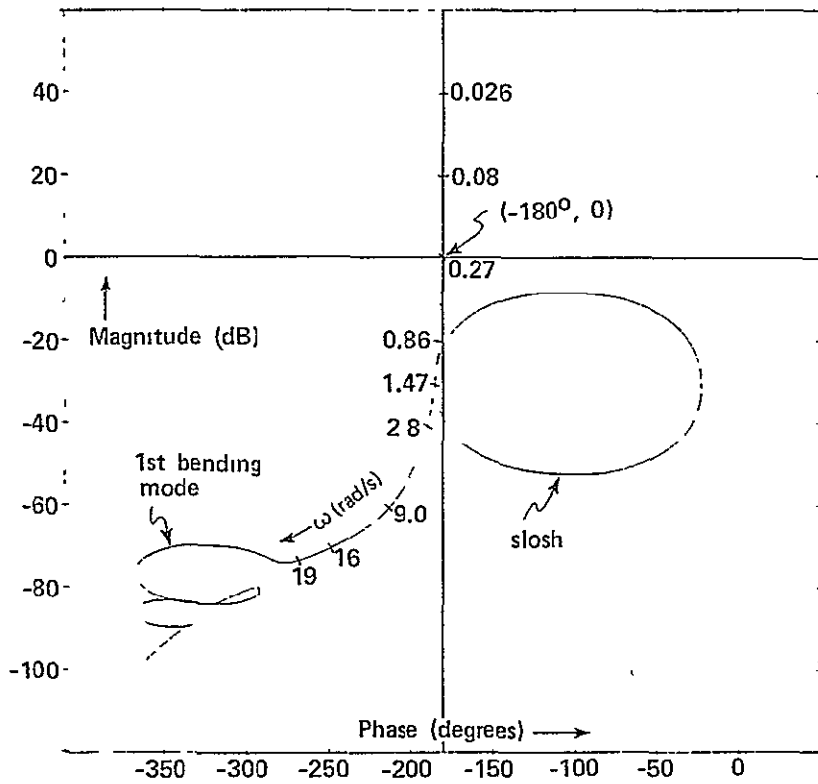


Figure 4.3.3-2. Frequency response of $G(w)$.

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almost on top of one another, and at a frequency just above or below the slosh mode frequency, they appear to cancel. The smaller loops are caused by the first and second bending modes. The crossover frequency of the uncompensated system is 0.27 rad/s, and the phase and gain margins are nonexistent. The attenuation of the rigid body at 70 percent of the first bending mode frequency is 69 dB. Referring to the performance and stability objectives listed above, a compensating filter is clearly necessary.

The filter used for the compensation is a third-order digital filter. Its w-transform is:

$$D(w) = 4 \frac{(w + 0.006)(w + 0.54)^2}{(w + 0.12)(w^2 + 0.12w + 0.0144)}$$

The overall gain of this filter with its lead-lag ratio of twenty provides the system with the proper crossover frequency and phase/gain margins. At the same time the slosh mode is phase stabilized because it occurs very close to the crossover frequency (1.555 rad/s). The second-order low-pass component of the filter provides attenuation of the bending modes without greatly affecting the phase characteristics near the crossover frequency.

The frequency response of the compensated system is shown in Figure 4.3.3-3. The crossover frequency is 1.005 rad/s. The attenuation of the rigid body at 70 percent of the frequency of the first bending mode is 45 dB, and 56 dB at the first bending mode frequency. The closed-loop resonant peak is 2.05 dB, and finally, the phase and gain margins are 55° and 12.9 dB respectively. These values either are very close to or exceed the design objectives.

Adding the TMC loop results in the frequency response of Figure 4.3.3-4. The w-transform of the TMC loop is:

$$M(w) = \frac{(w + 0.001)^2}{w(w + 0.002)}$$

Comparing Figures 4.3.3-3 and 4.3.3-4, it can be seen that the TMC loop is a low-frequency effect. Because the TMC loop adds an integration in the forward loop at low frequencies, the phase angle for very low frequencies is -270° instead of -180° as it is for the system without the TMC loop. This causes the magnitude versus phase curve to bend back

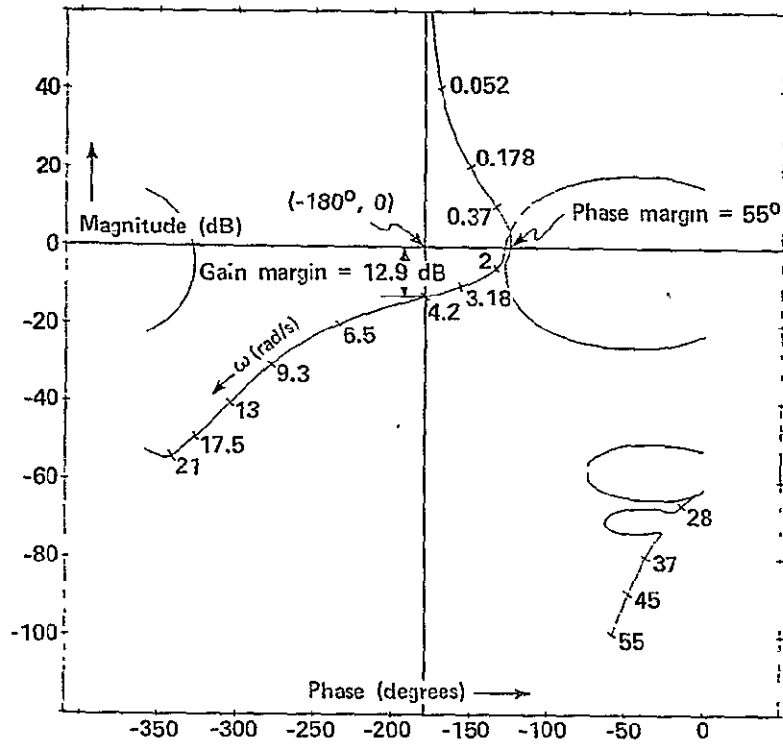


Figure 4.3.3-3. Frequency response of $D(\omega)G(\omega)$.

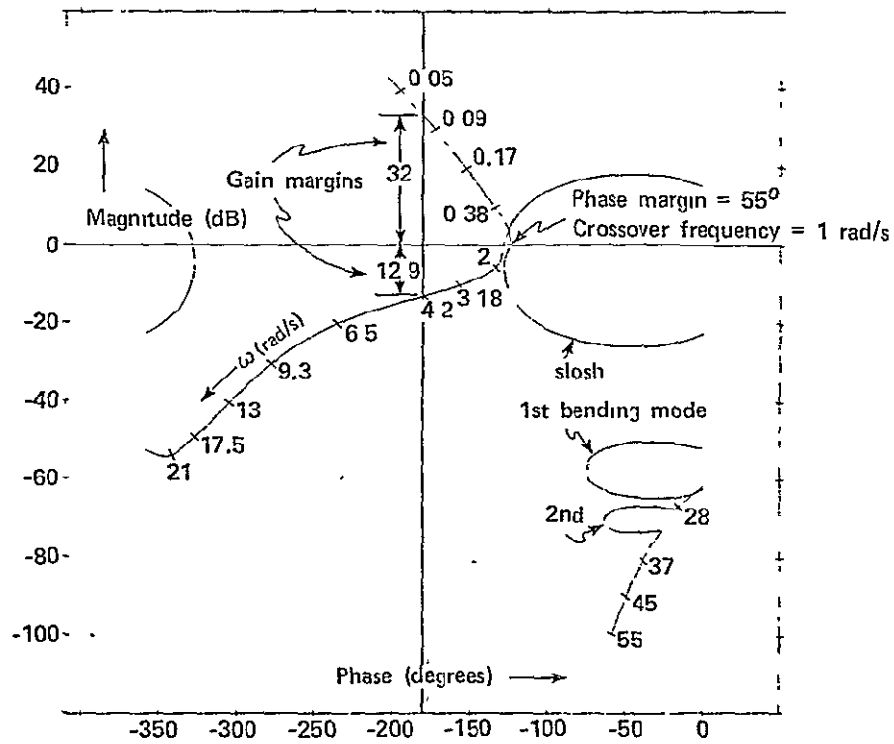


Figure 4.3.3-4. Frequency response of $D(\omega)M(\omega)G(\omega)$.

