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Evaluation of Automated Decisionmaking Methodologies and Development of an Integrated Robotic System Simulation

Appendix A. Software Documentation

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Langley Research Center
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Appendix A - Software Documentation

EVALUATION OF AUTOMATED DECISIONMAKING METHODOLOGIES AND DEVELOPMENT OF AN INTEGRATED ROBOTIC SYSTEM SIMULATION

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This work was performed for NASA Langley Research Center under contract NAS1-16759.

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N82-34130#

FOREWORD

This document covers the work performed on contract NAS1-16759, Evaluation of Automated Decision-Making Methodologies and Development of Integrated Robotic System Simulation, for the Langley Research Center of the National Aeronautics and Space Administration. It was prepared by Martin Marietta Aerospace in accordance with the contract, Part II, Statement of Work.

The final report for this study consists of three volumes:

NASA CR-165975 - Study Results

NASA CR-165976 - Appendix A, Software Documentation

NASA CR-165977 - Appendix B, Derivation of Requirements Tool Dynamics
Appendix C, Derivation of Simulation Tool Dynamics
Appendix D, Derivation of Requirements Tool Control Law
Appendix E, Simulation Methodologies

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Figure (cont)

1.0 INTRODUCTION

The Robotic Simulation Program (ROBSIM) has been designed to provide a wide range of computer capabilities in robotic system design and analysis. The program structure is composed of three major functions controlled by a program executive as shown in Figure A1-1. The three major ROBSIM functions are:

1) System definition;

2) Analysis tools;

3) Postprocessing.

Each of the major functions is designed in a modular fashion to allow for easy future expansion.

The System Definition function handles user input of system parameters and creates a disk file to be used as input to the Analysis Tools and Postprocessing functions. The Analysis Tools function handles the computational requirements of the ROBSIM program. Currently, a requirements analysis tool and a simulation tool are being implemented. Additional analysis tools are easily included within the program structure. The simulation tool is being developed outside the ROBSIM program structure as a standalone program. The documentation of the simulation tool program is contained in a separate section of this document. The Postprocessing function allows for more detailed study of the results of the Analysis Tools function execution. Current postprocessing capabilities include a playback of the system motion using the program graphics and generation of parameter versus parameter plots.

1.1 DOCUMENT STRUCTURE

The remainder of Section 1.0 provides hierarchy diagrams for the software developed to date under the ROBSIM contract and a short discussion of the visual control logic representation (VCLR) diagrams used to show program logic flow.

Section 2.0 contains the documentation of the subroutines that make up the ROBSIM program and presents a description of the ROBSIM executive. Subsections 2.1 through 2.3 contain descriptions of the routines required in the System Definition, Analysis Tools, and Postprocessing functions, respectively; Subsection 2.4, descriptions of several program utility routines used throughout the ROBSIM program; Subsection 2.5, descriptions of several math utilities used throughout the ROBSIM program; Subsections 2.6 and 2.7, short descriptions of the Evans and Sutherland graphics routines and the DISSPLA plotting routines used in ROBSIM.

