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JSC-12628

REMOTE MANIPULATOR SYSTEM
STEERING CAPABILITY FOR SVDS

Job Order 86-069

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Prepared By

Lockheed Electronics Company, Inc.
Systems and Services Division
Houston, Texas

Contract NAS 9-15200

For

MISSION PLANNING AND ANALYSIS DIVISION

National Aeronautics and Space Administration

LYNDON B. JOHNSON SPACE CENTER

Houston, Texas

May 1977

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TECHNICAL REPORT INDEX/ABSTRACT

(See instructions on reverse side.)

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13. ABSTRACT

This document presents the details of the Remote Manipulator System steering capability to be implemented into the Space Vehicle Dynamics Simulator. The resolve rate law is included as part of the overall steering capability. The steering model includes three automatic modes, four manual-augmented modes, and a single joint rate mode.

14. SUBJECT TERMS

CONTENTS

FIGURE

REMOTE MANIPULATOR SYSTEM STEERING CAPABILITY FOR SVDS

1. INTRODUCTION

The purpose of this document is to present the details of the Remote Manipulator System (RMS) steering capability to be implemented into the Space Vehicle Dynamics Simulator (SVDS). The resolve rate law (ref. 1) is included as part of the overall steering capability. The steering model includes eight modes: three automatic, four manual augmented, and a single joint rate mode.

The automatic modes have an operator-specified final position and orientation of the RMS end effector in the orbiter reference frame. Mode 1, the position mode, determines the RMS joint angle rate commands to be the time average value of the difference between the final RMS angles minus the initial RMS angles such that no joint angle rate exceeds its limit value. Mode 2, closed loop-velocity mode, commands the RMS joint angle rate commands such that the tip of the end effector translates in a straight line and rotates at a constant rate to simultaneously reach the specified final end effector conditions. Mode 2 corrects any steering errors; Mode 3, open-loop velocity mode, uses the initial solution of Mode 2 and does not correct.

The manual augmented modes correspond to the operator-specified hand controller inputs of desired translational and rotational velocities. The four selections of the coordinate frames for the velocity commands are: Mode 4, the orbiter frame; Mode 5, the end effector frame; Mode 6, the payload frame; and Mode 7, a mixed frame with rotational velocity in the payload frame and translational velocity in the orbiter frame. Mode 8, the single joint rate mode, enables one RMS joint to be moved while the remaining joints are held at their initial values.

The steering model is formulated from references 2 and 3 with acceleration/deceleration taken into account for all modes.

Section 2 presents a brief overview of the RMS steering model capability as it is proposed for SVDS interface. Section 3 contains detailed engineering flow diagrams of the RMS steering model.

2. SVDS-RMS STEERING INTERFACE

The RMS steering capability to be implemented into the SVDS program (fig. 1) will provide the commanded RMS joint angle rates for all modes. The kinematic capability given in reference 1 is included within the RMS steering model. The RMS steering capability will be interfaced with other modules such as RMS rigid body and flexible body dynamics and RMS servo modules.

The RMS steering capability is interfaced at four places: (1) Arm initialization for a case; (2) Phase initialization of simulated operator inputs; (3) RMS steering via commanded joint angle rates to the integration driver; and (4) Termination phase time (ETA) which is computed in the automatic steering modes and input for the other modes.

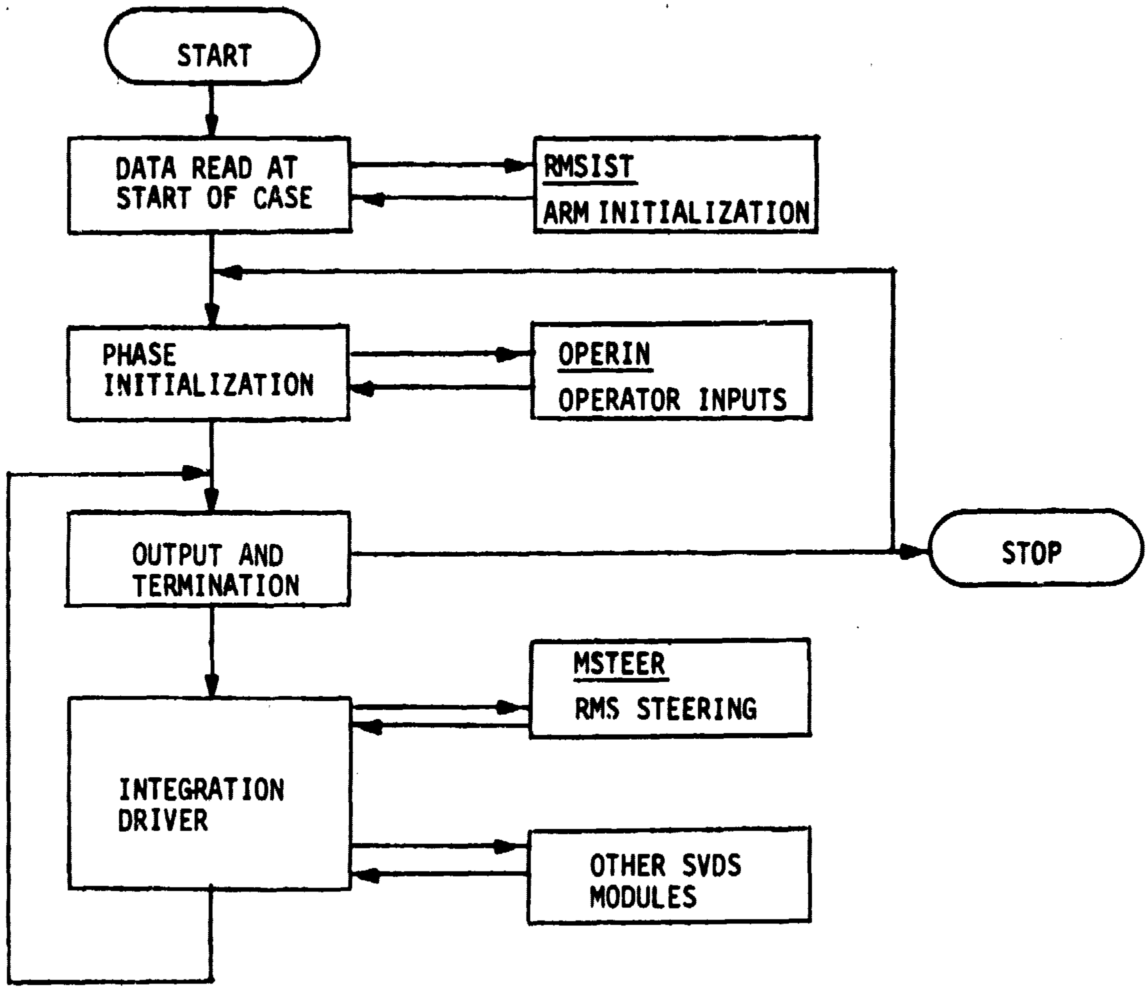


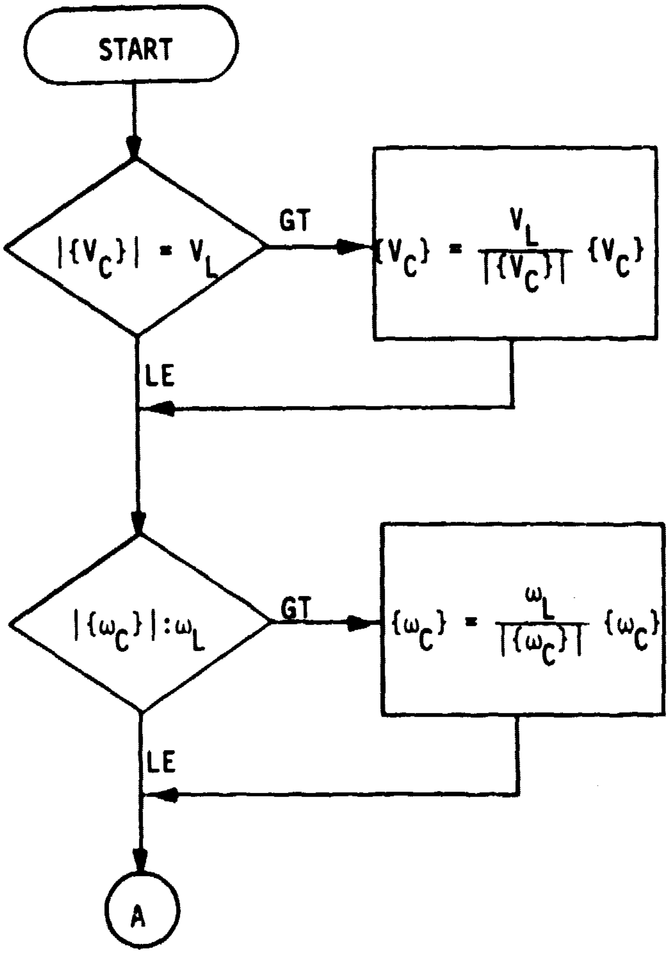
Figure 1.- Overview of proposed SVDS with RMS steering capability.

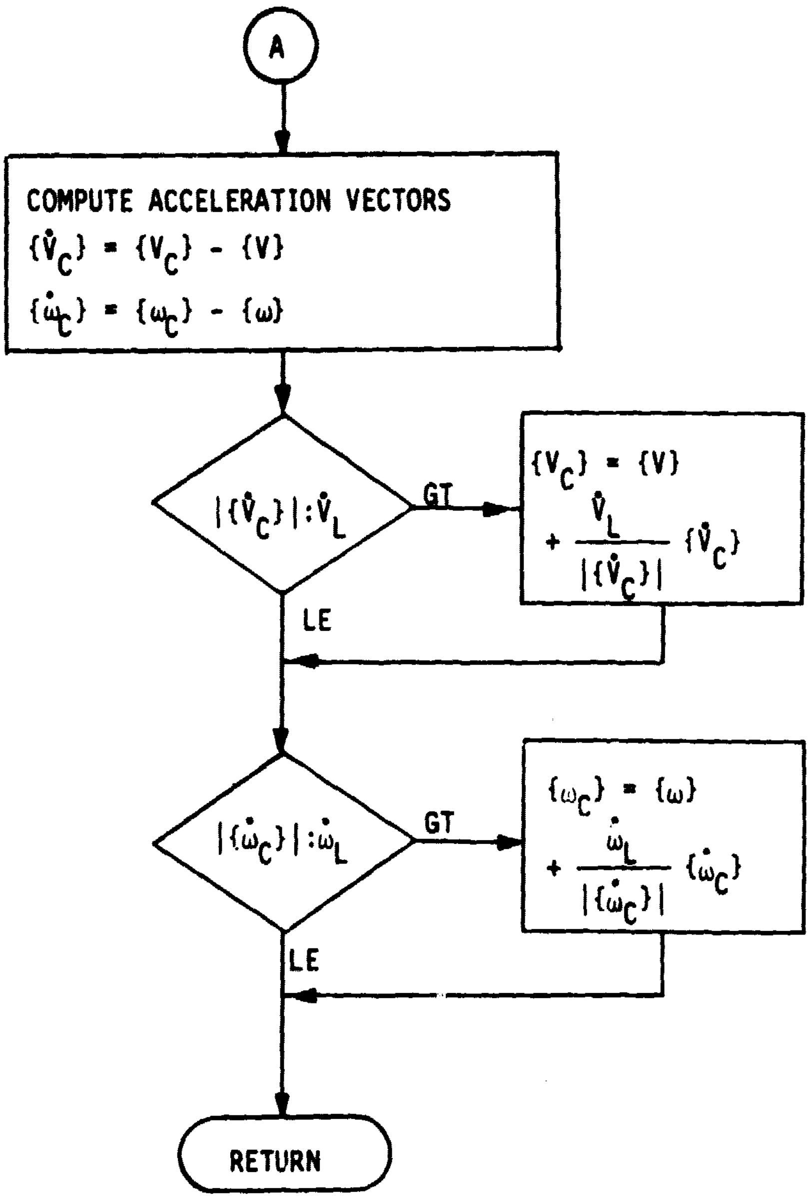
3. ENGINEERING FLOWCHARTS

This section contains flowcharts of the subroutines to be introduced into SVDS to provide RMS steering capability. These flowcharts use engineering symbols and form the base for the routines to be coded or rearranged in SVDS. The purpose of this section is to provide logic flow in a terminology more familiar to an engineer than FORTRAN code. Definition of symbols used are included at the end of this section.

SUBROUTINE AVCLMT

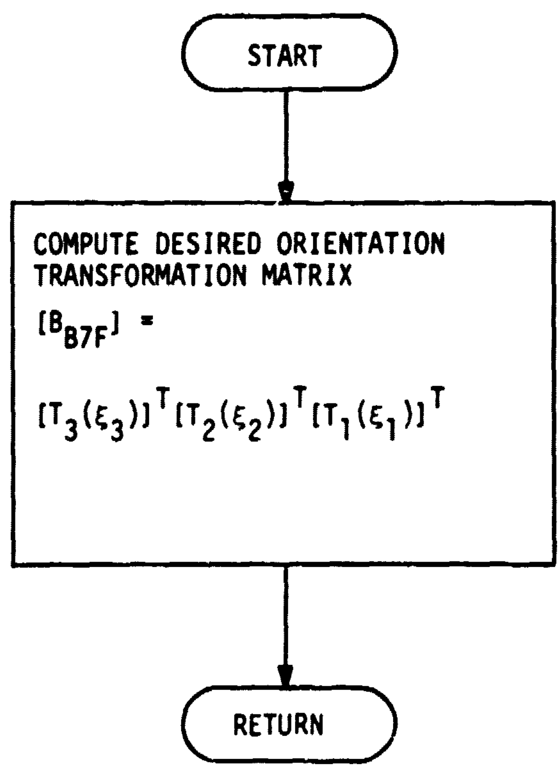
Subroutine AVCLMT checks the commanded translational and rotational velocities of the end effector against the acceleration and velocity limits. If a velocity exceeds its velocity or acceleration limit, this subroutine sets it equal to the limit.