4-17 $j\omega$

to the left at frequencies below crossover frequency. The addition of the TMC loop does not, in this case, affect the phase/gain margins, closed-loop peaking, or the bending mode attenuation, but creates an additional 180° crossover with an attendant gain margin which is 32 dB.

As was pointed out in the opening paragraph of this subsection, the current gimbal servo model uses a bang-bang amplifier. Neglecting other nonlinearities, the simplified block of the servo is shown in Figure 4.3.3-5. The feedback signal will be sampled and the servo loop closure, i.e., summation of the digital command δ_c and feedback δ , will be done in the TVC DAP. However, since the sampling rate is high (25 times a second), and since it serves the purpose of this discussion, it is reasonable to neglect the sampling effects and examine the model in the s-plane. Using the describing function for the bang-bang block and a Nichols chart, the closed-loop frequency characteristics were obtained for this model. These are plotted in Figure 4.3.3-6 for three values of the parameter a, the ratio of the sinusoidal error signal amplitude to the deadband of 0.4 degrees. In the same figure, gain and phase characteristics of the previous servo model are plotted to illustrate the drastic differences between the two servo models. Whereas the old servo had negligible lag at the autopilot crossover frequency of 1 rad/s, the new servo model has considerable lag at this frequency and also gain other than unity for all signal amplitudes. Thus the stability margins of the present DAP are affected.

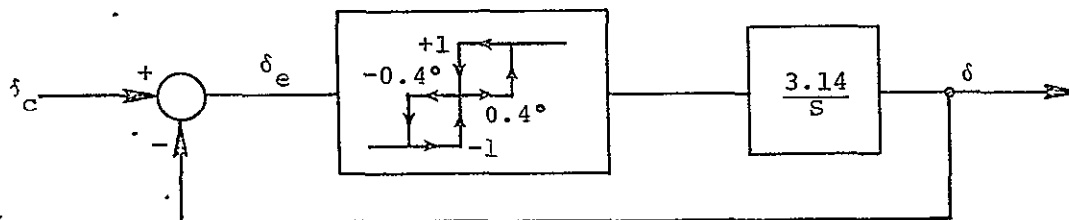


Figure 4.3.3-5. Block diagram of the current servo model (simplified).

Table 4.3.3-1 lists the stability margins with this new servo and the current autopilot. A review of the design is necessary since the margins do not meet the specifications.

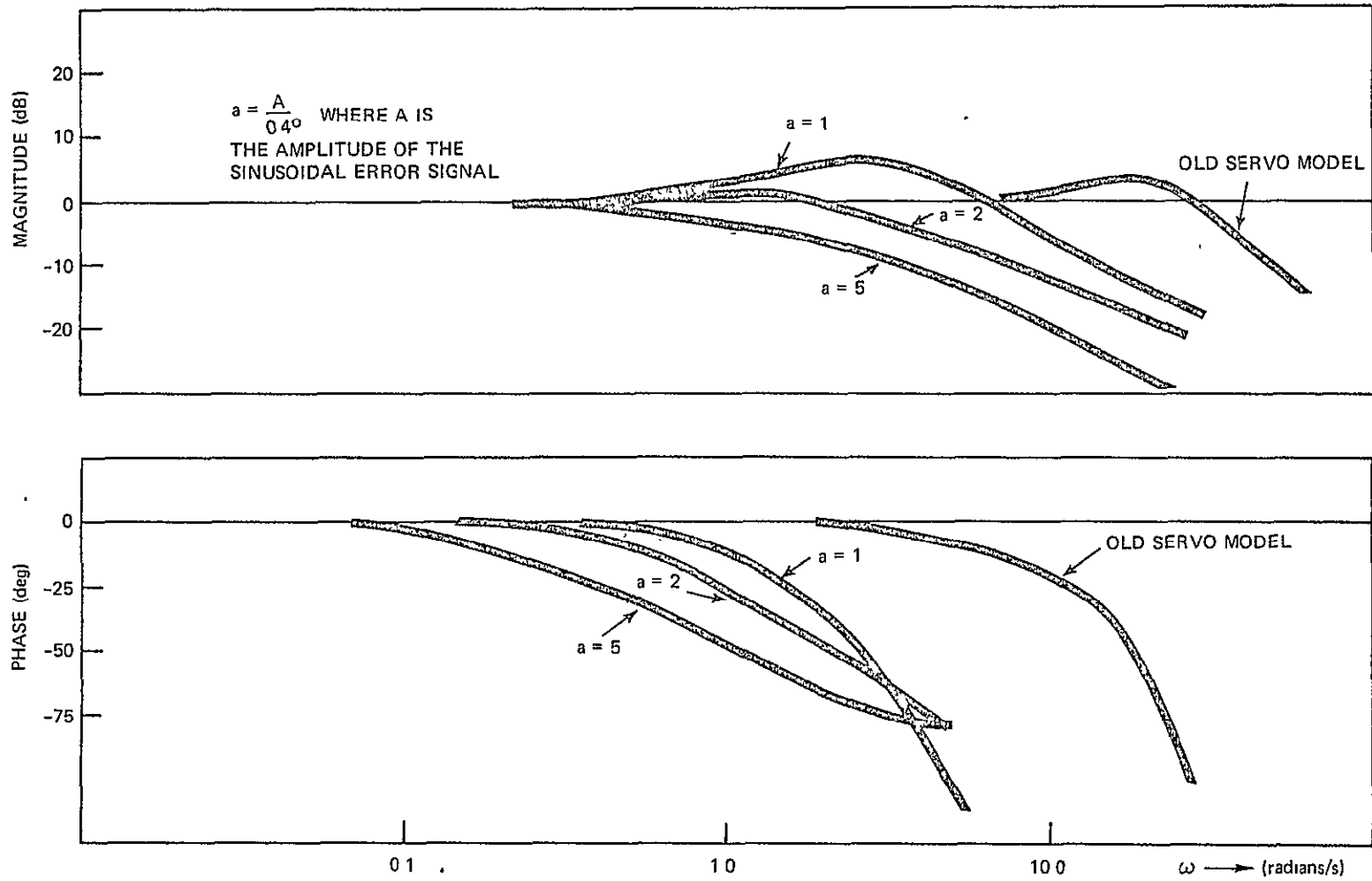


Figure 4.3.3-6. Magnitude versus ω and phase versus ω plots of OMS engine gimbal servo.

Table 4.3.3-1. Stability margins of the present TVC DAP with the new servo model.

Parameter	Gain Margin	Phase Margin	1st Bending Mode*
a = 1	2 dB	25°	16 dB
a = 2	4 dB	30°	20 dB
a = 5	8 dB	16°	30 dB

* Approximate increase at bending mode frequency as compared to old servo model.

It is interesting to note that preliminary results of engineering simulations show that the performance of the TVC loop with this new servo model is satisfactory despite the degraded margins. Further study is underway.

Guidance-Autopilot Loop Analysis

During external ΔV burns, the guidance or steering controls the burn by applying appropriate commands to the inner autopilot loop. In the case of cross-product steering, guidance computation results in a rate command $\vec{\omega}$ defined by

$$\vec{\omega} = \frac{\vec{\Delta V} \times \vec{V}_g}{|\Delta V| |V_g|} = \hat{i} \sin(\alpha_{\Delta V} - \alpha_{V_g}) \quad (4.3.3-1)$$

$\alpha_{\Delta V}$ is the angle of the ΔV vector or velocity increment achieved over the past guidance sample period T_s , and α_{V_g} is the angle of the velocity-to-be-gained vector.

The derivation of guidance loop relationships, given below, considers the guidance problem in a single plane. Thus, in the coordinate system of a plane shown in Figure 4.3.3-7, the x axis is defined as the desired thrust direction, and components of velocity in the y-axis direction are the cross-axis or undesirable velocity errors.