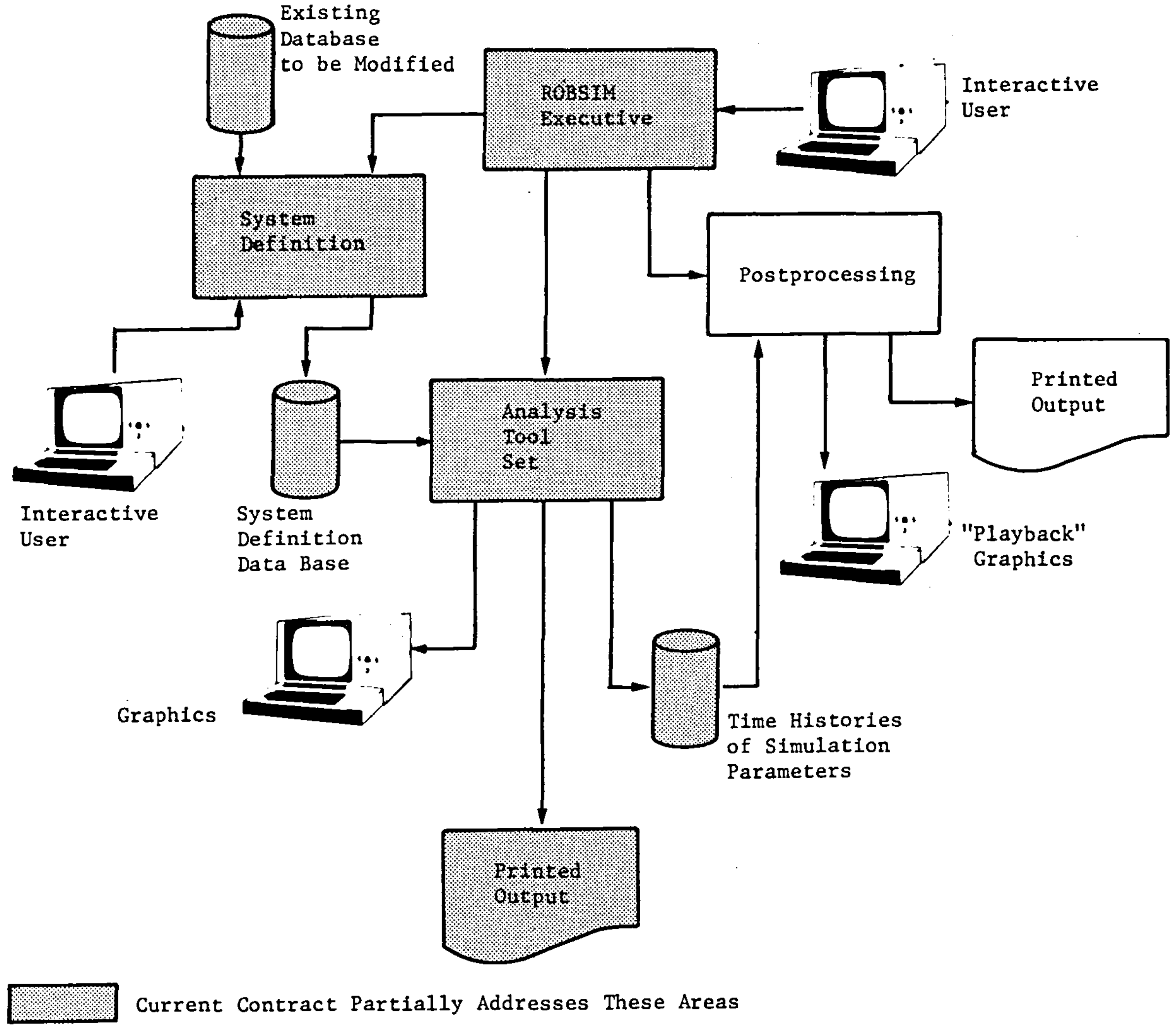


Figure A1-1 ROBSIM Framework

Section 3.0 contains the documentation of the subroutines that make up the simulation tool program, Joint Model (JNTMOD). Subsection 3.1 contains descriptions of the input routines, the initialization routine, the print routine, and several routines used in multiple locations in the JNTMOD program; Subsection 3.2, descriptions of the control routines; Subsections 3.3 through 3.6, descriptions of amplifier model, motor model, power train, and load model routines, respectively; Subsection 3.7, descriptions of the Kalman filter routines; Subsection 3.8, descriptions of the plot file generation routines; and Subsection 3.9, descriptions of the math routines.

The documentation of each routine in Sections 2.0 and 3.0 contains a general discussion of the function performed and a VCLR for that routine.

1.2 HIERARCHY DIAGRAMS

Hierarchy diagrams for the ROBSIM and JNTMOD programs are given in Figures A1-2 through A1-13. The numbers associated with each block in the hierarchy diagrams indicate the section number within this document containing the description of the subroutine that handles that block function. Figure A1-2 shows the top-level hierarchy diagram for the ROBSIM program. Figures A1-3 through A1-5 show the hierarchy diagrams for the three major ROBSIM functions--System Definition, Analysis Tools, and Postprocessing, respectively. Figures A1-6 through A1-13 show the hierarchy diagrams for the JNTMOD program.