A
COMPUTE ACCELERATION VECTORS
$\{\dot{V}_C\} = \{V_C\} - \{V\}$
$\{\dot{\omega}_C\} = \{\omega_C\} - \{\omega\}$
$|\{\dot{V}_C\}| : \dot{V}_L$
GT
$\{V_C\} = \{V\} + \frac{\dot{V}_L}{|\{\dot{V}_C\}|} \{\dot{V}_C\}$
LE
$|\{\dot{\omega}_C\}| : \dot{\omega}_L$
GT
$\{\omega_C\} = \{\omega\} + \frac{\dot{\omega}_L}{|\{\dot{\omega}_C\}|} \{\dot{\omega}_C\}$
LE
RETURN

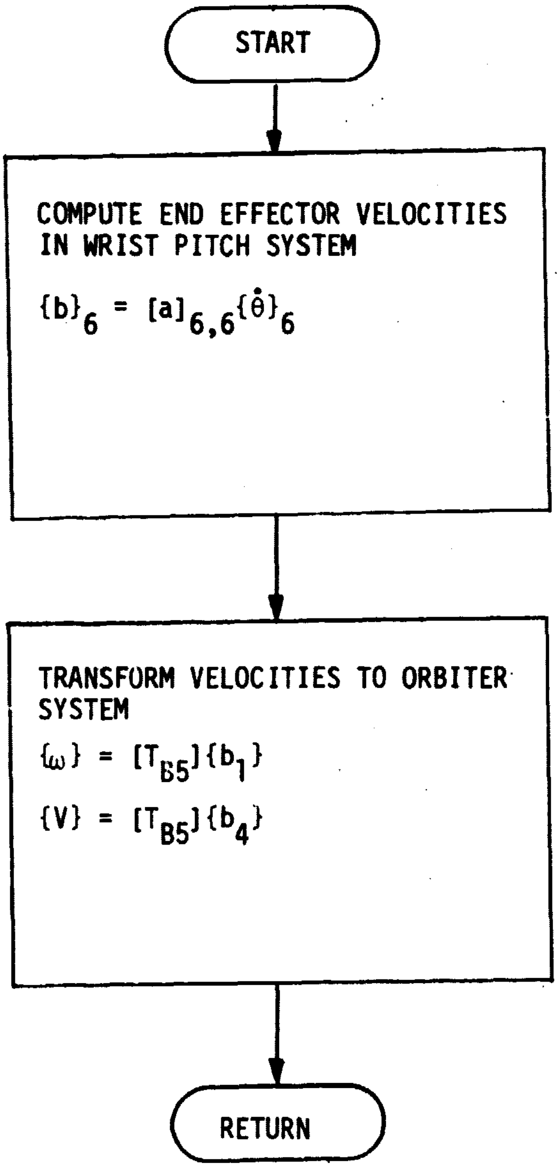
SUBROUTINE ENDORI

Subroutine ENDORI computes the desired orientation of the end effector in the orbiter system from a set of Euler angles specified. The order of rotation is azimuth/yaw, elevation/pitch, and roll.



SUBROUTINE ERATES

Subroutine ERATES computes the rotational and translational velocity of the end effector based on the joint angle rates using the resolved rate law.



SUBROUTINE JACOBI

Subroutine JACOBI computes the Jacobian matrix from the current joint angles.

START

CALCULATE ELEMENTS OF JACOBIAN MATRIX

$\theta_{234} = \theta_2 + \theta_3 + \theta_4$

$a_{11} = -\sin \theta_{234}$

$a_{16} = \cos \theta_5$

[illegible]$_{6} = \cos \theta_5$

$a_{31} = \cos \theta_{234}$

$a_{41} = -L_5 \cos \theta_{234} \sin \theta_5$

$a_{51} = L_2 \cos \theta_2 + L_2 \cos (\theta_2 + \theta_3) + (L_4 + L_5 \cos \theta_5) \cos \theta_{234}$

$a_{61} = -L_5 \sin \theta_{234} \sin \theta_5$

$a_{42} = L_2 \sin (\theta_3 + \theta_4) + L_3 \sin \theta_4$

$a_{62} = -L_2 \cos (\theta_3 + \theta_4) - L_3 \cos \theta_4 - L_5 \cos \theta_5 - L_4$

$a_{43} = L_3 \sin \theta_4$

$a_{63} = -L_4 - L_5 \cos \theta_5 - L_3 \cos \theta_4$

$a_{64} = -(L_4 + L_5 \cos \theta_5)$

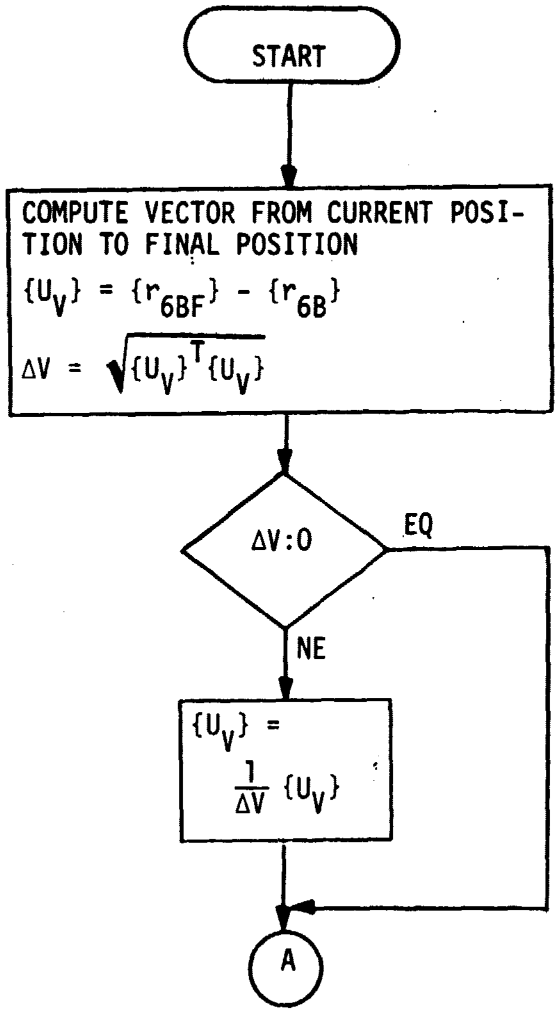
$a_{45} = -L_5 \sin \theta_5$

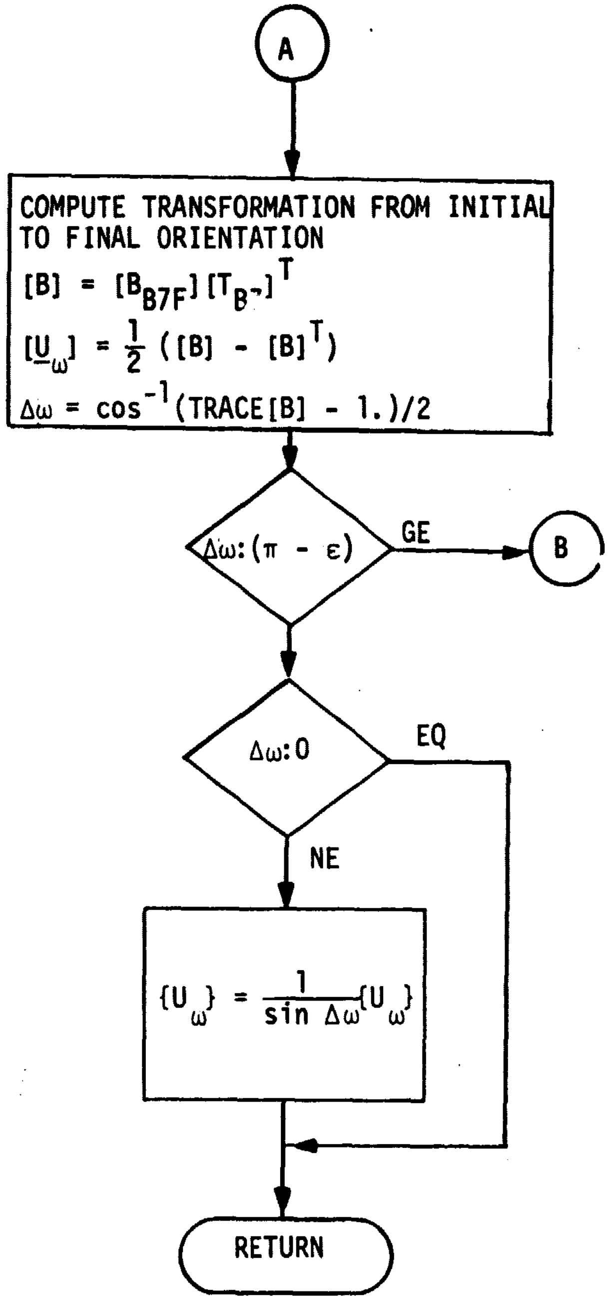
$a_{55} = L_5 \cos \theta_5$

RETURN

SUBROUTINE LATRAJ

Subroutine LATRAJ computes the line-of-sight and angle-of-sight unit vectors and magnitudes for steering in the automatic modes.




A
COMPUTE TRANSFORMATION FROM INITIAL TO FINAL ORIENTATION
$[B] = [B_{B7F}][T_{B^-}]^T$
$[\underline{U}_\omega] = \frac{1}{2}([B] - [B]^T)$
$\Delta\omega = \cos^{-1}(\text{TRACE}[B] - 1.)/2$
$\Delta\omega:(\pi - \varepsilon)$
GE
B
$\Delta\omega:0$
EQ
NE
$\{U_\omega\} = \frac{1}{\sin \Delta\omega}\{U_\omega\}$
RETURN

(B)

180° ROTATION REQUIRED
COMPUTE ROTATION AXIS

$[T] = [B] - \lceil I \rfloor$

$U_{\omega_i} = \frac{1}{2}\sqrt{2T_{u} - TRACE[T]} \quad i=1,2,3$

DETERMINE LARGEST COMPONENT OF $\{U_\omega\}$

LET U_{ω_K} BE THE LARGEST COMPONENT,
THEN

$U_{\omega_i} = \frac{T_{K_i}}{2U_{\omega_K}} \qquad i \neq K$

RETURN

SUBROUTINE LNKAGE

Subroutine LNKAGE computes the end effector position and orientation relative to the orbiter. The transpose of the orbiter to wrist pitch orientation is saved for use by subroutine JACOBI. If a payload is attached (PA = 1), the payload center and orientation are computed.

START

COMPUTE END EFFECTOR POSITION AND ORIENTATION

$$\{r_{NB}\} = \{r_{1B}\} - [T_{LB}]^T\{1_3\}L_1$$

$$[T_{BN}] = [T_{LB}]^T[T_3(\theta_1)]^T[T_2(\theta_2)]^T$$

$$\{r_{NB}\} = \{r_{NB}\} + [T_{BN}]\{1_1\}L_2$$

$$[T_{BN}] = [T_{BN}][T_2(\theta_3)]^T$$

$$\{r_{NB}\} = \{r_{NB}\} + [T_{BN}]\{1_1\}L_3$$

$$[T_{B5}] = [T_{BN}][T_2(\theta_4)]^T$$

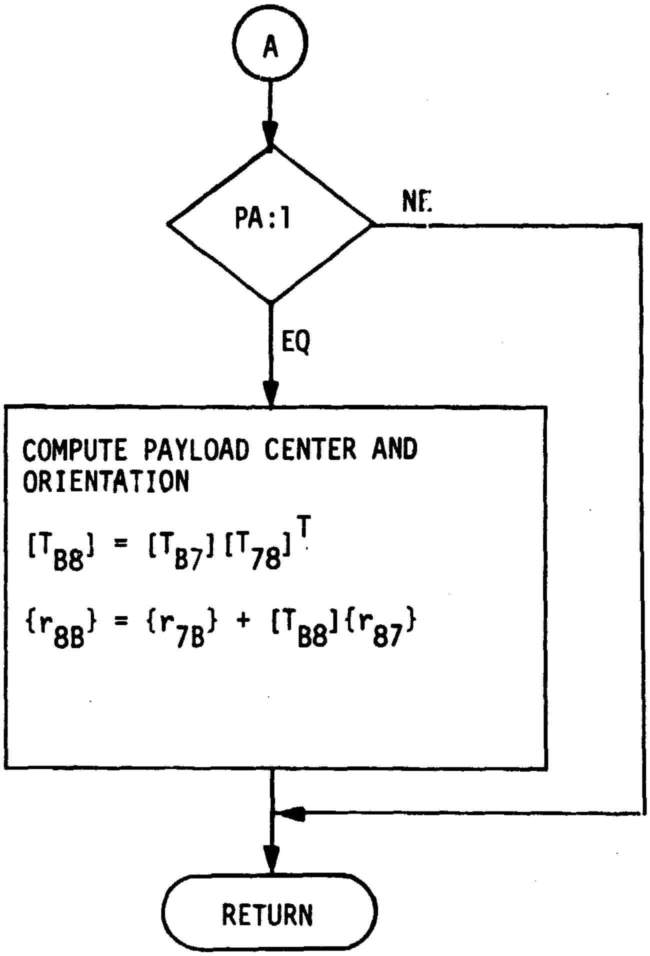
$$\{r_{NB}\} = \{r_{NB}\} + [T_{B5}]\{1_1\}L_4$$

$$[T_{BN}] = [T_{B5}][T_3(\theta_5)]^T$$

$$[r_{68}] = \{r_{NB}\} + [T_{BN}]\{1_1\}L_5$$

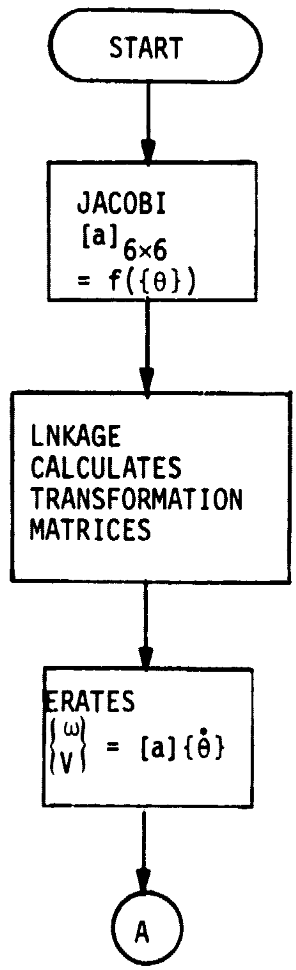
$$[T_{B7}] = [T_{BN}][T_1(\theta_6)]^T$$