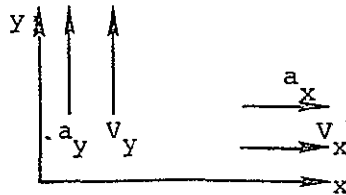


Figure 4.3.3-7. Plane coordinate system.

During a burn, guidance takes snapshots of velocities, as measured by the accelerometers, at sampling intervals T_s . A typical velocity vector diagram is shown in Figure 4.3.3-8. From Figure 4.3.3-8 the angle $\alpha_{\Delta V}$ of the ΔV vector is given by

$$\alpha_{\Delta V} = \tan^{-1} \frac{\Delta V_y}{\Delta V_x} = \tan^{-1} \left[\frac{V_{y_n} - V_{y_{(n-1)}}}{V_{x_n} - V_{x_{(n-1)}}} \right] \quad (4.3.3-2)$$

and the angle α_{V_g} of velocity vector V_g is given by

$$\alpha_{V_g} = \tan^{-1} \frac{V_{g_y}}{V_{g_x}} = \tan^{-1} \left[\frac{-V_{y_n}}{V_r - V_{x_n}} \right] \quad (4.3.3-3)$$

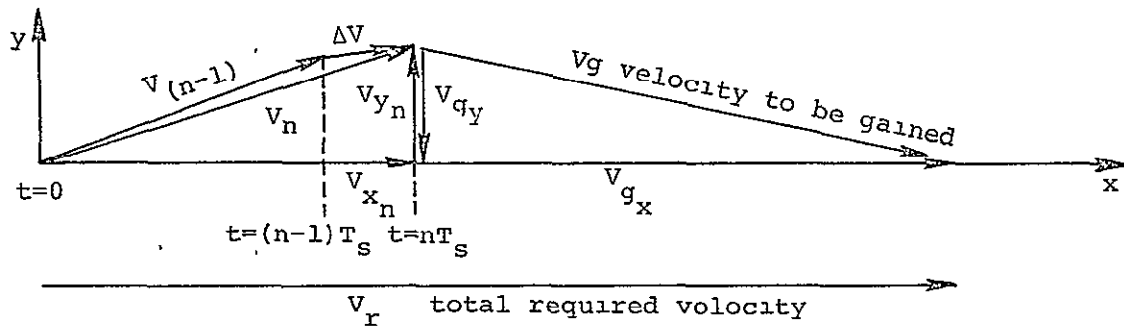


Figure 4.3.3-8. Velocity vector diagram.

In Eqs. (4.3.3-2) and (4.3.3-3) the subscript n represents the present sample period and $(n-1)$ the previous sample period of the guidance loop. Note that in Figure 4.3.3-8 and in Eq. (4.3.3-3) the velocity-to-be-gained vector in the y direction (the undesirable velocity component) is exactly equal and opposite to the present cross-axis velocity.

Now, it will be shown that these velocity components, measured by guidance, are related to dynamic quantities of the vehicle attitude θ and the engine angle δ . Figure 4.3.3-9 shows the vehicle in the x - y plane.

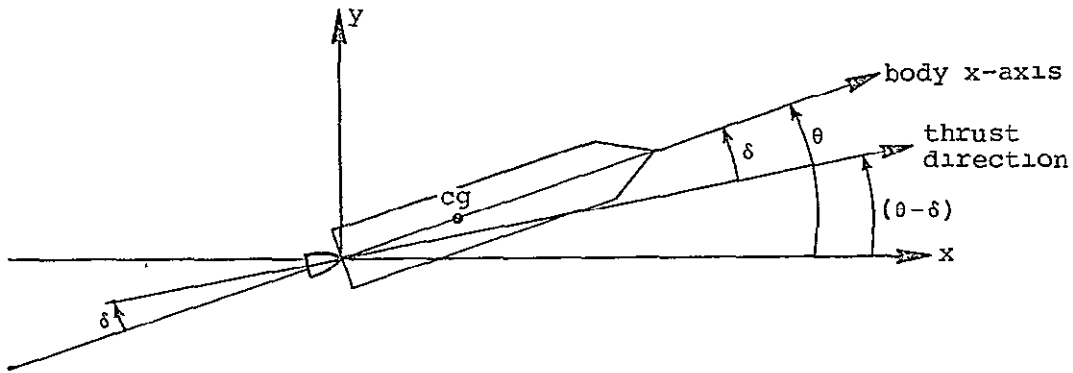


Figure 4.3.3-9. Vehicle in x-y plane.

In Figure 4.3.3-9, the resultant of the two OMS engine angles is shown by the engine angle δ . It is measured from the body x axis and is defined positive when it generates a positive moment and a positive angular acceleration $\ddot{\theta}$. Then, the thrust direction angle is the difference between the attitude angle θ and the engine angle δ . With linear acceleration of the vehicle equal to thrust T divided by mass M , the velocity components in the x and y directions at time = t, expressed in terms of θ and δ , are given by

$$v_x = \frac{T}{M} \int_0^t \cos(\theta - \delta) dt \quad (4.3.3-4)$$

$$v_y = \frac{T}{M} \int_0^t \sin(\theta - \delta) dt \quad (4.3.3-5)$$

(The burn starts at $t = 0$.)

For small values of $(\theta - \delta)$

$$\cos(\theta - \delta) \cong 1$$

$$\sin(\theta - \delta) \cong \theta - \delta$$

and at $t = nT_s$ Eqs. 4.3.3-4 and 4.3.3-5 become

$$v_{x_n} \cong \frac{T}{M} nT_s \quad (4.3.3-6)$$

$$v_{Y_n} \cong \frac{T}{M} \int_0^{nT_s} (\theta - \delta) dt \quad (4.3.3-7)$$

Similar expressions are obtained at $t = (n-1)T_s$. By substituting Eqs. (4.3.3-6) and (4.3.3-7) into Eqs. (4.3.3-2) and (4.3.3-3), the angles $\alpha_{\Delta V}$ and α_{V_g} are expressed in terms of $(\theta - \delta)$:

$$\begin{aligned} \alpha_{\Delta V} &= \tan^{-1} \left[\frac{\frac{T}{M} \int_0^{nT_s} (\theta - \delta) dt - \frac{T}{M} \int_0^{(n-1)T_s} (\theta - \delta) dt}{\frac{T}{M} [nT_s - (n-1)T_s]} \right] \\ &= \tan^{-1} \left[\frac{\int_0^{nT_s} (\theta - \delta) dt - \int_0^{(n-1)T_s} (\theta - \delta) dt}{T_s} \right] \quad (4.3.3-8) \end{aligned}$$

$$\begin{aligned} \alpha_{V_g} &= \tan^{-1} \left[\frac{\frac{T}{M} \int_0^{nT_s} (\theta - \delta) dt}{\frac{T}{M} (t_{\max} - nT_s)} \right] \\ &= \tan^{-1} \left[\frac{\int_0^{nT_s} (\theta - \delta) dt}{t_{\max} - nT_s} \right] \quad (4.3.3-9) \end{aligned}$$

The denominator of Eq. (4.3.3-9) is the difference between the burn time required to achieve the desired velocity and the elapsed burn time, or time-to-go (t_{go}). Using small angle approximation the arctangent functions are eliminated and Eqs. (4.3.3-8) and (4.3.3-9) become

$$\alpha_{\Delta V} = \frac{1}{T_s} \left[\int_0^{nT_s} (\theta - \delta) dt - \int_0^{(n-1)T_s} (\theta - \delta) dt \right] \quad (4.3.3-10)$$

$$\alpha_{V_g} = -\frac{1}{t_{go}} \int_0^{nT_s} (\theta - \delta) dt \quad (4.3.3-11)$$

Substituting Eqs. (4.3.3-10) and (4.3.3-11) into Eq. (4.3.3-1) and again invoking small angle approximation, the result of guidance computation, ω , is obtained:

$$\omega \cong \frac{1}{T_s} \left[\int_0^{nT_s} (\theta - \delta) dt - \int_0^{(n-1)T_s} (\theta - \delta) dt \right] - \left[-\frac{1}{t_{go}} \int_0^{nT_s} (\theta - \delta) dt \right] \quad (4.3.3-12)$$

A block diagram of Eq. (4.3.3-12) is given in Figure 4.3.3-10.