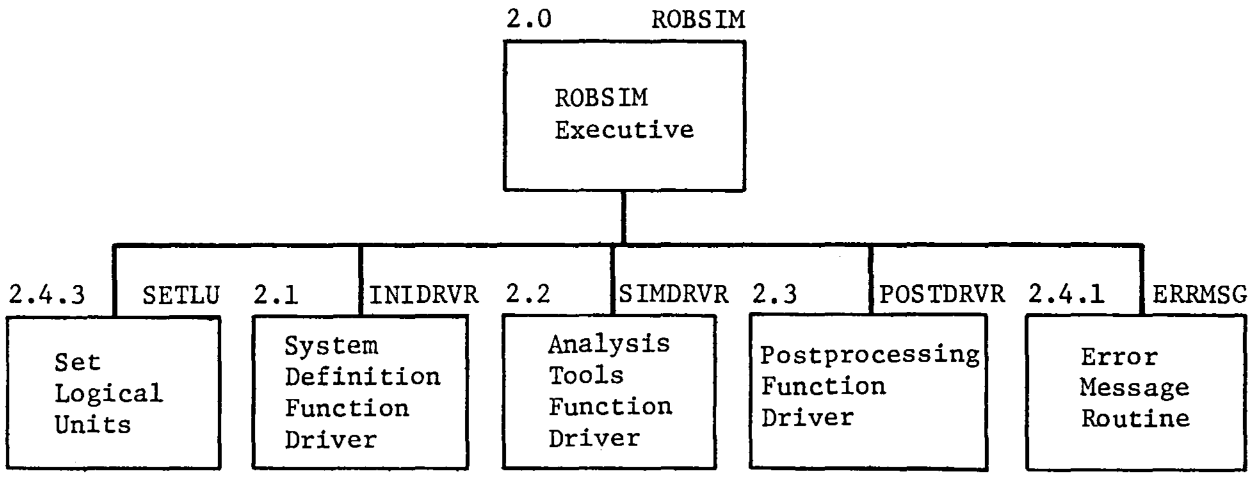


Figure A1-2 Top-Level ROBSIM Hierarchy Diagram

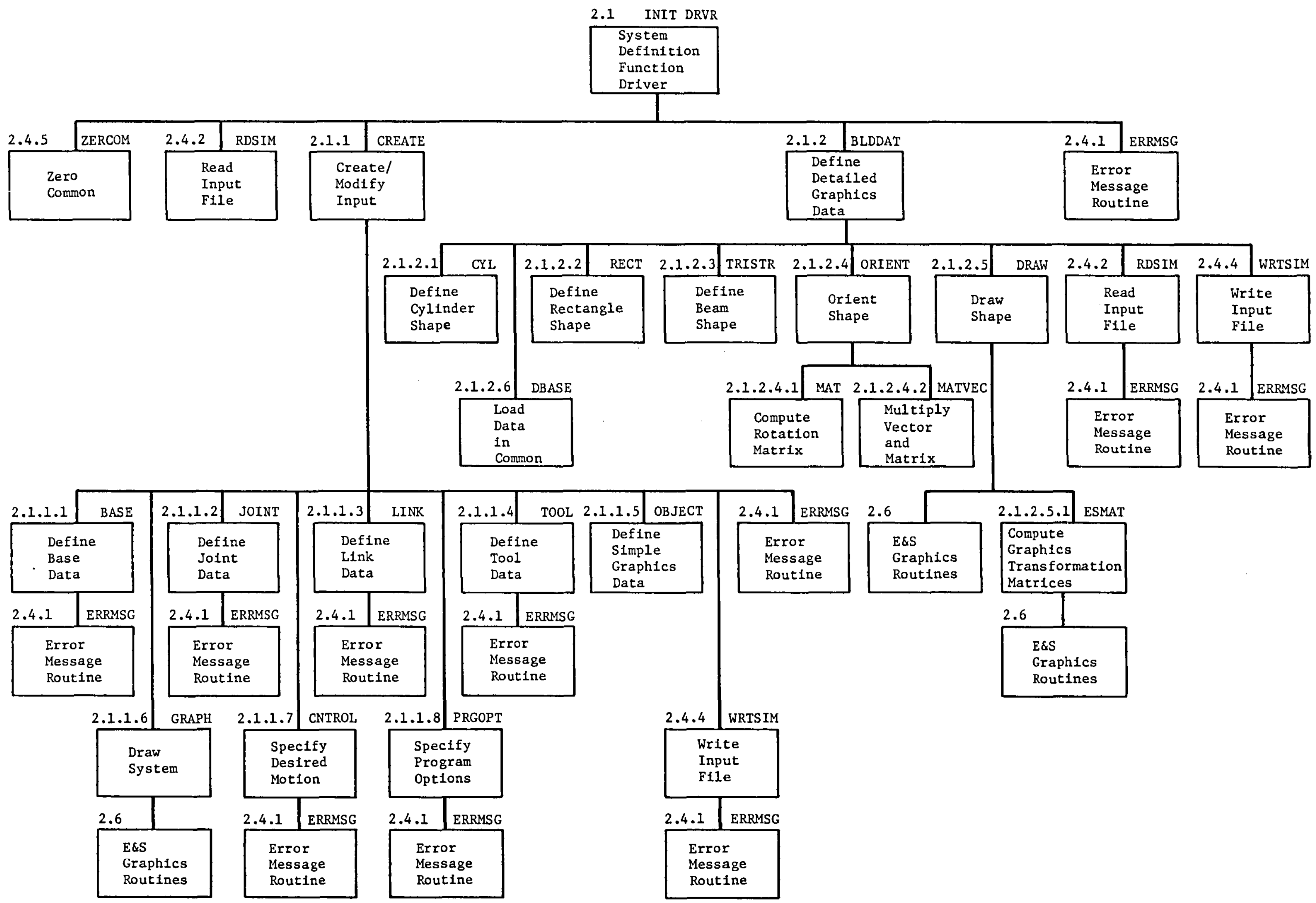