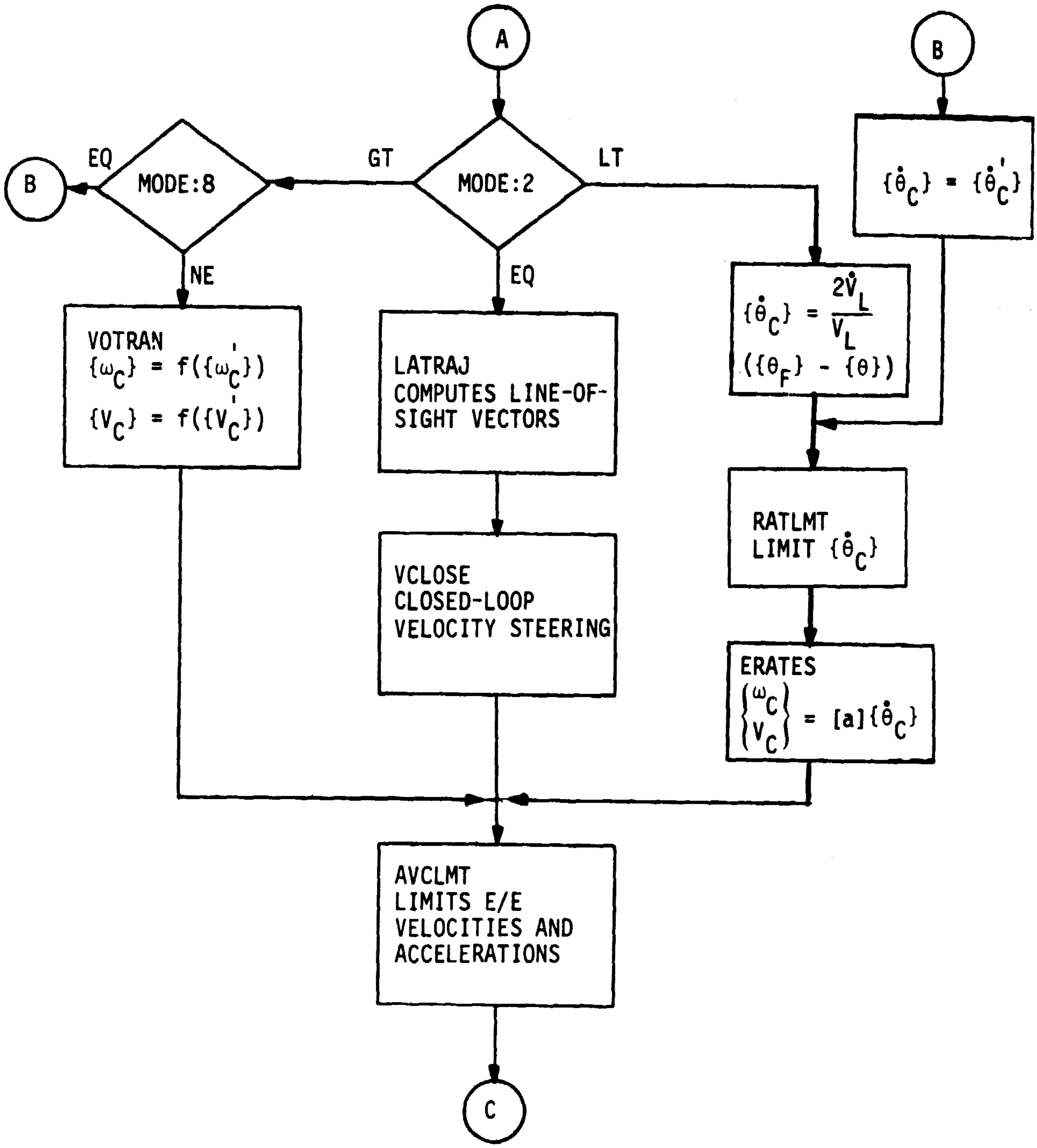
A

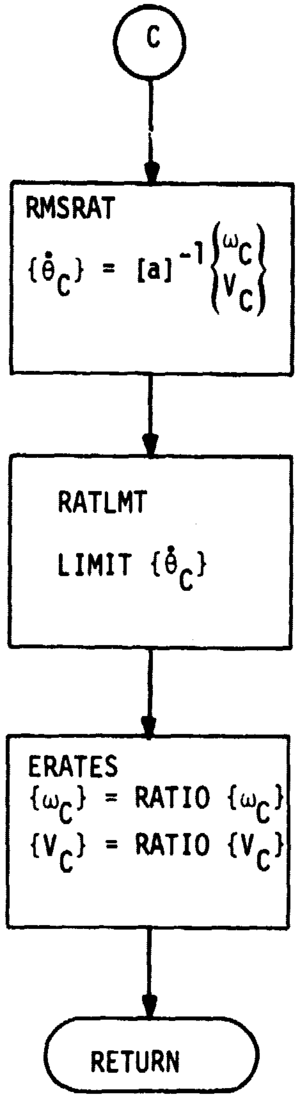

A
PA:1
NE
EQ
COMPUTE PAYLOAD CENTER AND ORIENTATION
$[T_{B8}] = [T_{B7}][T_{78}]^T$
$\{r_{8B}\} = \{r_{7B}\} + [T_{B8}]\{r_{87}\}$
RETURN

SUBROUTINE MSTEER

Subroutine MSTEER is the main subroutine that computes the commanded joint steering rates of the RMS arm. Based on the value of MODE, the specific steering is executed.

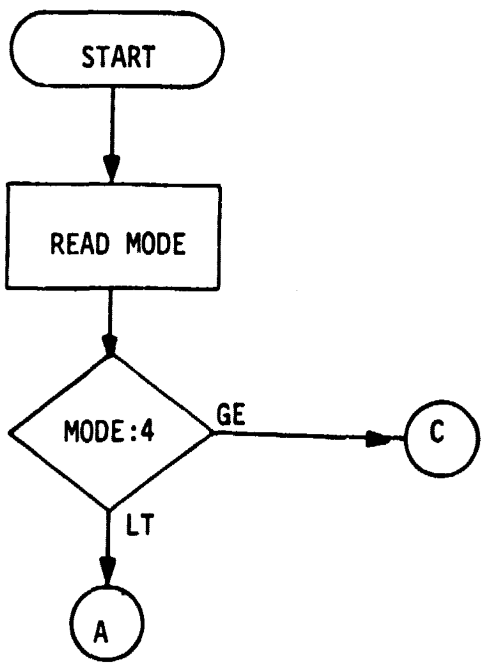



A
B
MODE:2
GT
LT
EQ
MODE:8
EQ
NE
B
{θ̇C} = {θ̇C'}
VOTRAN
{ωC} = f({ωC'})
{VC} = f({VC'})
LATRAJ
COMPUTES LINE-OF-SIGHT VECTORS
{θ̇C} = 2V̇L/VL ({θF} - {θ})
VCLOSE
CLOSED-LOOP
VELOCITY STEERING
RATLMT
LIMIT {θ̇C}
ERATES
{ωC, VC} = [a]{θ̇C}
AVCLMT
LIMITS E/E
VELOCITIES AND
ACCELERATIONS
C

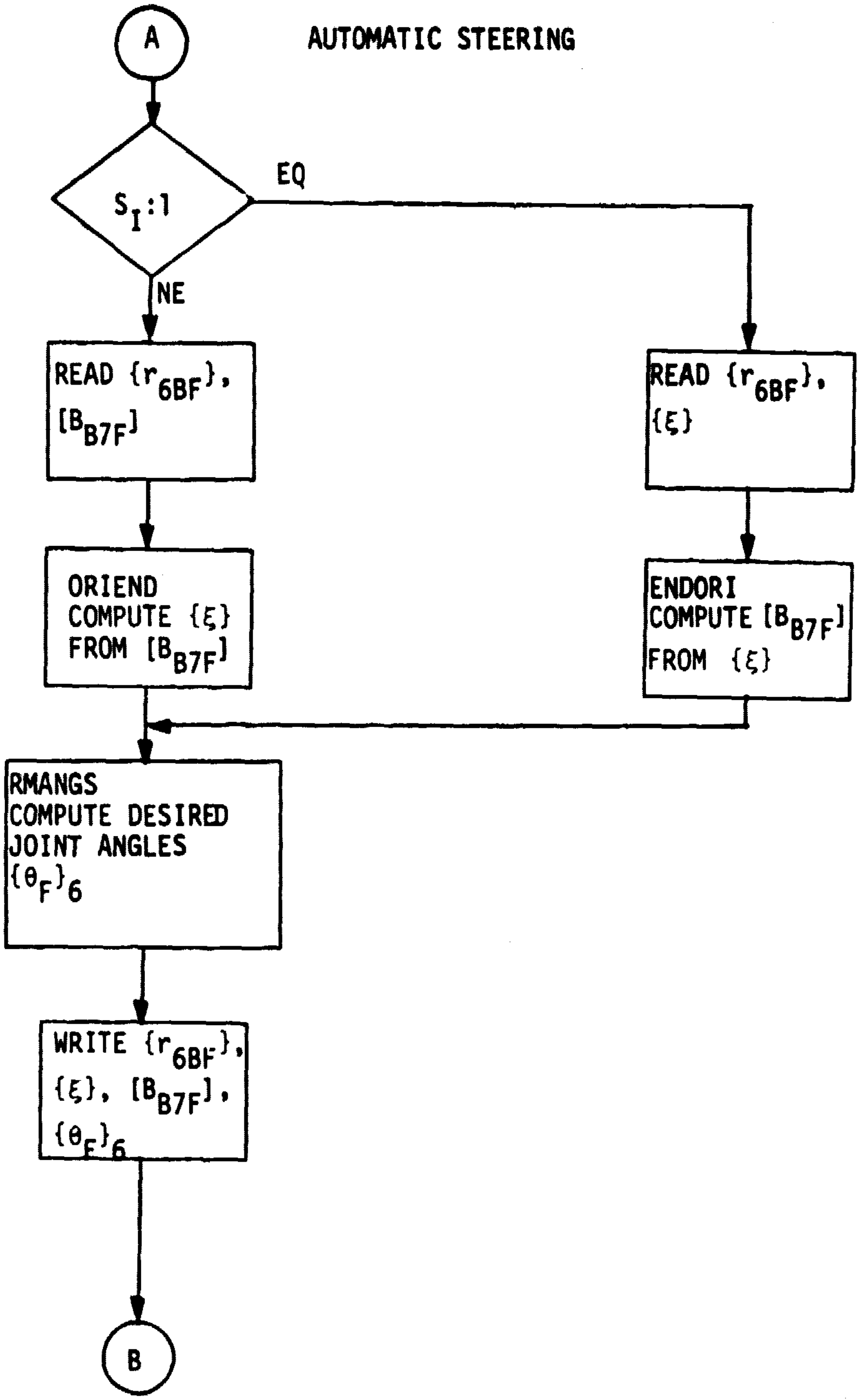

C
RMSRAT
$\{\dot{\theta}_C\} = [a]^{-1}\begin{Bmatrix}\omega_C \\ V_C\end{Bmatrix}$
RATLMT
LIMIT $\{\dot{\theta}_C\}$
ERATES
$\{\omega_C\}$ = RATIO $\{\omega_C\}$
$\{V_C\}$ = RATIO $\{V_C\}$
RETURN