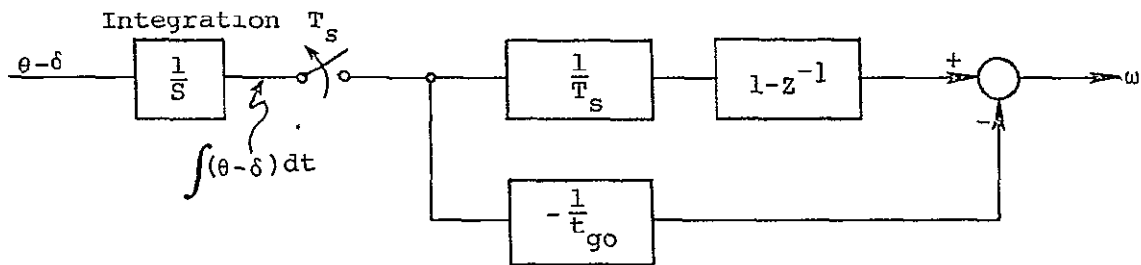
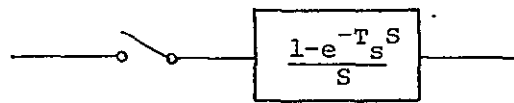
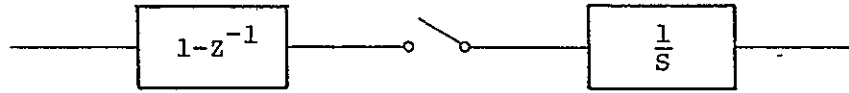


Figure 4.3.3-10. Block diagram of guidance command computation.

where z^{-1} indicates a one sample period delay. The guidance command ω is valid for the entire guidance sample period T_s which, in block diagram notation, is represented by a zero-order-hold function as follows:



which is equivalent to:



Since the inner (autopilot) loop is an attitude loop the guidance rate command, scaled by gain factor K_{steer} , must first be integrated ($1/s$) and the resultant attitude increments applied to the autopilot. A complete diagram of the guidance-autopilot loop is shown in Figure 4.3.3-11, where the high sample rate (25 sps) inner loop is approximated by continuous transfer functions. This is a valid approximation for the low frequency range of the steering loop with its crossover frequency occurring at about $\omega = K_{\text{steer}}$ and K_{steer} typically ranging from 0.1 to 0.5. Analysis of this loop is done in the w -plane. Let $F(w)$ be the open loop transfer function. Then

$$F(w) = F_1(w) F_2(w) \quad (4.3.3-13)$$

$F_1(w)$ is a w -transform of the continuous transfer function $F(s)$ given by

$$F(s) = \frac{K_{\text{steer}}}{s^2} \frac{[\theta(s) - \delta(s)]}{\theta_c(s)} = \frac{K_{\text{steer}}}{s^2} \frac{\theta(s)}{\theta_c(s)} \left[1 - \frac{\delta(s)}{\theta(s)} \right] \quad (4.3.3-14)$$

In Eq. 4.3.3-14,

$$\frac{\theta(s)}{\theta_c(s)}$$

is the closed loop transfer function of the inner loop. The term

$$\frac{\delta(s)}{\theta(s)} = \frac{s^2 I_{yy}}{t l_x}$$

relates engine angle and vehicle rigid-body attitude. The w -transform of Eq. (4.3.3-14) is obtained using a computer program. $F_2(w)$ is obtained from bilinear transformation* of $F_2(z)$ of Figure 4.3.3-11 as follows:

$$F_2(w) = F_2(z) \Big|_{z = \frac{1+w}{1-w}} \quad (4.3.3-15)$$

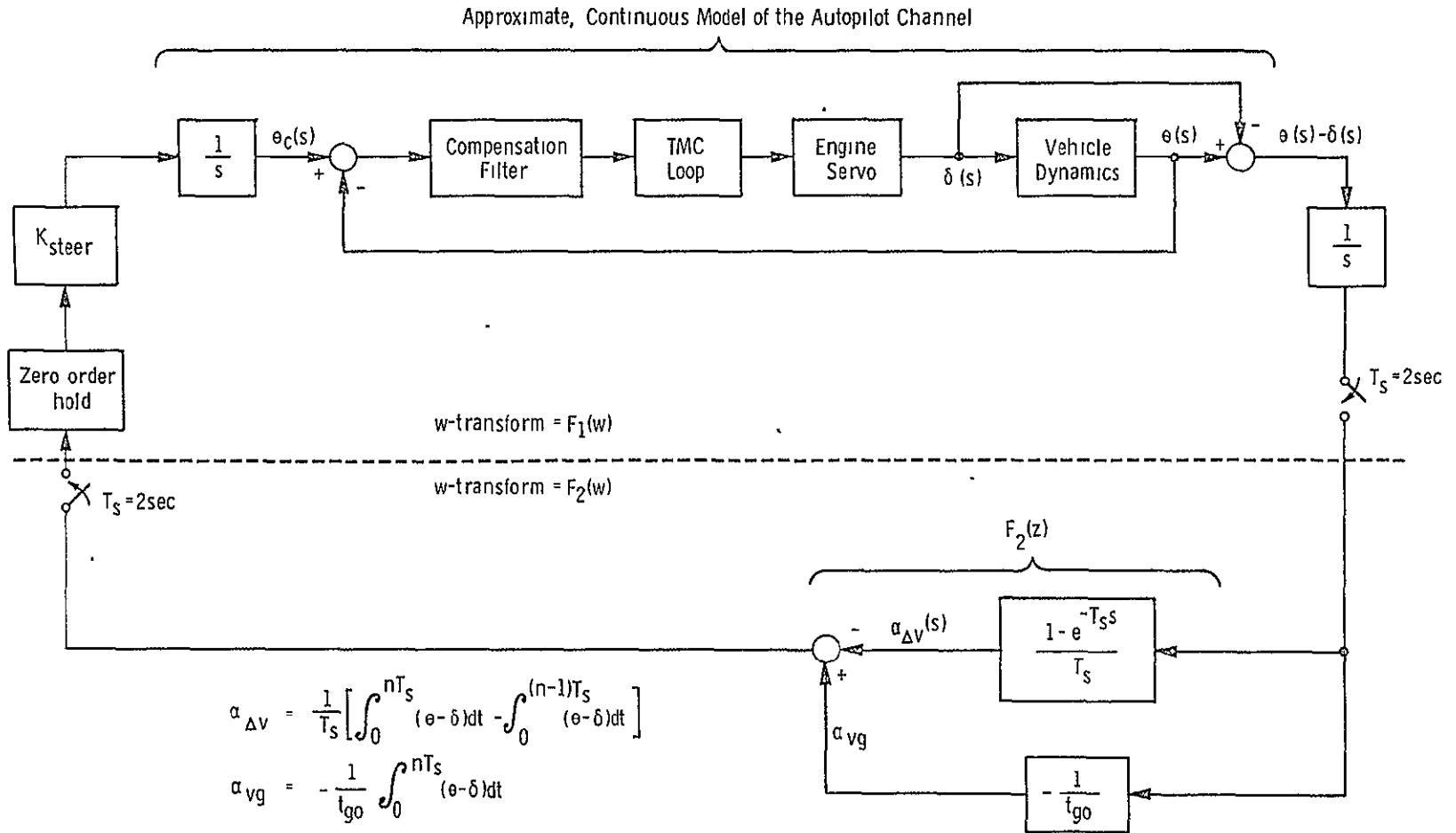


Figure 4.3.3-11. Approximate analytical model of an autopilot channel and its associated steering loop.