Figure A1-3 System Definition Function Hierarchy Diagram

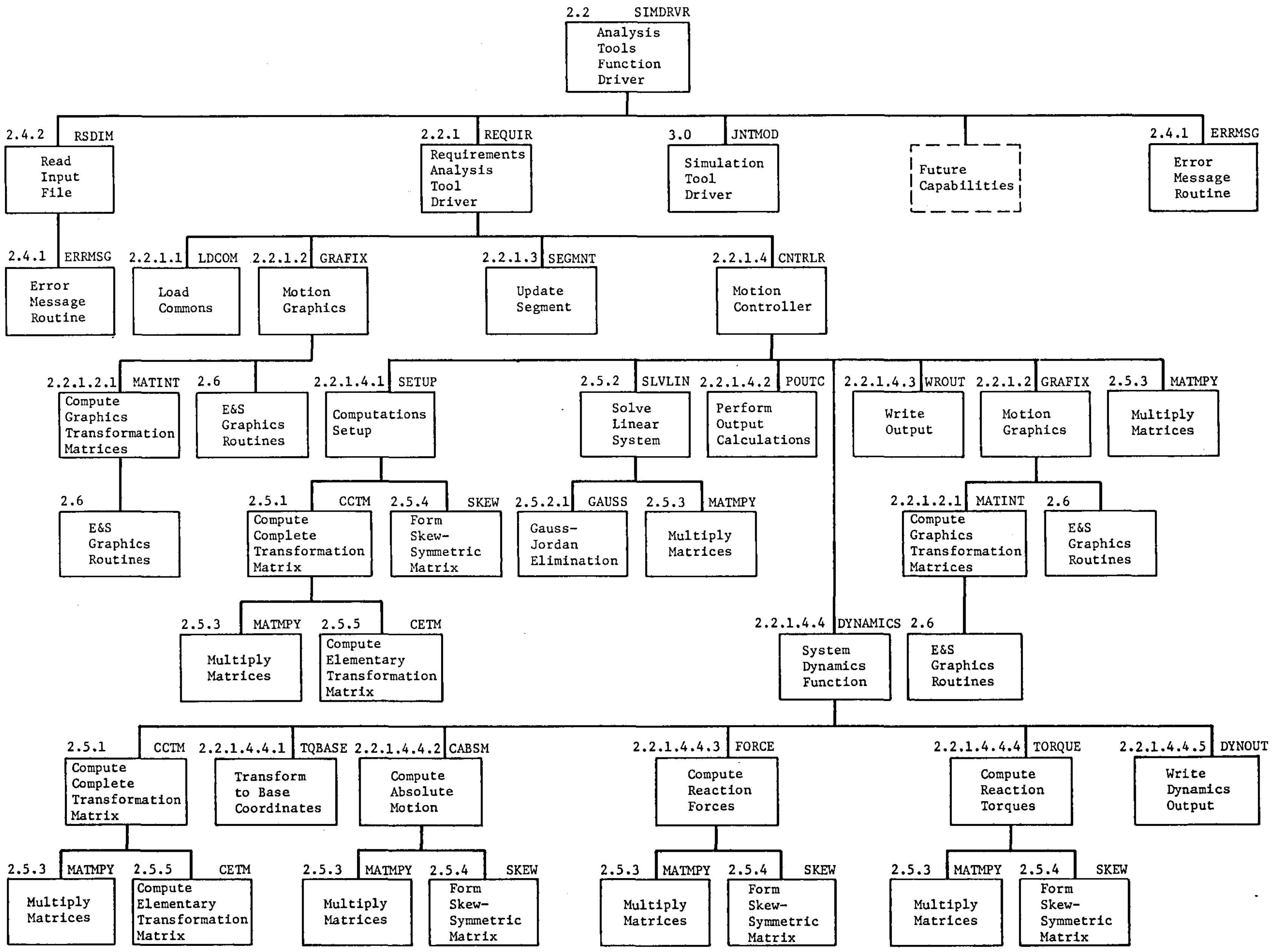