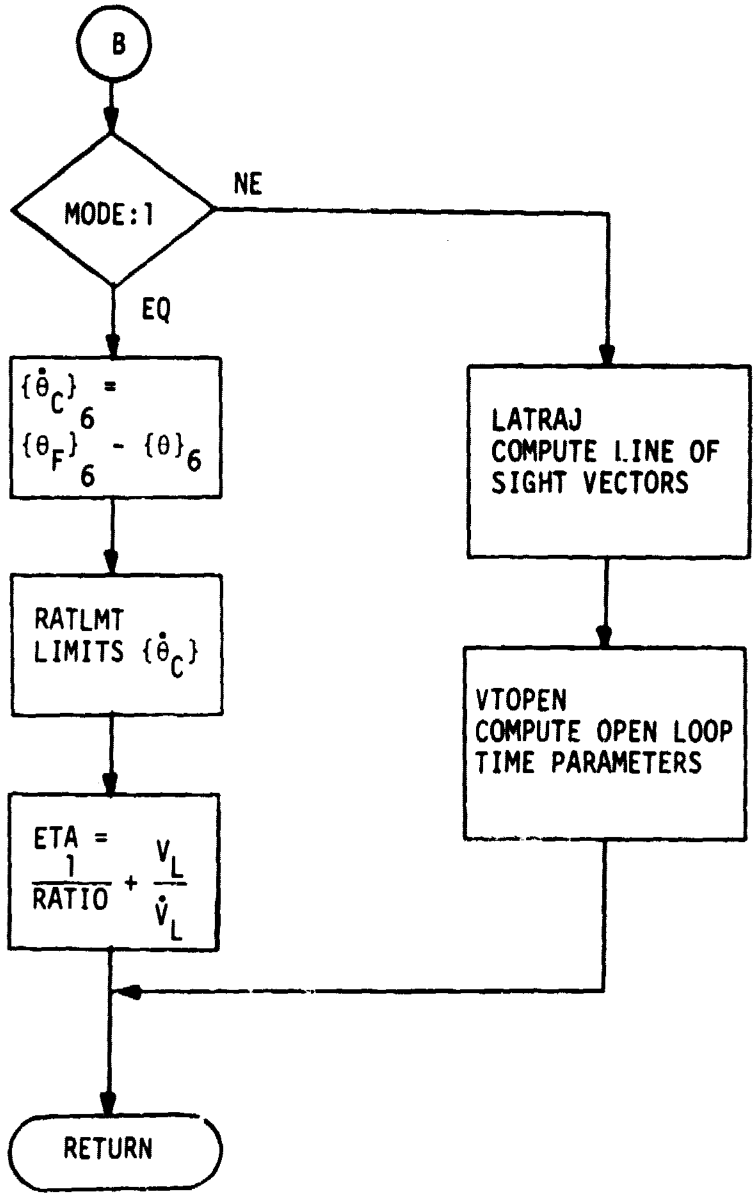
SUBROUTINE OPERIN

Subroutine OPERIN computes the initial values at the beginning of each phase, depending on the values of MODE. If MODE = 1, automatic position steering is selected. If MODE = 2 or 3, automatic velocity steering is selected (closed loop by MODE = 2 or open loop by MODE = 3). If MODE = 4, 5, 6, or 7, manual augmented steering is selected with the reference frame selected as orbiter by MODE = 4, end effector by MODE = 5, payload by MODE = 6, or mixed by MODE = 7. For the automatic steering, S_I = 1 implies that the Euler angles are being input in the orbiter reference frame rather than the transformation matrix. If MODE = 8, single joint rate steering is selected.

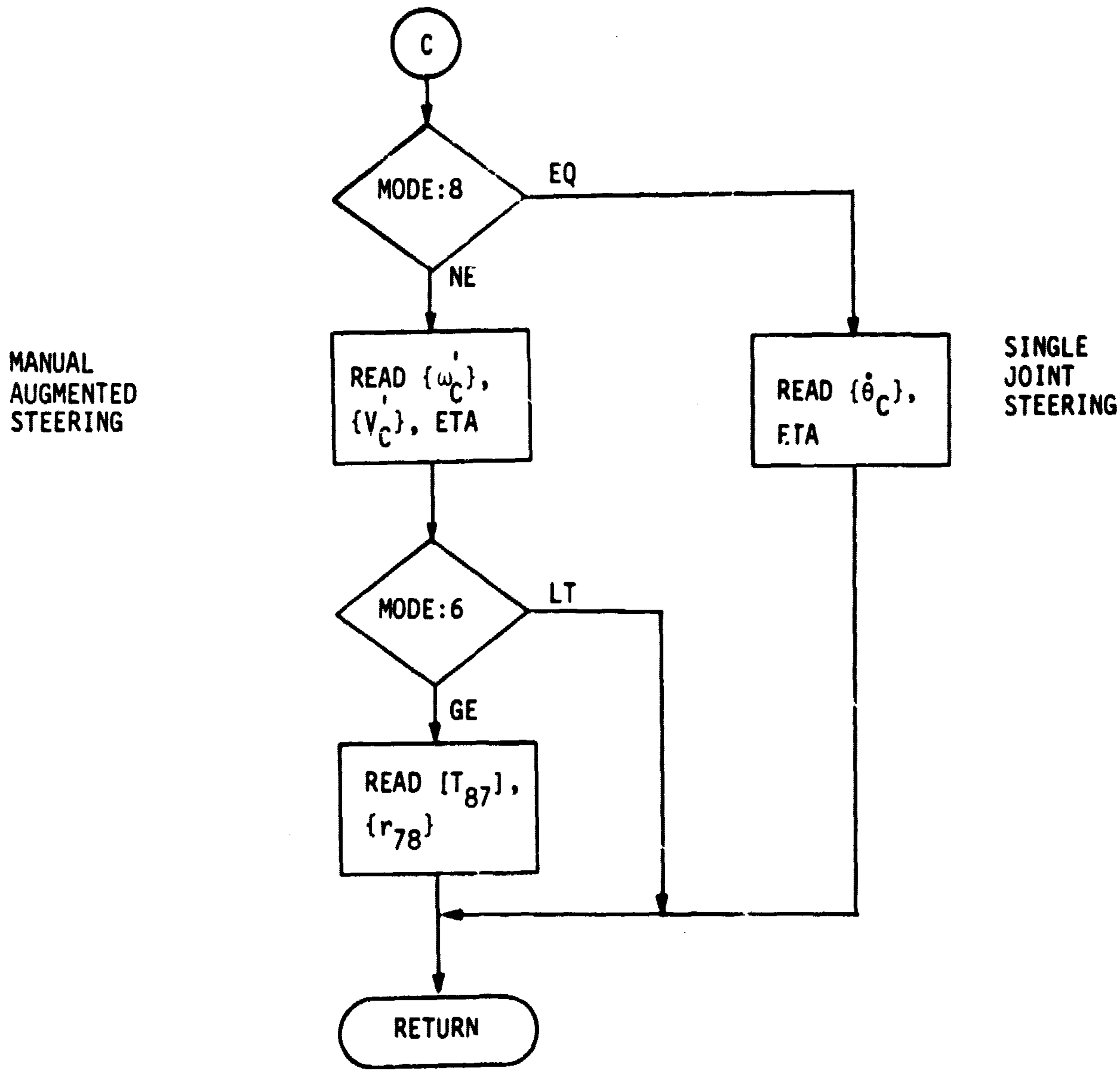


AUTOMATIC STEERING



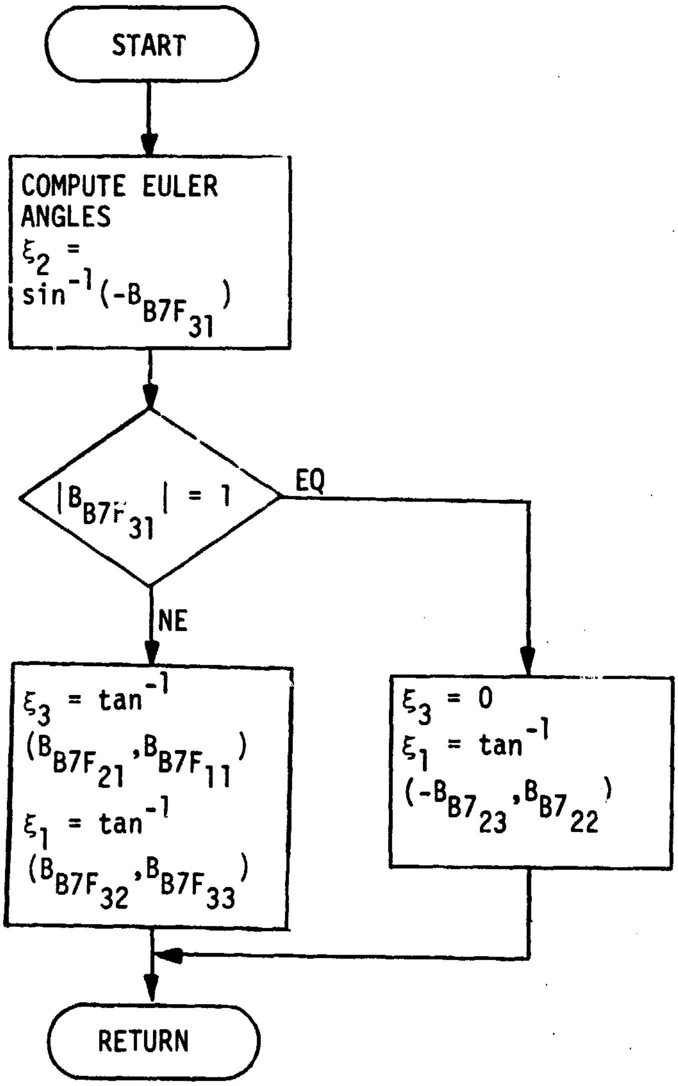


B
MODE:1
NE
EQ
{θ̇C}6 =
{θF}6 - {θ}6
RATLMT
LIMITS {θ̇C}
ETA =
1/RATIO + VL/V̇L
LATRAJ
COMPUTE LINE OF
SIGHT VECTORS
VTOPEN
COMPUTE OPEN LOOP
TIME PARAMETERS
RETURN


C
MODE:8
EQ
NE
MANUAL
AUGMENTED
STEERING
READ {ω'C}, {V'C}, ETA
READ {θ̇C}, ETA
SINGLE
JOINT
STEERING
MODE:6
LT
GE
READ [T87], {r78}
RETURN

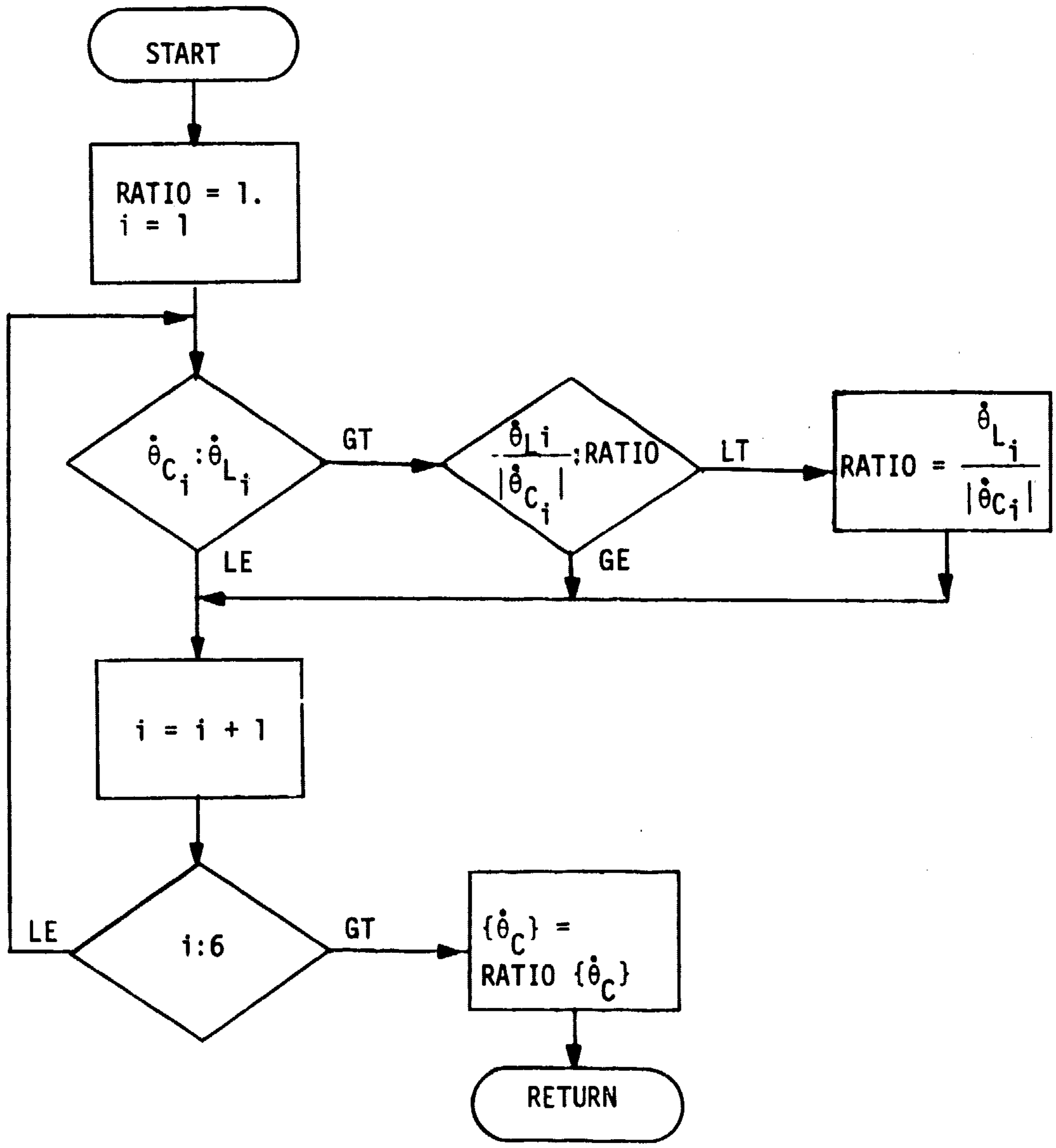
SUBROUTINE ORIEND

Subroutine ORIEND computes the Euler angles contained in the specified desired orientation of the end effector provided as the transformation matrix from the orbiter system. The Euler angles represent the order of rotation of azimuth/yaw, elevation/pitch, and roll in the orbiter system.