$F_2(z)$ is

$$F_2(z) = \left(\frac{z-1}{z}\right) \left(\frac{z-1}{T_s z} + \frac{1}{t_{go}}\right) \quad (4.3.3-16)$$

and $F_2(w)$ becomes

$$F_2(w) = \frac{2w \left[\left(1 + \frac{1}{t_{go}}\right)w + \frac{1}{t_{go}} \right]}{(1+w)^2} \quad (4.3.3-17)$$

Plots of steering loop magnitude versus phase are shown in Figures 4.3.3-12 and 4.3.3-13 for $t_{go} = 20$ seconds and $t_{go} = \infty$. The plots show that the uncompensated steering loop is unstable in both cases. A compensation is required to stabilize the loop. The compensation selected consists of a single order lag-lead function given by

$$S(w) = \frac{1}{3} \frac{(w + 0.51)}{(w + 0.17)} \quad (4.3.3-18)$$

The compensated functions are also shown in Figures 4.3.3-12 and 4.3.3-13. The gain margin is 6 dB, and the phase margin is 31° when $t_{go} = 20$ seconds and 50° when $t_{go} = \infty$.

Bending and Sloshing Stability Analysis

The results of an analysis of bending modes and propellant sloshing stability for the orbiter's TVC mode of operation are presented in this section. The analysis was carried out in terms of frequency response of the autopilot loop. The bending data used in this analysis were obtained from Reference 4.3.3-1. Slosh data, which were unavailable, were estimated based on considerations of propellant tank size and shape, and acceleration level. The vehicle data summary used herein is given in Table 4.3.3-2.

Using this data, transfer functions relating pitch/yaw attitude and engine position were generated by a computer program. The vehicle equations of motion used in this computer program are given in the subsection of this appendix titled "Equations of Motion Including Vehicle Bending Effects and Propellant Sloshing".

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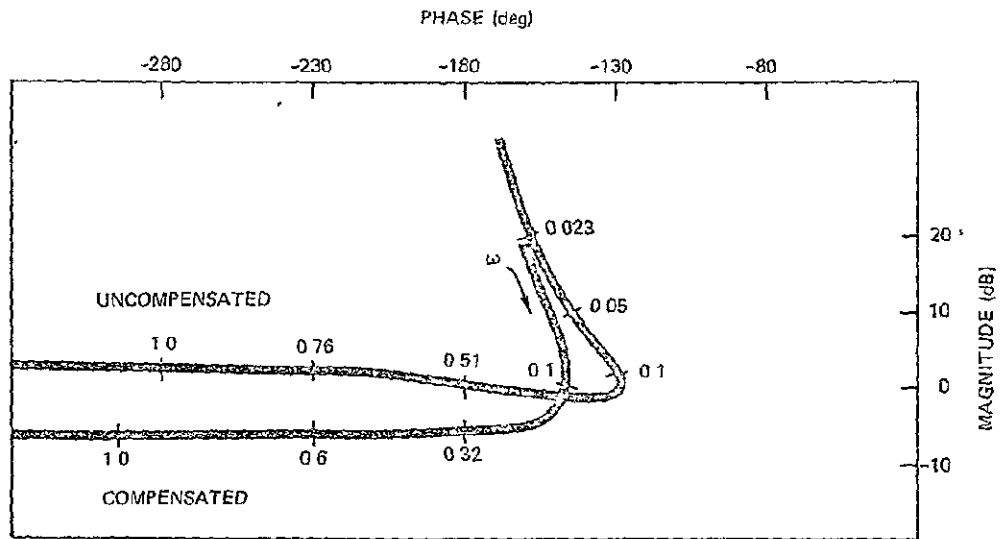


Figure 4.3.3-12. Magnitude versus phase plot of the steering loop for $t_{go} = 20$ seconds.

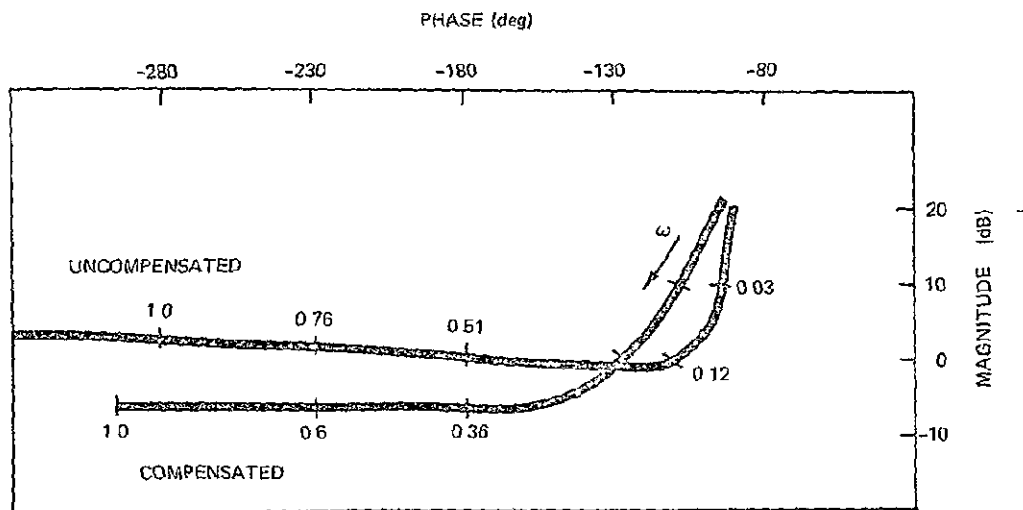


Figure 4.3.3-13. Magnitude versus phase plot of the steering loop for $t_{go} = \infty$.

Table 4.3.3-2. Vehicle data summary.*

Symbol	Description	Value	RI Symbol
M	Vehicle mass (insertion)	5400 slugs	
I_{YY}	Vehicle moment of inertia about y axis	6.116×10^6 slug-ft ²	
I_{ZZ}	Vehicle moment of inertia about z axis	6.359×10^6 slug-ft ²	
T	Thrust (two engines)	12000 lbs	
I_e	Engine moment of inertia	80 slug-ft ²	
l_x	Distance from vehicle cg to engine hinge point	32.9 ft	
l_e	Distance from engine cg to engine hinge point	0.892 ft	
m_e	Engine mass (two engines)	16.97 slugs	
ω_1	First bending mode frequency (symmetric-pitch)	29.538 rad/s	
ω_2	Second bending mode frequency (symmetric-pitch)	39.84 rad/s	
ω_1	First bending mode frequency (antisymmetric-yaw)	25.3 rad/s	
ω_2	Second bending mode frequency (antisymmetric-yaw)	40.26 rad/s	
ζ	Bending mode damping ratio (pitch and yaw)	0.005	
$m_{1,2}$	Generalized bending mass	5650 slugs	
	Bending deflections at engine hinge point (pitch plane):		
$\phi_1(x_T)$	First mode	0.7334 in./in.	F_z
$\phi_2(x_T)$	Second mode	0.29209 in./in.	F_z
	Bending deflections at engine hinge point (yaw plane):		
$\phi_1(x_T)$	First mode	-0.42156 in./in.	F_y
$\phi_2(x_T)$	Second mode	0.68 in./in.	F_y

* Taken from Ref. 4.3.3-1.

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Table 4.3.3-2. Vehicle data summary (Cont.).

Symbol	Description	Value	RI Symbol
	Bending slopes at engine hinge point (pitch plane):		
$\sigma_1(x_T)$	First mode	-0.0676 rad/ft	M_Y
$\sigma_2(x_T)$	Second mode	-0.01812 rad/ft	M_Y
	Bending slopes at engine hinge point (yaw plane):		
$\sigma_1(x_T)$	First mode	0.00628 rad/ft	M_Z
$\sigma_2(x_T)$	Second mode	0.0502 rad/ft	M_Z
	Bending slopes at IMU station (pitch plane):		
$\sigma_1(x_A)$	First mode	-0.1058 rad/ft	M_Y
$\sigma_2(x_A)$	Second mode	-0.0436 rad/ft	M_Y
	Bending slopes at IMU station (yaw plane):		
$\sigma_1(x_A)$	First mode	0.00742 rad/ft	M_Z
$\sigma_2(x_A)$	Second mode	0.0162 rad/ft	M_Z
l_s	Slosh mass moment arm**	16.67 ft	
m_s	Slosh mass (4 tanks reinforcing)	60 slugs	
ω_s	Slosh mode frequency	1.555 rad/s	
ζ_s	Slosh mode damping ratio	0.0004	
	Bending deflections at slosh mass position (pitch plane):		
$\phi_1(x_S)$	First mode	-0.2635 in./in.	
$\phi_2(x_S)$	Second mode	0.067 in./in.	
	Bending deflections at slosh mass position (yaw plane):		
$\phi_1(x_S)$	First mode	-5.3549×10^{-2} in./in.	
$\phi_2(x_S)$	Second mode	-7.2214×10^{-2} in./in.	