Figure A1-4 Analysis Tools Function Hierarchy Diagram

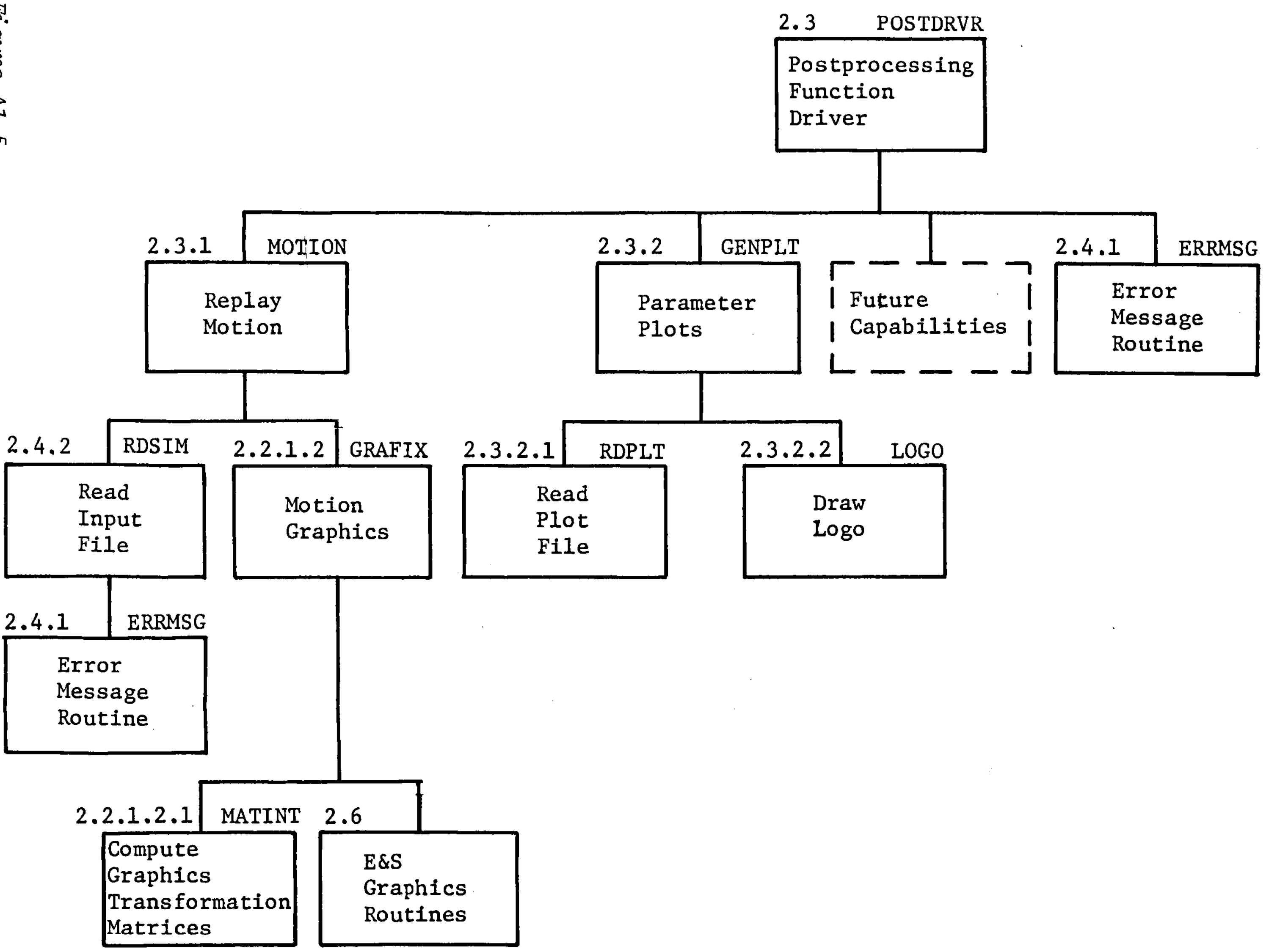