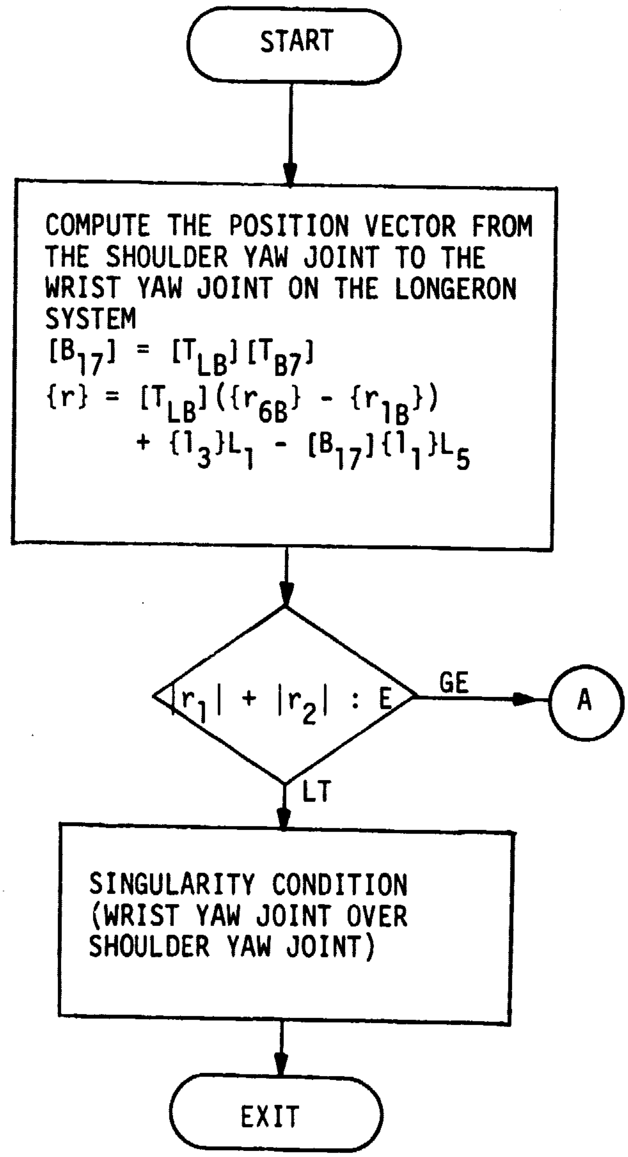
SUBROUTINE RATLMT

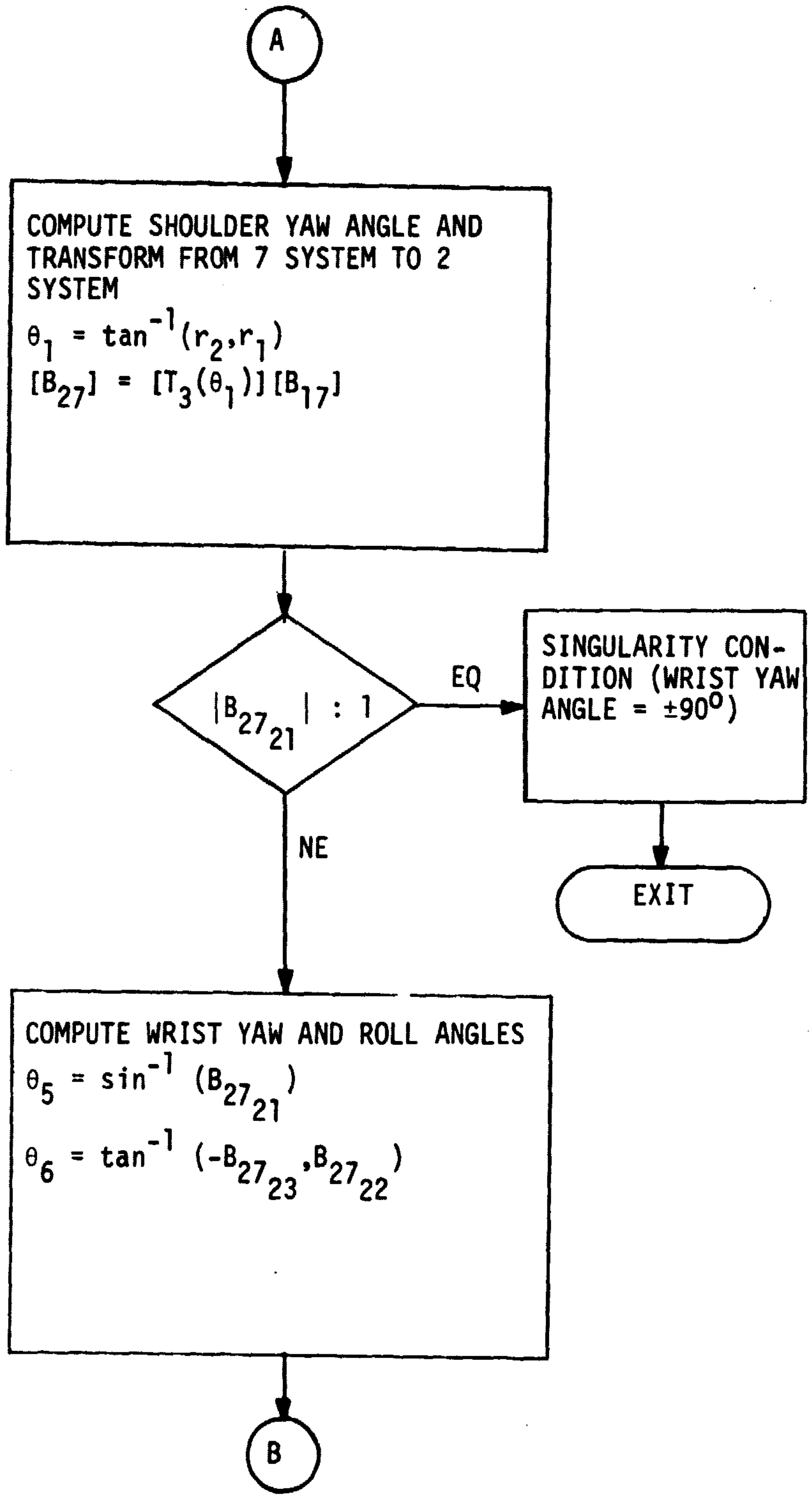
Subroutine RATLMT checks each commanded joint rate against its limit. If one or more limits are exceeded, the commanded joint rates are reduced proportionally so that one commanded joint rate equals its limit, and the others are within limits.

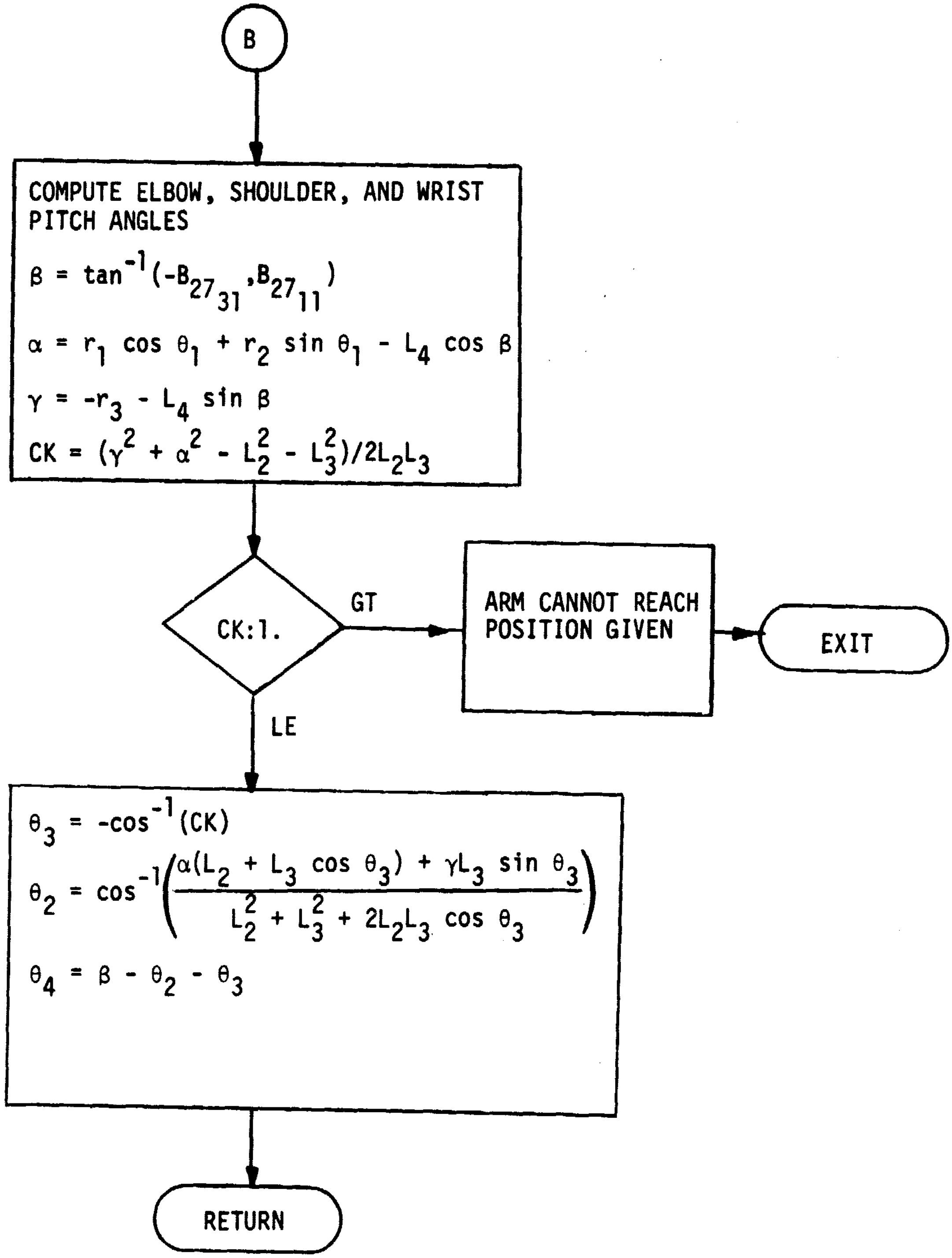


SUBROUTINE RMANGS

Subroutine RMANGS computes the RMS joint angles, given the position and orientation of the end effector relative to the orbiter.

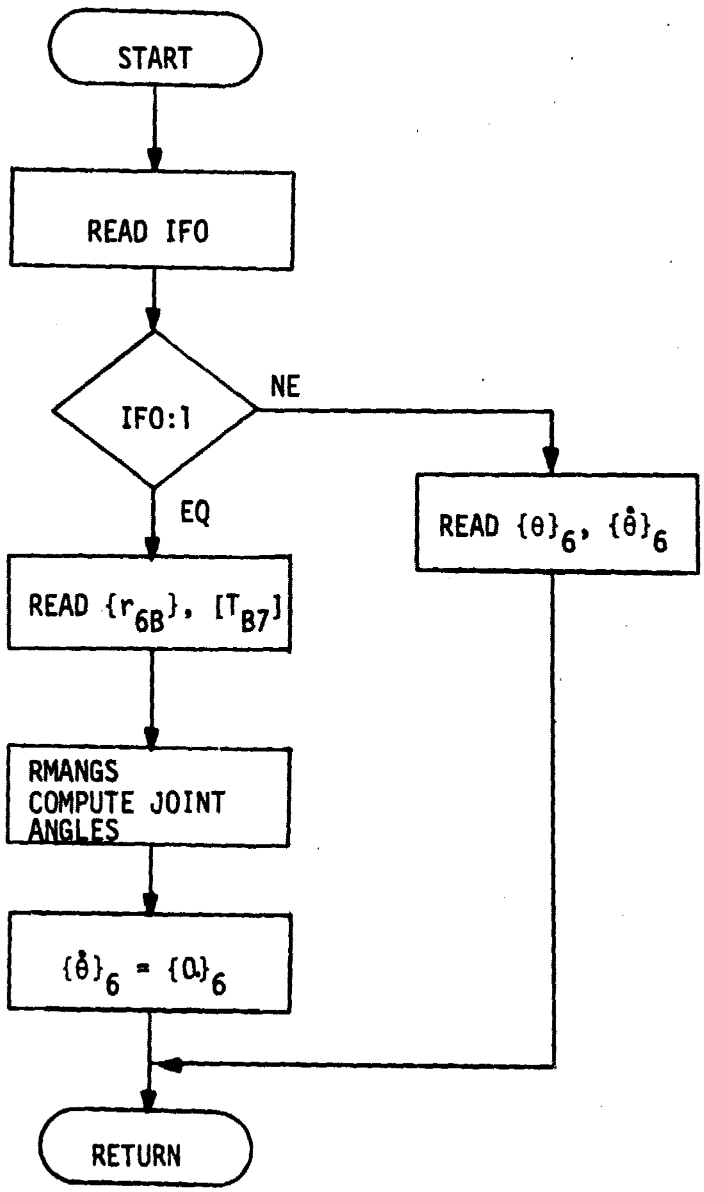



A
COMPUTE SHOULDER YAW ANGLE AND TRANSFORM FROM 7 SYSTEM TO 2 SYSTEM
$\theta_1 = \tan^{-1}(r_2, r_1)$
$[B_{27}] = [T_3(\theta_1)][B_{17}]$
$|B_{27_{21}}| : 1$
EQ
SINGULARITY CONDITION (WRIST YAW ANGLE = $\pm 90^{\circ}$)
EXIT
NE
COMPUTE WRIST YAW AND ROLL ANGLES
$\theta_5 = \sin^{-1}(B_{27_{21}})$
$\theta_6 = \tan^{-1}(-B_{27_{23}}, B_{27_{22}})$
B


B
COMPUTE ELBOW, SHOULDER, AND WRIST PITCH ANGLES
$\beta = \tan^{-1}(-B_{27_{31}}, B_{27_{11}})$
$\alpha = r_1 \cos\theta_1 + r_2 \sin\theta_1 - L_4 \cos\beta$
$\gamma = -r_3 - L_4 \sin\beta$
$CK = (\gamma^2 + \alpha^2 - L_2^2 - L_3^2)/2L_2L_3$
CK:1.
GT
ARM CANNOT REACH POSITION GIVEN
EXIT
LE
$\theta_3 = -\cos^{-1}(CK)$
$\theta_2 = \cos^{-1}\left(\frac{\alpha(L_2 + L_3 \cos\theta_3) + \gamma L_3 \sin\theta_3}{L_2^2 + L_3^2 + 2L_2L_3 \cos\theta_3}\right)$
$\theta_4 = \beta - \theta_2 - \theta_3$
RETURN

SUBROUTINE RMSIST

Subroutine RMSIST computes the initial state variables of the remote manipulator arm. If the input is position and orientation, the joint angles are computed.