** Slosh data are based on estimates.

The resultant transfer functions are presented here as products of numerator and denominator s-plane factors as follows:

$$\frac{\theta_B}{\delta}(s) = \frac{K_{V_{p/y}} \prod_{i=1}^8 (s + a_i)}{\prod_{j=1}^8 (s + b_j)}$$

The pitch-plane factors are listed in Table 4.3.3-3 and yaw-plane factors in Table 4.3.3-4. Addition of the gimbal servo loop transfer function to the above specifies the major analog elements of the autopilot loop. The servo transfer function in the linear range of operation is:

$$\frac{\delta}{\delta_c} = \frac{625}{s^2 + 25s + 625}$$

Going from continuous to sampled transfer functions, w-plane factors were obtained for the vehicle-engine servo combination. These are listed in Table 4.3.3-5 for the pitch plane and in Table 4.3.3-6 for the yaw plane, together with the digital compensation filter factors. The corresponding frequency plots were produced and are shown in magnitude versus phase plots in Figures 4.3.3-14 and 4.3.3-15.

In both the pitch and yaw planes the slosh resonance occurs at 1.55 rad/s. This resonance is phase-lead compensated as it loops away from the -180° , 0 dB point. Of the four bending modes considered (two in pitch and two in yaw), only one displays a strong resonance peak, and that is the first bending mode in the pitch plane shown in Figure 4.3.3-14. It occurs at 29.5 rad/s and its peak is at -25 dB. The reason for its high rise is that the complex zero pair associated with this bending mode is far away in frequency from the poles and occurs at 16.3 rad/s. In the case of other bending modes the complex zero pairs are closer to the poles and consequently the resonances are not as strongly pronounced. Summarizing this set of bending data, the gain margins for the bending modes are 25 dB for the first pitch bending mode and higher for others.

Table 4.3.3-3. Pitch transfer function factors.

Denominator Roots		
Real Roots		
0.000000000 × 10 ⁰		
0.000000000 × 10 ⁰		
Complex Root Pairs		
Real Part:	Imaginary Part:	
-6.220148347 × 10 ⁻⁴	1.565524513 × 10 ⁰	Slosh
-1.991470818 × 10 ⁻¹	3.983380202 × 10 ¹	2nd bending mode
-1.474077255 × 10 ⁻¹	2.950912238 × 10 ¹	1st bending mode
Numerator Roots		
Complex Root Pairs		
Real Part:	Imaginary Part:	
-6.219909787 × 10 ⁻⁴	1.559404128 × 10 ⁰	Slosh
-1.924299000 × 10 ⁻¹	3.884157674 × 10 ¹	2nd bending mode
2.647588929 × 10 ⁻²	2.219705468 × 10 ¹	Tail-wags-dog
-5.912087315 × 10 ⁻²	1.635702142 × 10 ¹	1st bending mode
Gain factor = $K_{V_P} = 4.44 \times 10^{-4}$		

Table 4.3.3-4. Yaw transfer function factors.

Denominator Roots		
Real Roots		
0.000000000 × 10 ⁰		
0.000000000 × 10 ⁰		
Complex Root Pairs		
Real Part:	Imaginary Part:	
-6.220149447 × 10 ⁻⁴	1.565522074 × 10 ⁰	Slosh
-2.010561992 × 10 ⁻¹	4.023471226 × 10 ¹	2nd bending mode
-1.264335288 × 10 ⁻¹	2.529283870 × 10 ¹	1st bending mode
Numerator Roots		
Complex Root Pairs		
Real Part:	Imaginary Part:	
-6.220155810 × 10 ⁻⁴	1.559490711 × 10 ⁰	Slosh
-2.602794919 × 10 ⁻¹	4.167287372 × 10 ¹	2nd bending mode
2.577081754 × 10 ⁻²	2.756424849 × 10 ¹	Tail-wags-dog
-1.218930441 × 10 ⁻¹	2.433274257 × 10 ¹	1st bending mode
Gain factor = $K_{V_y} = 8.5 \times 10^{-5}$		

Table 4.3.3-5. w-plane factors of the pitch-plane autopilot.

w-Transform Poles Are:		
0.000000000×10^0		Rigid body
0.000000000×10^0		Rigid body
$-1.199999999 \times 10^{-1}$		DAP
$-5.999999999 \times 10^{-2}$	$\pm 1.039999999 \times 10^{-1}$	DAP
$-1.245199999 \times 10^{-5}$	$\pm 3.131999999 \times 10^{-2}$	Slosh
$-8.149999999 \times 10^{-3}$	$\pm 1.021999999 \times 10^0$	2nd bending mode
$-4.269999999 \times 10^{-3}$	$\pm 6.697999999 \times 10^{-1}$	1st bending mode
$-2.935999999 \times 10^{-1}$	$\pm 4.293999999 \times 10^{-1}$	Servo
w-Transform Zeroes Are:		
$-5.999999999 \times 10^{-3}$		DAP
$-5.399999999 \times 10^{-1}$		DAP
$-5.399999999 \times 10^{-1}$		DAP
-6.026899999×10^0		Zero caused by sampling
1.000000000×10^0		Zero caused by sampling
$-8.314699999 \times 10^{-3}$	$\pm 9.826069999 \times 10^{-1}$	2nd bending mode
$-7.539999999 \times 10^{-4}$	$\pm 4.765999999 \times 10^{-1}$	Tail-wags-dog
$-9.812783999 \times 10^{-4}$	$\pm 3.384409999 \times 10^{-1}$	1st bending mode
$-1.245199999 \times 10^{-5}$	$\pm 3.119809999 \times 10^{-2}$	Slosh
$K_p = -9.65 \times 10^{-5}$		

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Table 4.3.3-6. w-plane factors of the yaw-plane autopilot.

w-Transform Poles Are:		
0.000000000×10^0		Rigid body
0.000000000×10^0		Rigid body
$-1.199999999 \times 10^{-1}$		DAP
$-5.999999999 \times 10^{-2}$	$\pm 1.039999999 \times 10^{-1}$	DAP
$-1.245199999 \times 10^{-5}$	$\pm 3.131999999 \times 10^{-2}$	Slosh
$-8.359999999 \times 10^{-3}$	$\pm 1.038999999 \times 10^0$	2nd bending mode
$-3.299999999 \times 10^{-3}$	$\pm 5.538999999 \times 10^{-1}$	1st bending mode
$-2.935699999 \times 10^{-1}$	$\pm 4.292999999 \times 10^{-1}$	Servo
w-Transform Zeroes Are:		
$-5.999999999 \times 10^{-3}$		DAP
$-5.399999999 \times 10^{-1}$		DAP
$-5.399999999 \times 10^{-1}$		DAP
-5.339999999×10^0		Zero caused by sampling
1.000000000×10^0		Zero caused by sampling
$-8.254299999 \times 10^{-3}$	$\pm 1.102879999 \times 10^0$	2nd bending mode
$2.185199999 \times 10^{-3}$	$\pm 6.144299999 \times 10^{-1}$	Tail-wags-dog
$-2.808999999 \times 10^{-3}$	$\pm 5.288999999 \times 10^{-1}$	1st bending mode
$-1.245189999 \times 10^{-5}$	$\pm 3.119989999 \times 10^{-2}$	Slosh
$K_y = -1.51 \times 10^{-5}$		