Figure A1-5 Postprocessing Function Hierarchy Diagram

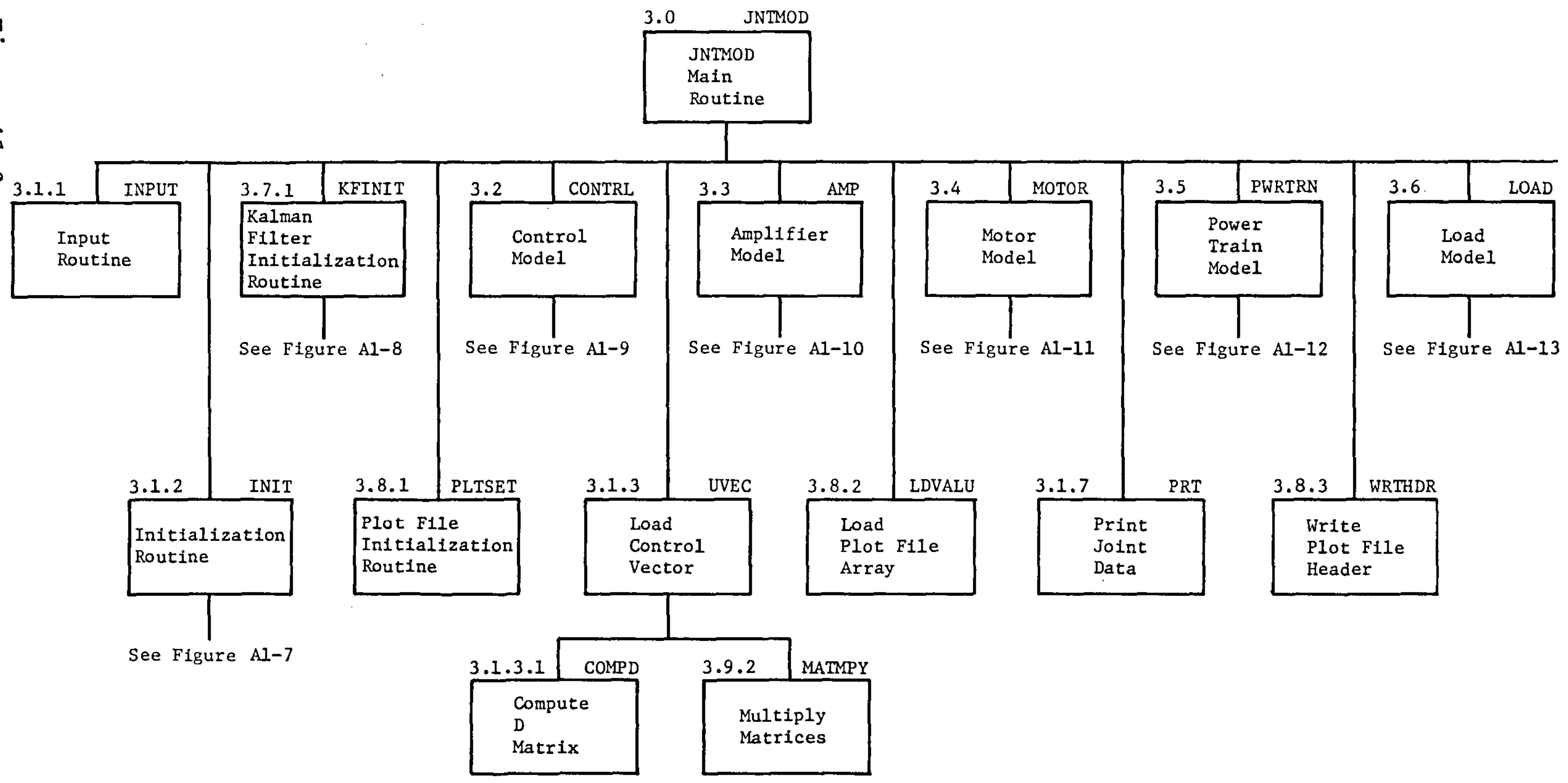


Figure A1-6 JNTMOD Program Hierarchy Diagram