SUBROUTINE RMSRAT

Subroutine RMSRAT computes the joint angle rates compatible with the commanded rotational and translational velocity of the end effector using the resolved rate law.

START

TRANSFORM END EFFECTOR VELOCITIES TO WRIST PITCH SYSTEM

$$\{b_1\} = [T_{B5}]^T\{\omega_C\}$$

$$\{b_4\} = [T_{B5}]^T\{V_C\}$$

SOLVE FOR JOINT ANGLES

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_5 \end{bmatrix} = \frac{1}{a_{31}a_{55} - a_{51}} \begin{bmatrix} a_{55} & -1 \\ -a_{51} & a_{31} \end{bmatrix} \begin{bmatrix} b_3 \\ b_5 \end{bmatrix}$$

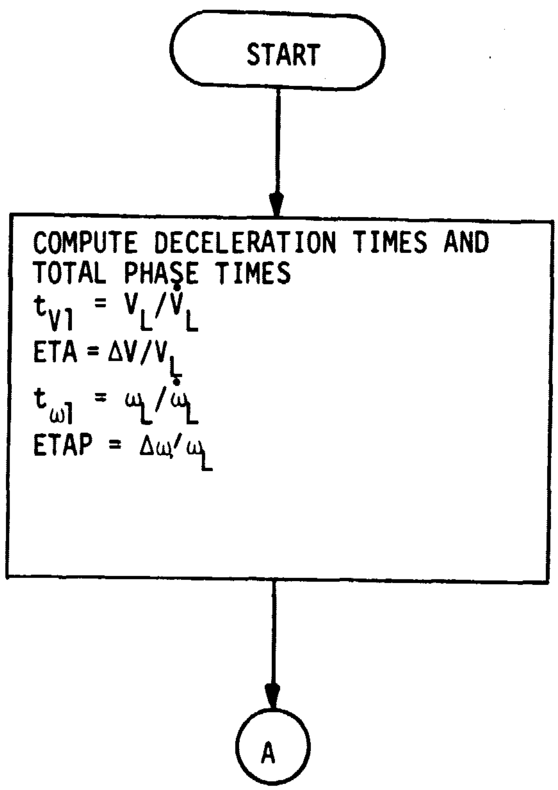
$$\dot{\theta}_6 = \frac{1}{a_{16}}\left(b_1 - a_{11}\dot{\theta}_1\right)$$

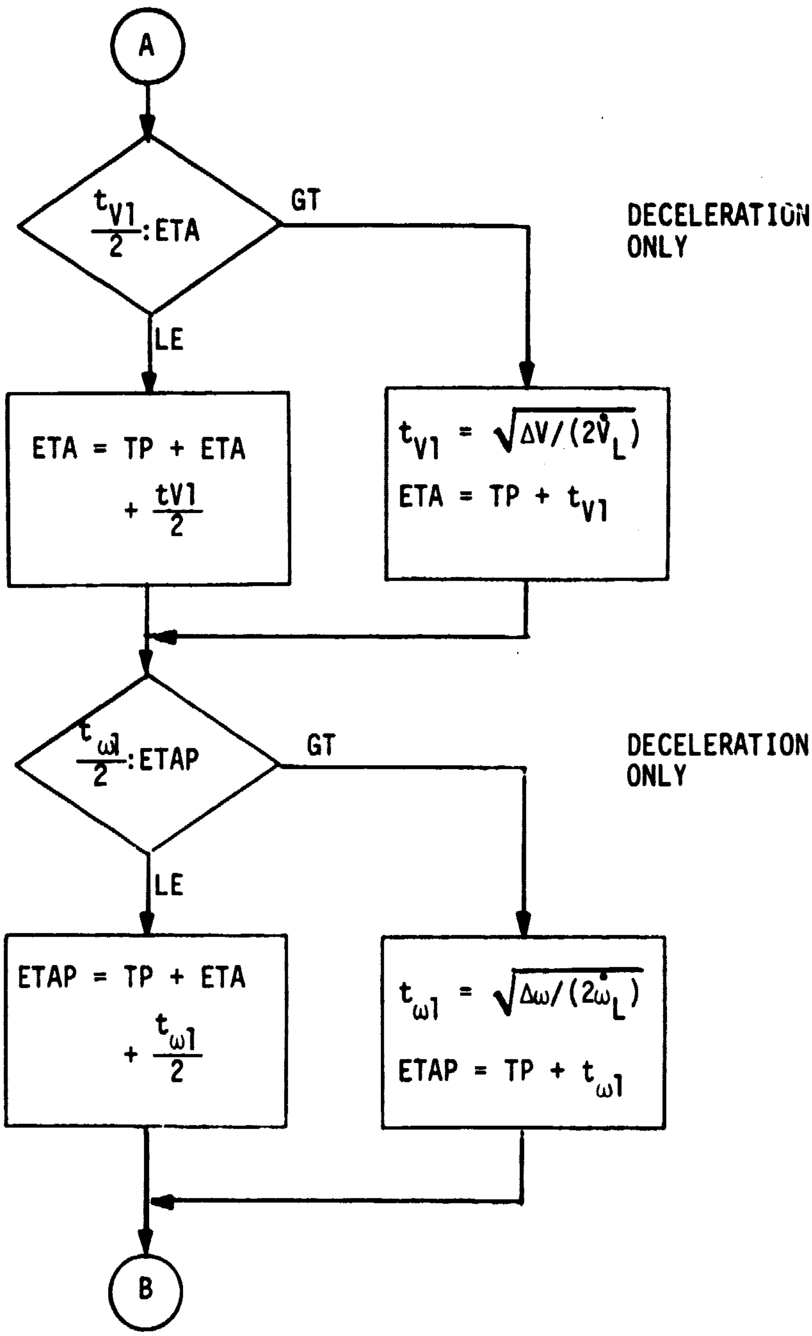
$$\begin{bmatrix} \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} = \frac{1}{a_{43}\left(a_{64} - a_{62}\right) - a_{42}\left(a_{64} - a_{63}\right)} \begin{bmatrix} a_{43}a_{64} & a_{63} - a_{64} & -a_{43} \\ -a_{42}a_{61} & a_{64} - a_{62} & a_{42} \\ a_{42}a_{63} - a_{62}a_{43} & a_{62} - a_{63} & a_{43} - a_{42} \end{bmatrix} \begin{bmatrix} b_2 - a_{26}\dot{\theta}_6 \\ b_4 - a_{41}\dot{\theta}_1 - a_{45}\dot{\theta}_5 \\ b_6 - a_{61}\dot{\theta}_1 \end{bmatrix}$$

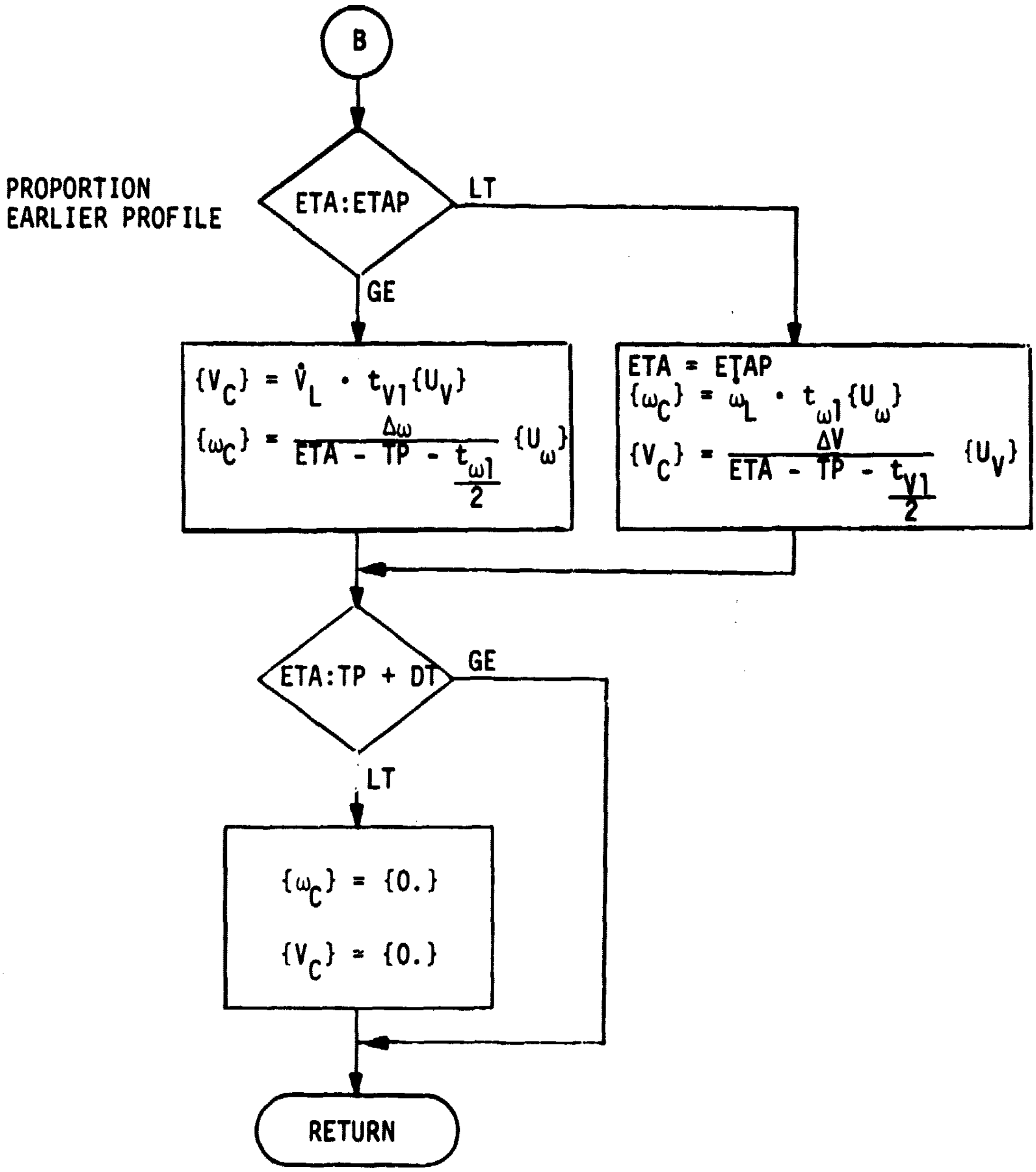
RETURN

SUBROUTINE VCLOSE

Subroutine VCLOSE computes the times of deceleration and maximum velocity for line-of-sight and angle-of-sight closed-loop steering. Depending on the maximum time of either the line-of-sight or angle-of-sight steer to reach the final state, the other steering is set proportional, preserving its deceleration time period. Effectively, both accelerations and decelerations will be at maximum values at the start and termination of the phase. Rate and velocity limiting will cause the phase to be automatically extended.