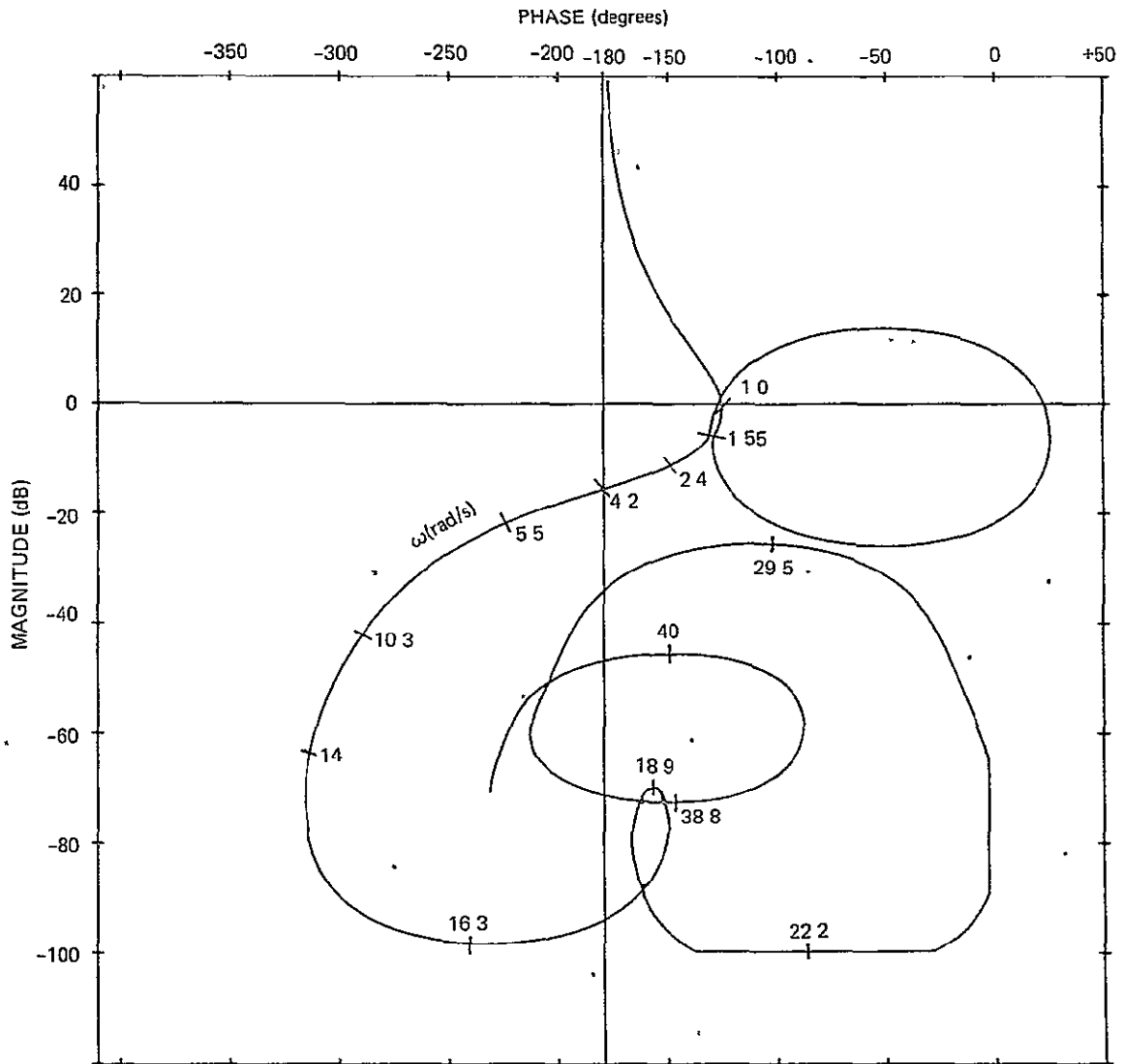


Figure 4.3.3-14. Magnitude versus phase plot of the pitch-plane transfer function with compensation.

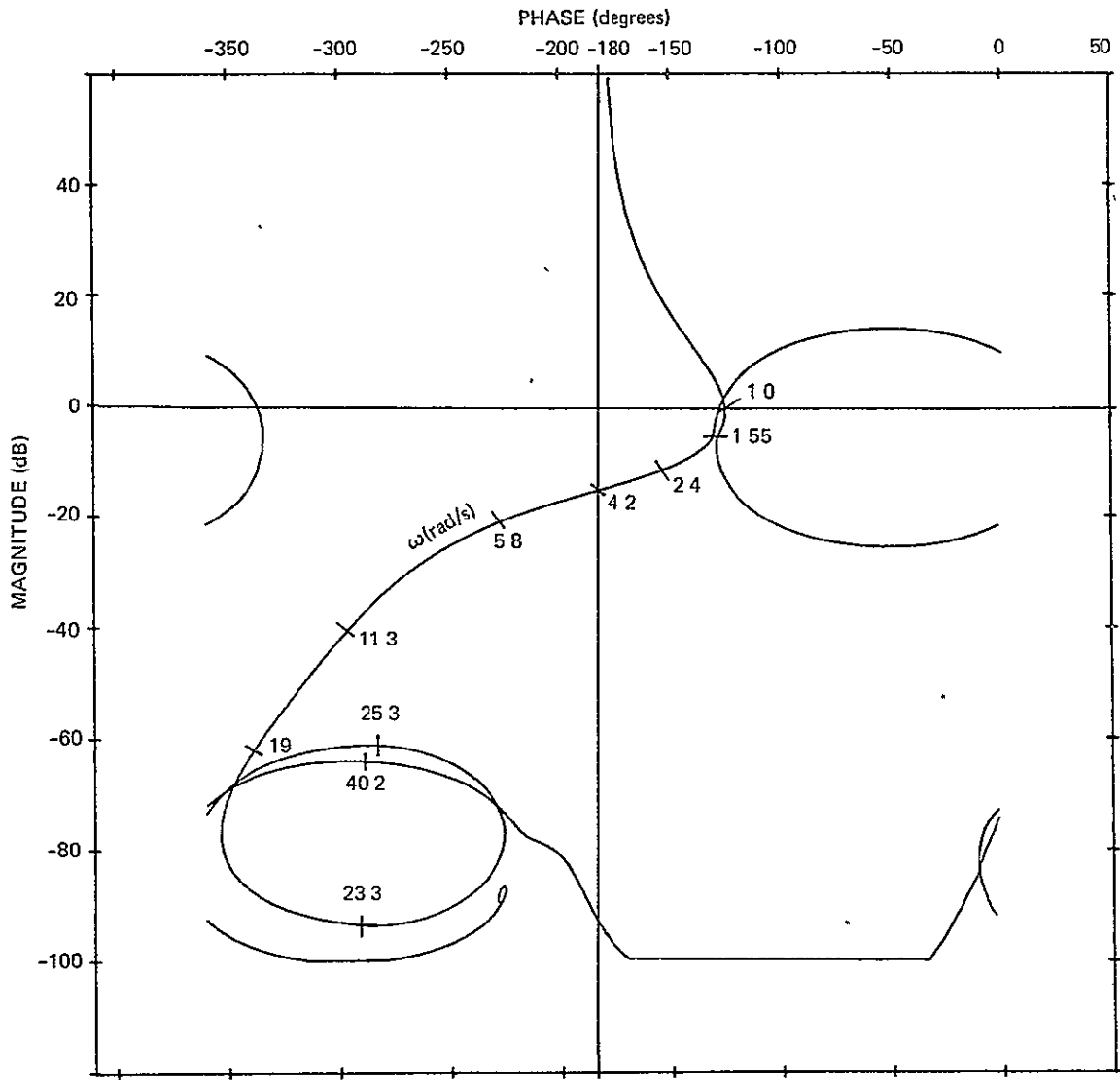


Figure 4.3.3-15. Magnitude versus phase plot of the yaw-plane transfer function with compensation.