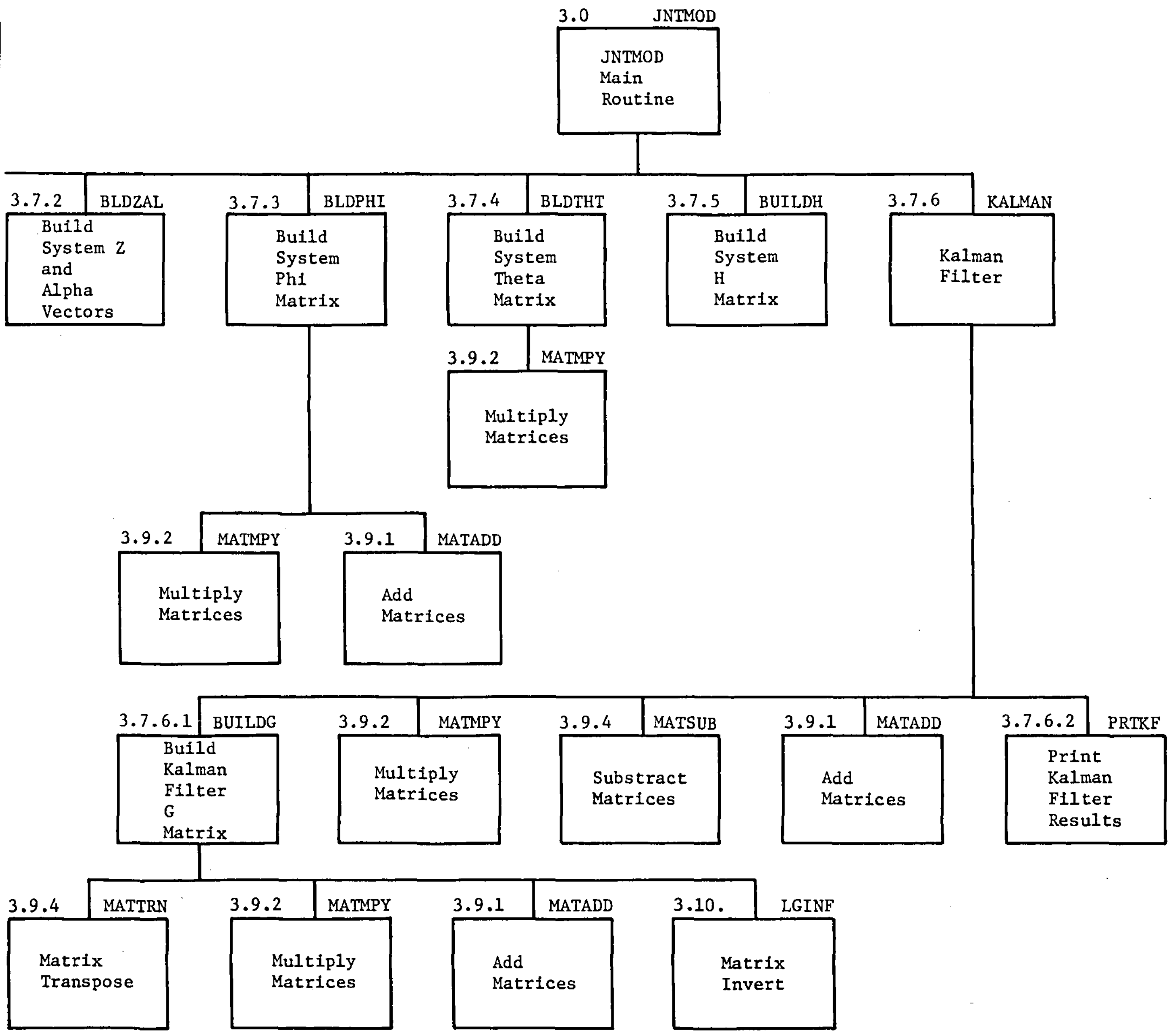


Figure A1-6 (concl)

Figure A1-6 (concl)

Figure A1-6 (contd)