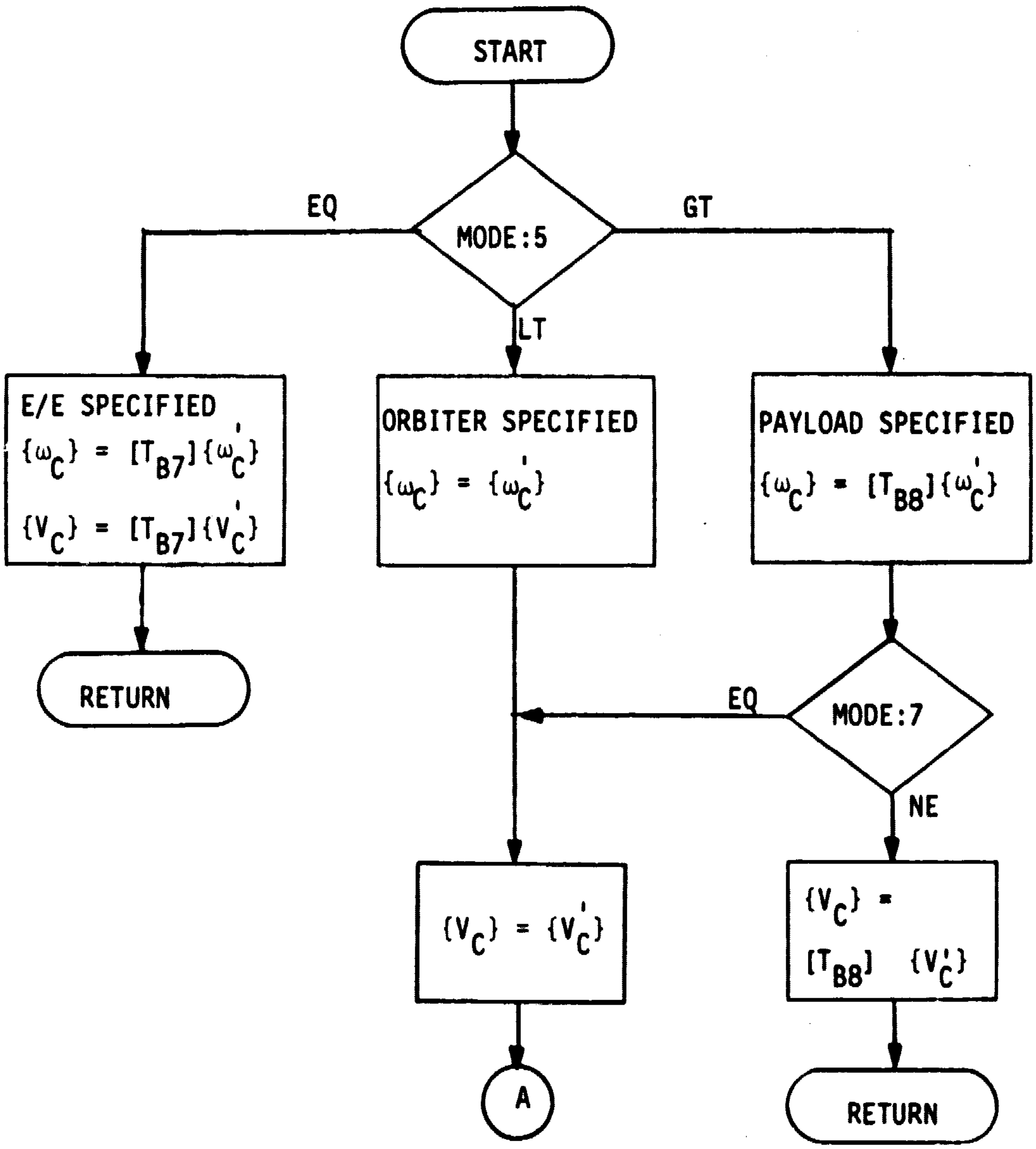


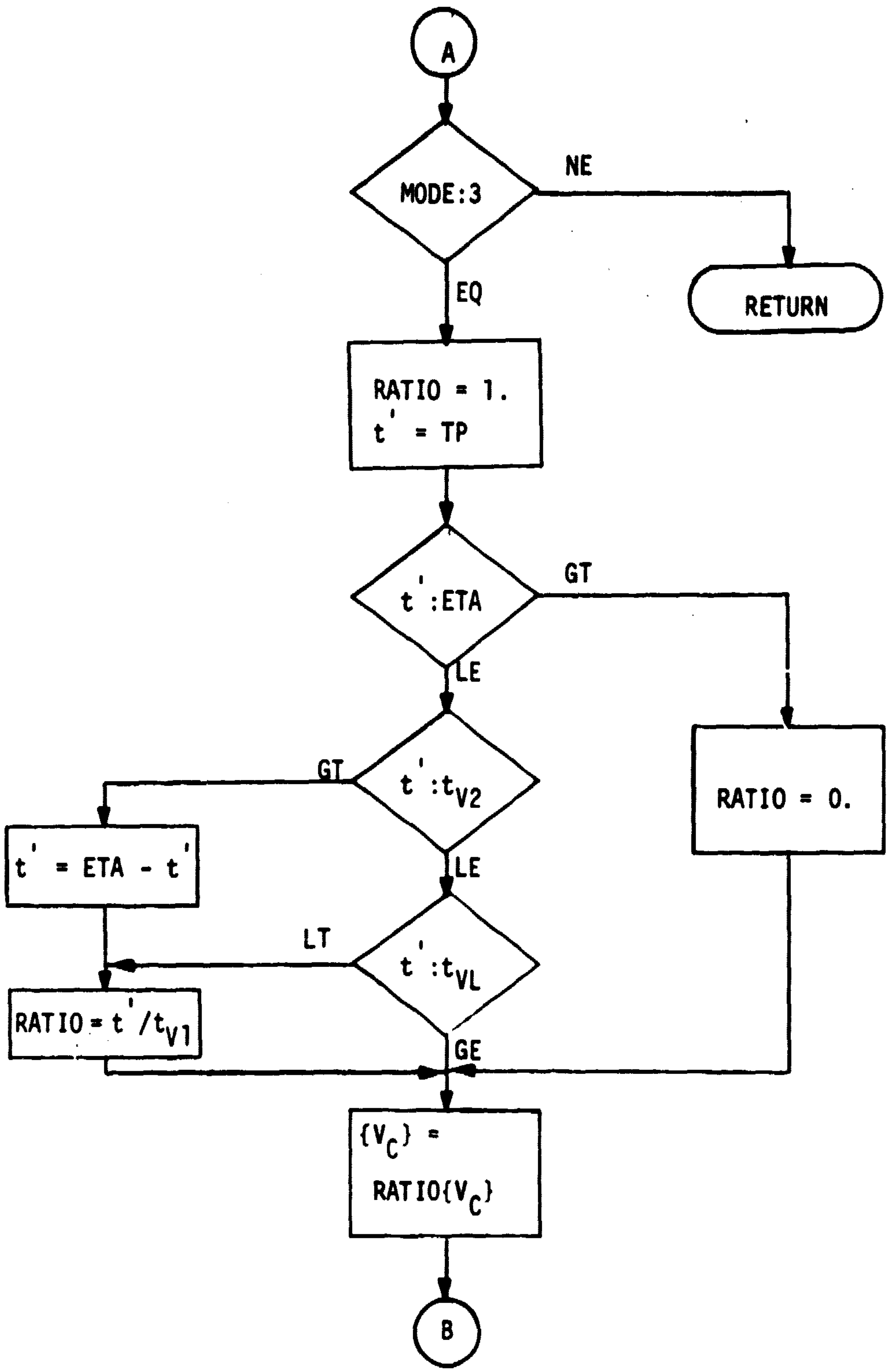

A
$\frac{t_{V1}}{2}$:ETA
GT
DECELERATION ONLY
LE
ETA = TP + ETA + $\frac{tV1}{2}$
$t_{V1} = \sqrt{\Delta V/(2\dot{V}_L)}$
ETA = TP + t_{V1}
$\frac{t_{\omega 1}}{2}$:ETAP
GT
DECELERATION ONLY
LE
ETAP = TP + ETA + $\frac{t_{\omega 1}}{2}$
$t_{\omega 1} = \sqrt{\Delta\omega/(2\dot{\omega}_L)}$
ETAP = TP + $t_{\omega 1}$
B

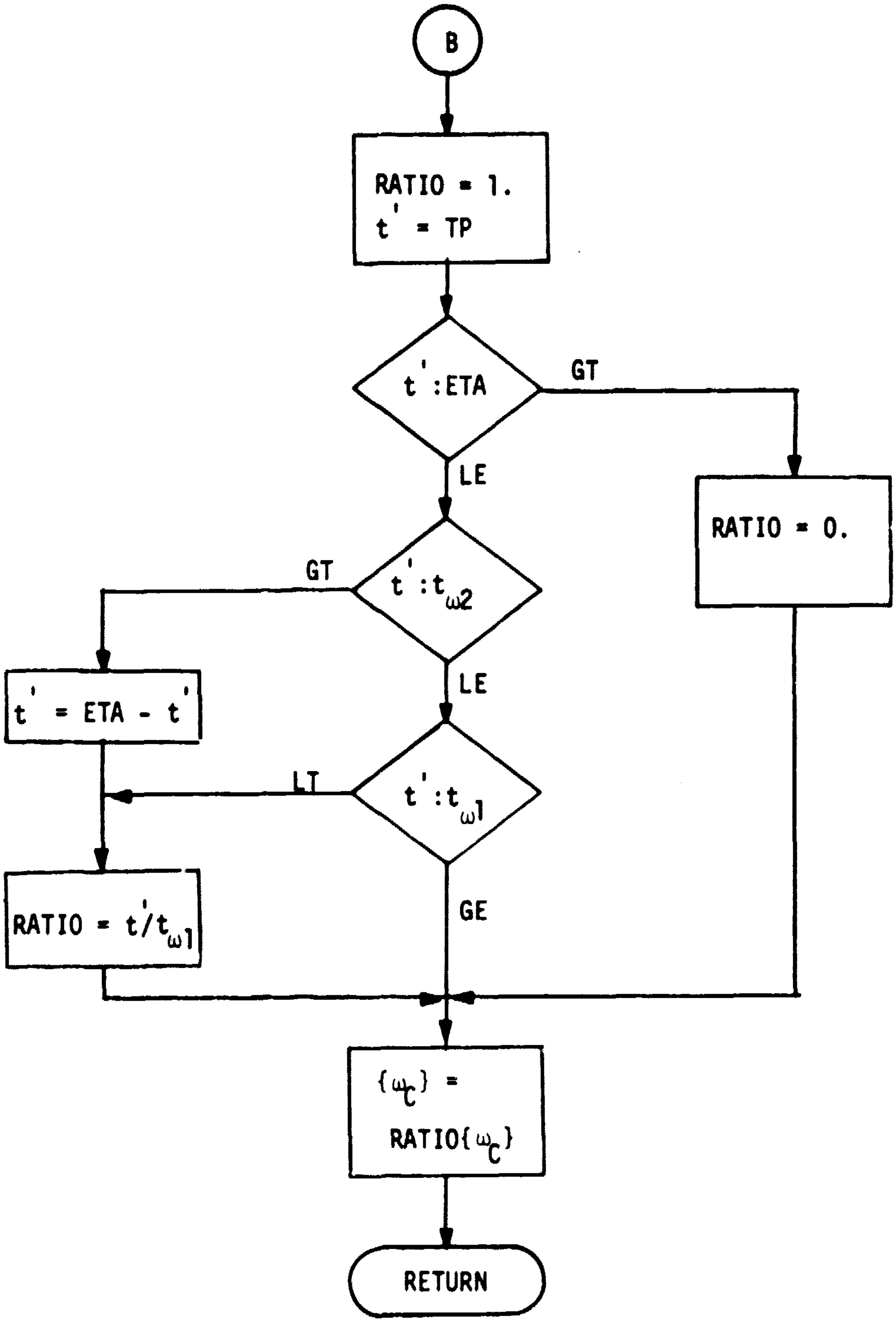

B
PROPORTION
EARLIER PROFILE
ETA:ETAP
LT
GE
{V_C} = V̇_L · t_V1 {U_V}
{ω_C} = Δω / (ETA - TP - t_ω1/2) {U_ω}
ETA = ETAP
{ω_C} = ω̇_L · t_ω1 {U_ω}
{V_C} = ΔV / (ETA - TP - t_V1/2) {U_V}
ETA:TP + DT
GE
LT
{ω_C} = {0.}
{V_C} = {0.}
RETURN

SUBROUTINE VOTRAN

Subroutine VOTRAN transforms the commanded rotational and translational velocities to the orbiter system. For open-loop velocity steering (MODE=3), the commanded velocities are limited during acceleration and deceleration phases.