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Equations of Motion Including Vehicle Bending Effects and Propellant Sloshing

Definition of Symbols:

- δ - engine deflection
- θ_R - rigid-body attitude
- θ_B - attitude including slosh and bending
- q_1 - generalized displacement of 1st bending mode
- q_2 - generalized displacement of 2nd bending mode
- $\sigma_1(x_A)$ - 1st bending mode slope at IMU
- $\sigma_2(x_A)$ - 2nd bending mode slope at IMU
- M - vehicle mass
- m_e - engine mass
- l_x - distance from vehicle cg to engine hinge point
- l_e - distance from engine cg to engine hinge point
- T - thrust
- I_{YY} - vehicle moment of inertia about y axis (for pitch)
- I_e - engine moment of inertia about its center of mass
- $I_R = I_e + m_e l_e^2$
- y_{cm} - lateral displacement of vehicle
- $\sigma_1(x_T)$ - 1st bending mode slope at engine hinge point
- $\sigma_2(x_T)$ - 2nd bending mode slope at engine hinge point
- $\phi_1(x_T)$ - 1st bending mode deflection at engine hinge point
- $\phi_2(x_T)$ - 2nd bending mode deflection at engine hinge point

l_s - slosh mass moment arm
 $K_s = \omega_s^2 m_s$
 m_s - slosh mass
 ω_s - slosh mode frequency
 m_1 - generalized bending mass for 1st mode
 m_2 - generalized bending mass for 2nd mode
 ω_1 - 1st bending mode frequency
 ω_2 - 2nd bending mode frequency
 ζ_1 - 1st bending mode damping ratio
 ζ_2 - 2nd bending mode damping ratio
 ζ_s - slosh mode damping ratio
 $\phi_1(x_s)$ - 1st bending mode deflection at slosh mass position
 $\phi_2(x_s)$ - 2nd bending mode deflection at slosh mass position
 $K(?) = 0$: bending data include engine mass and inertial effects
 $K(?) = 1$: bending data do not include effects of engine mass and inertia

Rotation Equation:

$$\begin{aligned}
 0 = & -[m_e \ell_x + m_e \ell_e] K(?) y_{cm} + \{I_{YY} + [I_e + m_e (\ell_e + \ell_x)^2] K(?)\} \ddot{\theta}_R \\
 & + [m_e \ell_e \ell_x \sigma_1(x_T) - m_e \ell_x \phi_1(x_T) + I_R \sigma_1(x_T) - m_e \ell_e \phi_1(x_T)] K(?) q_1 \\
 & + T [\ell_x \sigma_1(x_T) + \phi_1(x_T)] q_1 \\
 & + [m_e \ell_e \ell_x \sigma_2(x_T) - m_e \ell_x \phi_2(x_T) + I_R \sigma_2(x_T) - m_e \ell_e \phi_2(x_T)] K(?) q_2 \\
 & + T [\ell_x \sigma_2(x_T) + \phi_2(x_T)] q_2 \\
 & + [\ell_s K_s - m_s \frac{T}{M}] y_s - [m_e \ell_e \ell_x + I_R] \ddot{\delta} - T \ell_x \delta
 \end{aligned}$$

Lateral Acceleration Equation:

$$\begin{aligned}
 0 = & [M + m_e K(?)] \dot{y}_{cm} - [m_e \ell_e + m_e \ell_x] K(?) \theta_R \\
 & + [-m_e \ell_e \sigma_1(x_T) + m_e \phi_1(x_T)] K(?) q_1 + [-T \sigma_1(x_T)] q_1 \\
 & + [-m_e \ell_e \sigma_2(x_T) + m_e \phi_2(x_T)] K(?) q_2 + [-T \sigma_2(x_T)] q_2 \\
 & - K_s y_s + m_e \ell_e \ddot{\delta} + T \delta
 \end{aligned}$$

Bending Equation (for j = 1, 2):

$$\begin{aligned}
 0 = & [-m_e \phi_j(x_T) + m_e \ell_e \sigma_j(x_T)] K(?) y_{cm} \\
 & + [m_e \ell_e \phi_j(x_T) + m_e \ell_x \phi_j(x_T) - I_R \sigma_j(x_T) - m_e \ell_e \ell_x \sigma_j(x_T)] K(?) \dot{\theta}_R \\
 & + [m_e \ell_e \phi_j(x_T) \sigma_1(x_T) - m_e \phi_j(x_T) \phi_1(x_T) - I_R \sigma_j(x_T) \sigma_1(x_T) \\
 & + m_e \ell_e \sigma_j(x_T) \phi_1(x_T)] K(?) \ddot{q}_1 \\
 & + [m_e \ell_e \phi_j(x_T) \phi_2(x_T) - m_e \phi_j(x_T) \phi_2(x_T) - I_R \sigma_j(x_T) \sigma_2(x_T) \\
 & + m_e \ell_e \sigma_j(x_T) \phi_2(x_T)] K(?) \ddot{q}_2 + K_s \phi_j(x_s) y_s \\
 & + [-m_e \ell_e \phi_j(x_T) + I_R \sigma_j(x_T)] \ddot{\delta} - T \phi_j(x_T) \delta \\
 & - m_j q_j - 2m_j \zeta_j \omega_j \dot{q}_j - m_j \omega_j^2 q_j
 \end{aligned}$$

Slosh Equation

$$0 = \ddot{y}_{cm} - l_s \ddot{\theta}_R + \phi_1(x_s) \ddot{q}_1 + \phi_2(x_s) \ddot{q}_2 + \ddot{y}_s + 2\zeta_s \omega_s \dot{y}_s + \omega_s^2 y_s$$

Attitude Equation:

$$\theta_B = \theta_R + \sigma_1(x_A) q_1 + \sigma_2(x_A) q_2$$

Transfer Function of the Vehicle:

$$G(s) = \frac{\theta_B}{\delta}$$

4.3.4.1.2.1.2 Appendix to VECPOINT. - The process used by VECPOINT in determining the terminal desired angles, $[\phi_c]$, is illustrated schematically in Figure 4.3.4.1.2.1-1. VECPOINT uses two frames of reference—the L frame and the M frame—in addition to the stable-member (SM) frame computed from initial gimbal angles, $[\phi]$. The vector \underline{u}_D is resolved from the stable-member frame into this frame as \underline{u}_{DL} using the transformation \hat{C}_{LSM}^{*T} . The L frame is then rotated so that \underline{u}_{AL} and \underline{u}_{DL} are coincident.

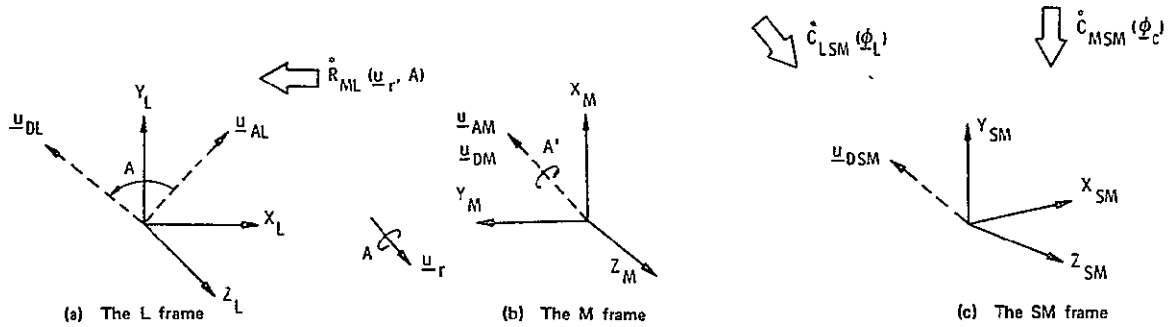


Figure 4.3.4.1.2.1-1. The coordinate frames and transformations used in VECPOINT.

REFERENCES

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- 4.3.2.4-1 Space Shuttle Flight Control System Procurement Specification, Document No. MC621-0043, Rev. A, May 31, 1974.
- 4.3.2.4-2 "FD-2 Configuration Description," Internal Letter SAS/FSA/74-164, Rockwell International Corporation, April 29, 1974.
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