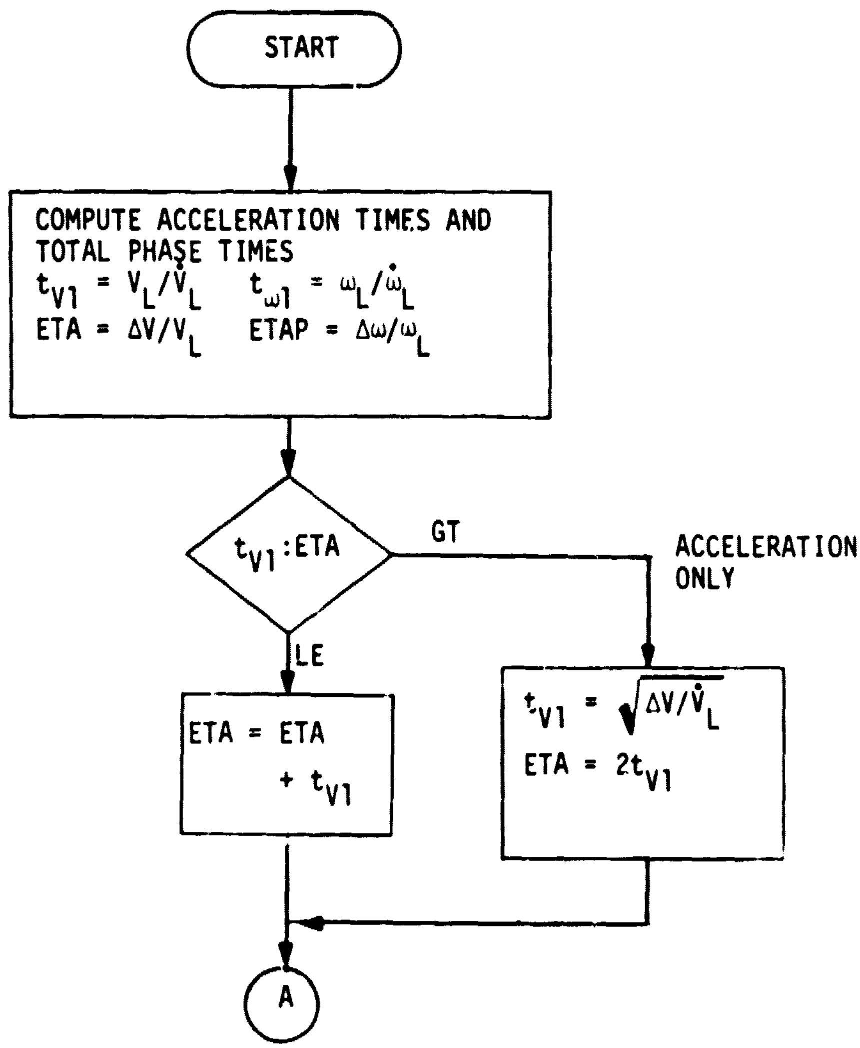


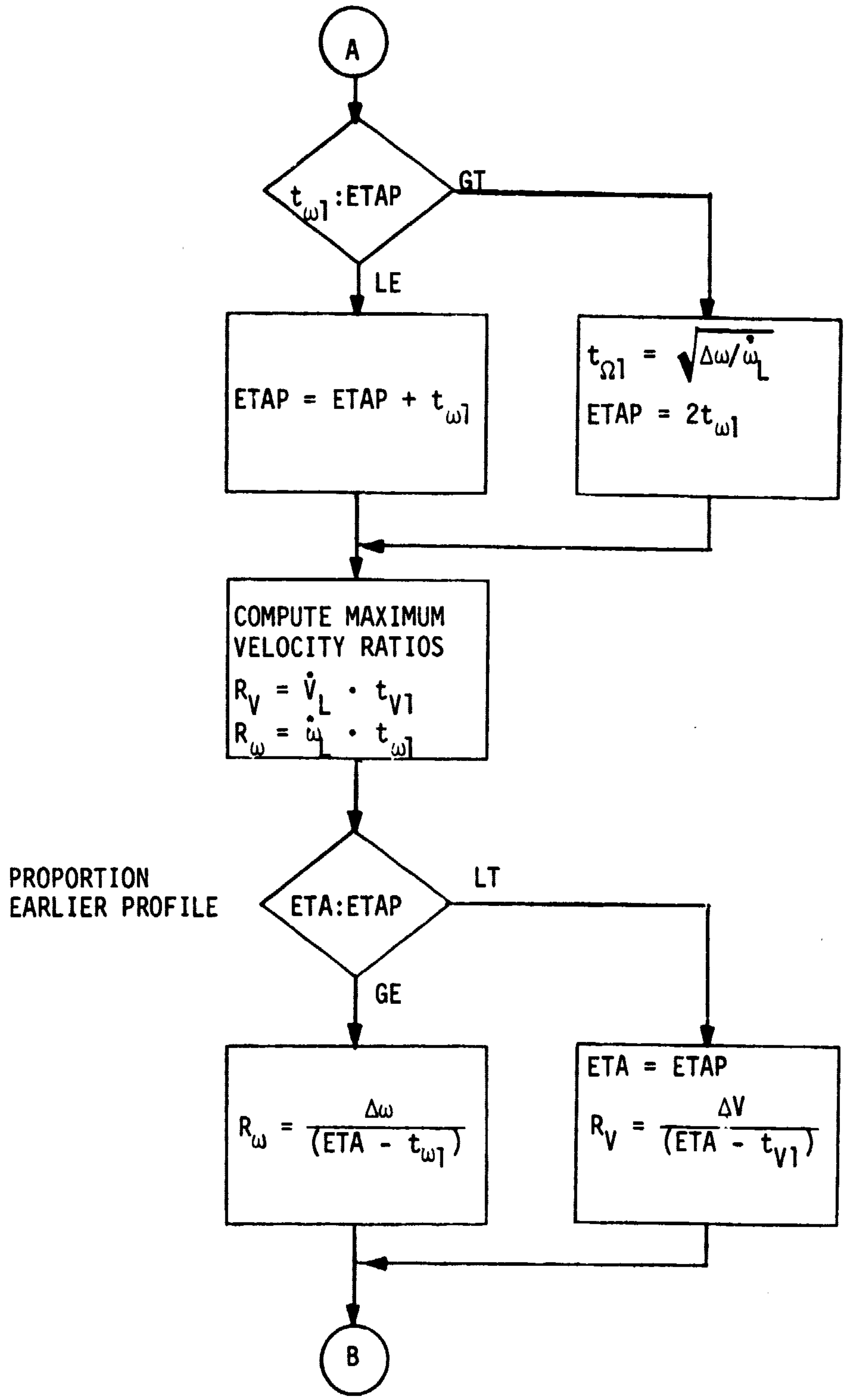

A
MODE:3
NE
RETURN
EQ
RATIO = 1.
t' = TP
t':ETA
GT
RATIO = 0.
LE
GT
t':t_V2
t' = ETA - t'
LE
LT
t':t_VL
RATIO = t'/t_V1
GE
{V_C} =
RATIO{V_C}
B

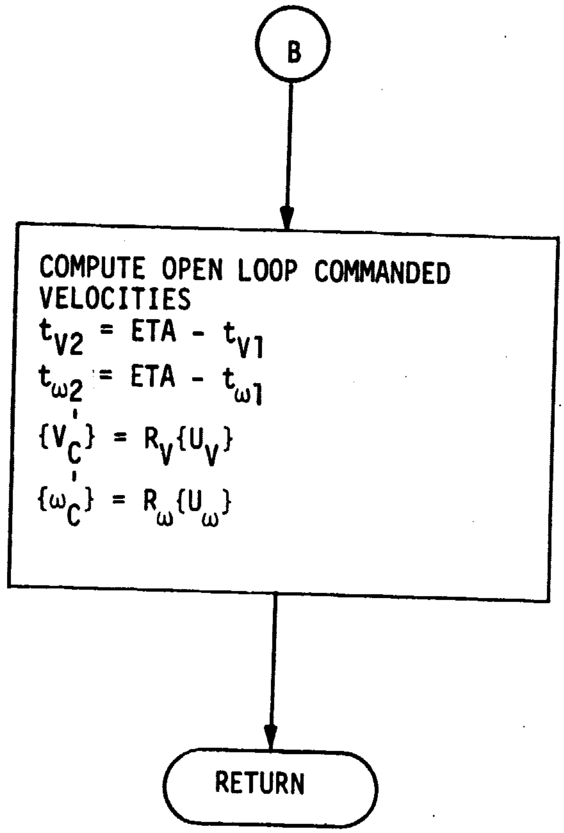

B
RATIO = 1.
t' = TP
t' : ETA
GT
LE
RATIO = 0.
t' : $t_{\omega 2}$
GT
LE
t' = ETA - t'
t' : $t_{\omega 1}$
LT
GE
RATIO = $t'/t_{\omega 1}$
{ω_C} =
RATIO{ω_C}
RETURN

SUBROUTINE VTOPEN

Subroutine VTOPEN computes the times fo acceleration and maximum velocity for line-of-sight and angle-of-sight open-loop steering. Depending on the maximum time of either the line-of-sight or angle-of-sight steering to reach the final state, the other steering is set proportional, preserving its acceleration time periods.




A
$t_{\omega 1}$:ETAP
GT
LE
ETAP = ETAP + $t_{\omega 1}$
$t_{\Omega 1} = \sqrt{\Delta\omega/\dot{\omega}_L}$
ETAP = $2t_{\omega 1}$
COMPUTE MAXIMUM
VELOCITY RATIOS
$R_V = \dot{V}_L \cdot t_{V1}$
$R_\omega = \dot{\omega}_L \cdot t_{\omega 1}$
PROPORTION
EARLIER PROFILE
ETA:ETAP
LT
GE
$R_\omega = \frac{\Delta\omega}{(ETA - t_{\omega 1})}$
ETA = ETAP
$R_V = \frac{\Delta V}{(ETA - t_{V1})}$
B


B
COMPUTE OPEN LOOP COMMANDED VELOCITIES
$t_{V2} = ETA - t_{V1}$
$t_{\omega 2} = ETA - t_{\omega 1}$
$\{V_C'\} = R_V\{U_V\}$
$\{\omega_C'\} = R_\omega\{U_\omega\}$
RETURN

DEFINITIONS OF SYMBOLS

a_{ij}	Coefficients of the Jacobian used in the resolved rate law
[B]	Transformation matrix from initial orientation of the end effector to the final
$[B_{B7_F}]$	Transformation matrix from final desired end effector orientation to orbiter body system
$\{b_1\}$	Column matrix of the commanded end effector angular velocity relative to the orbiter expressed in the wrist pitch system
$\{b_4\}$	Column matrix of the components of the commanded end effector translational velocity relative to the orbiter expressed in the wrist pitch system
$[B_{17}]$	Transformation matrix from the end effector system to the longeron system
$[B_{27}]$	Transformation matrix from the end effector system to the shoulder yaw system
DT	Integration step size
CK	Cosine value using the law of cosines
ETA	Estimated time of the current maneuver
ETAP	Estimated time to complete the angular rotations specified for the end effector at maximum angular velocity
IFO	Flag indicating whether the initial orientation of the RMS is to be specified by the position and orientation of the tip of the end effector in the orbiter body system (=0) or by joint angles and joint angle rates (=1)
L_1	Distance from the RMS attach point to shoulder pitch pivot point
L_2	Length of upper arm
L_3	Length of lower arm

L_4	Distance from wrist pitch joint to wrist yaw joint
L_5	Distance from wrist yaw joint to the tip of the end effector
MODE	Flag indicating the particular steering desired: (1) Automatic steering, position mode; (2) Automatic steering, closed-loop velocity mode; (3) Automatic steering, open-loop velocity mode; (4) Manual augmented steering, orbiter frame; (5) Manual augmented steering, end effector frame; (6) Manual augmented steering, payload frame; (7) Manual augmented steering, mixed-rotations in payload frame and translations in orbiter frame; (8) Single joint rate steering mode
PA	Flag indicating that a payload is attached (=1)
$\{r\}$	Column matrix of the components of position vector from the shoulder pitch joint to the wrist yaw joint expressed in the longeron system
$\{r_{NB}\}$	Temporary column matrix of the components of position vector from the center of mass (CM) of the orbiter to different joints in the orbiter body system
R_V	Ratio used to scale down the commanded translational velocity
$\{r_{1B}\}$	Column matrix of the components of the position vector from the CM of the orbiter to the RMS attach point in the orbiter body system
$\{r_{6B}\}$	Column matrix of the components of the position vector from the CM of the orbiter to the tip of the end effector in the orbiter body system
$\{r_{6B_F}\}$	Column matrix of the components of the position vector from the CM of the orbiter to the final desired position of the tip of the end effector expressed in the orbiter body system
$\{r_{7B}\}$	Column matrix of the components of the position vector from the CM of the orbiter to the CM of the payload in the orbiter body system
R_ω	Ratio used to scale down the commanded angular velocity

RATIO	Ratio used to scale down commanded velocities or commanded joint angle rates
S_I	Flag indicating whether the specified final orientation of the end effector is a transformation matrix (=0) or Euler angles (=1) in the orbiter body system
t'	Time from start of acceleration or time remaining for deceleration in the open-loop velocity steering mode
$[T_{BN}]$	Temporary transformation matrix from the various RMS joint systems to the orbiter body system
$[T_{B5}]$	Transformation matrix from the wrist pitch system to the orbiter body system
$[T_{B7}]$	Transformation matrix from the end effector system to the orbiter body system
$[T_{B8}]$	Transformation matrix from the payload system to the orbiter body system
$[T_{LB}]$	Transformation matrix from the orbiter body system to the longeron system
t_{V1}	Phase time to stop constant acceleration and start constant translational velocity commands
t_{V2}	Phase time to stop constant translational velocity commands and start constant deceleration
$[T_1(\theta)]$	Transformation matrix representing a θ rotation about the 1-axis
$[T_2(\theta)]$	Transformation matrix representing a θ rotation about the 2-axis
$[T_3(\theta)]$	Transformation matrix representing a θ rotation about the 3-axis
$[T_{78}]$	Transformation matrix from the payload system to the end effector system
$t_{\omega 1}$	Phase time to stop a constant acceleration and start constant angular velocity commands

$t_{\omega 2}$	Phase time to stop constant angular velocity commands and start constant deceleration
TP	Actual phase time
$\{U_V\}$	Column matrix representing the unit vector along the line of sight
$\{U_\omega\}$	Column matrix representing the unit axis of rotation vector
$\{V\}$	Column matrix of components of the actual translational velocity expressed in the orbiter body system
$\{V_C\}$	Column matrix of components of the commanded translational velocity expressed in the orbiter body system
$\{V_C'\}$	Column matrix of components of the commanded translational velocity in the system specified by MODE
$\{\dot{V}_C\}$	Column matrix of components of commanded minus actual translational velocity expressed in the orbiter body system
V_L	Maximum translational velocity of the end effector relative to the orbiter
$\dot{V}_L$	Maximum translational acceleration of the end effector relative to the orbiter
α	Parameter used in arm angle initialization computations
β	Parameter used in arm angle initialization computations
γ	Parameter used in arm angle initialization computations
ΔV	Distance from current position of the end effector to final desired position of the end effector
$\Delta\omega$	Rotation angle from current orientation of the end effector to final desired orientation of the end effector
θ_1	Shoulder yaw angle
θ_2	Shoulder pitch angle
θ_3	Elbow pitch angle

θ_4 Wrist pitch angle

θ_5 Wrist yaw angle

θ_6 Hand roll angle

$\{\theta_F\}$ Column matrix of final desired joint angles

$\{\dot{\theta}\}$ Column matrix of actual or commanded joint angle rates

$\{\dot{\theta}_C\}$ Column matrix of commanded joint angle rates

$\{\dot{\theta}_C'\}$ Column matrix of specified commanded joint angle rates

$\{\dot{\theta}_L\}$ Column matrix of maximum commanded joint angle rates

ξ_1 Final desired roll angle of the end effector in the orbiter body system

ξ_2 Final desired elevation (pitch) angle of the end effector in the orbiter body system

ξ_3 Final desired azimuth (yaw) angle of the end effector in the orbiter body system

$\{\omega\}$ Column matrix of components of the actual angular velocity expressed in the orbiter system

$\{\omega_C\}$ Column matrix of components of the commanded angular velocity expressed in the orbiter system

$\{\omega_C'\}$ Column matrix of components of the commanded angular velocity in the system specified by MODE

$\{\dot{\omega}_C\}$ Column matrix of components of commanded minus actual angular velocity expressed in the orbiter body system

ω_L Maximum angular velocity of the end effector relative to the orbiter

$\dot{\omega}_L$ Maximum angular acceleration of the end effector relative to the orbiter

4. REFERENCES

1. Flanders, H.: Kinematic Capability in the SVDS, LEC-10246, March 1977.

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3. SRMS Software Detailed Algorithms, SPAR-SG.460, Issue A, March 1977.