Figure A1-7

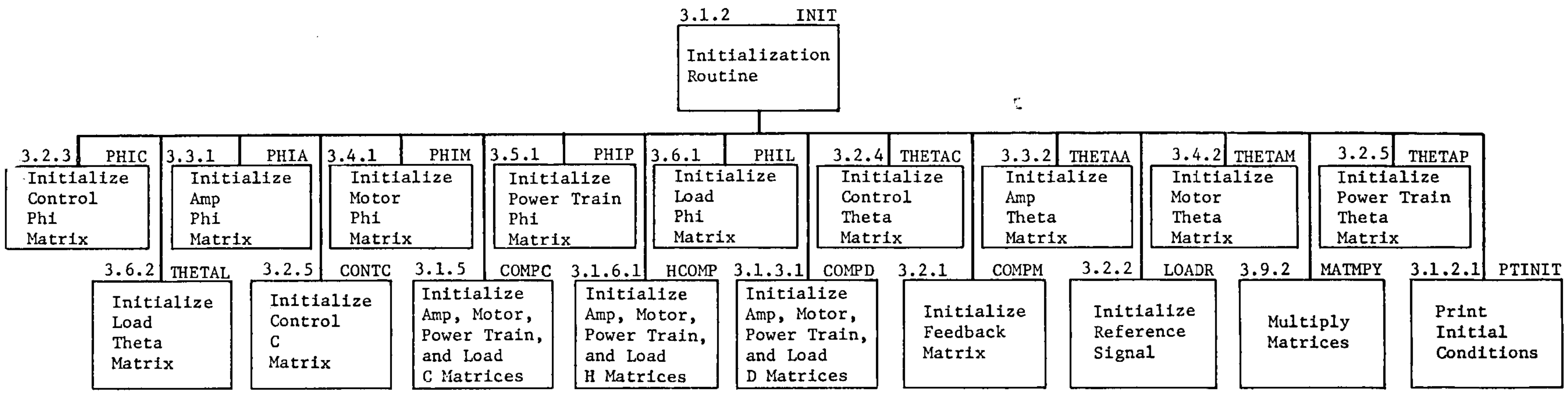

3.1.2 INIT Initialization Routine
3.2.3 PHIC Initialize Control Phi Matrix
3.3.1 PHIA Initialize Amp Phi Matrix
3.4.1 PHIM Initialize Motor Phi Matrix
3.5.1 PHIP Initialize Power Train Phi Matrix
3.6.1 PHIL Initialize Load Phi Matrix
3.2.4 THETAC Initialize Control Theta Matrix
3.3.2 THETAA Initialize Amp Theta Matrix
3.4.2 THETAM Initialize Motor Theta Matrix
3.2.5 THETAP Initialize Power Train Theta Matrix
3.6.2 THETAL Initialize Load Theta Matrix
3.2.5 CONTC Initialize Control C Matrix
3.1.5 COMPC Initialize Amp, Motor, Power Train, and Load C Matrices
3.1.6.1 HCOMP Initialize Amp, Motor, Power Train, and Load H Matrices
3.1.3.1 COMPD Initialize Amp, Motor, Power Train, and Load D Matrices
3.2.1 COMPM Initialize Feedback Matrix
3.2.2 LOADR Initialize Reference Signal
3.9.2 MATMPY Multiply Matrices
3.1.2.1 PTINIT Print Initial Conditions

Figure A1-7 *Initialization Hierarchy Diagram*

Figure A1-7

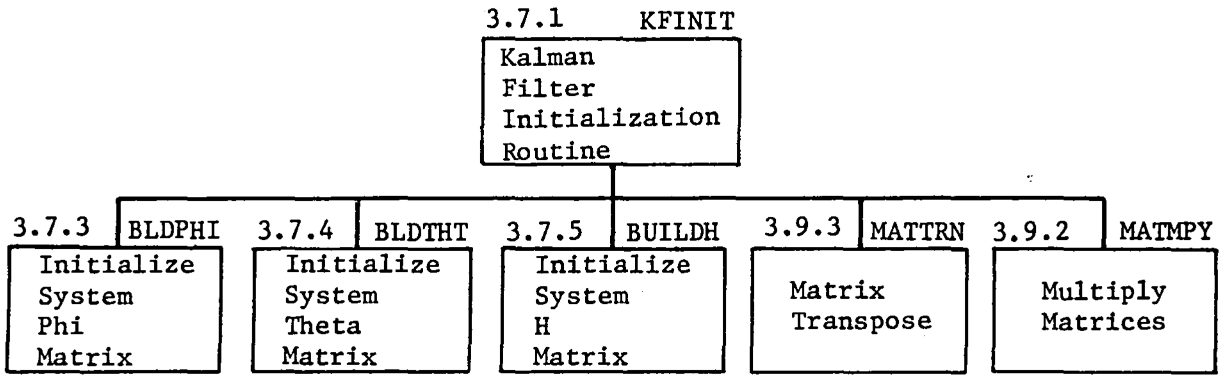

3.7.1 KFINIT
Kalman Filter Initialization Routine
3.7.3 BLDPHI
Initialize System Phi Matrix
3.7.4 BLDTHT
Initialize System Theta Matrix
3.7.5 BUILDH
Initialize System H Matrix
3.9.3 MATTRN
Matrix Transpose
3.9.2 MATMPY
Multiply Matrices

Figure A1-8 Kalman Filter Initialization Hierarchy Diagram

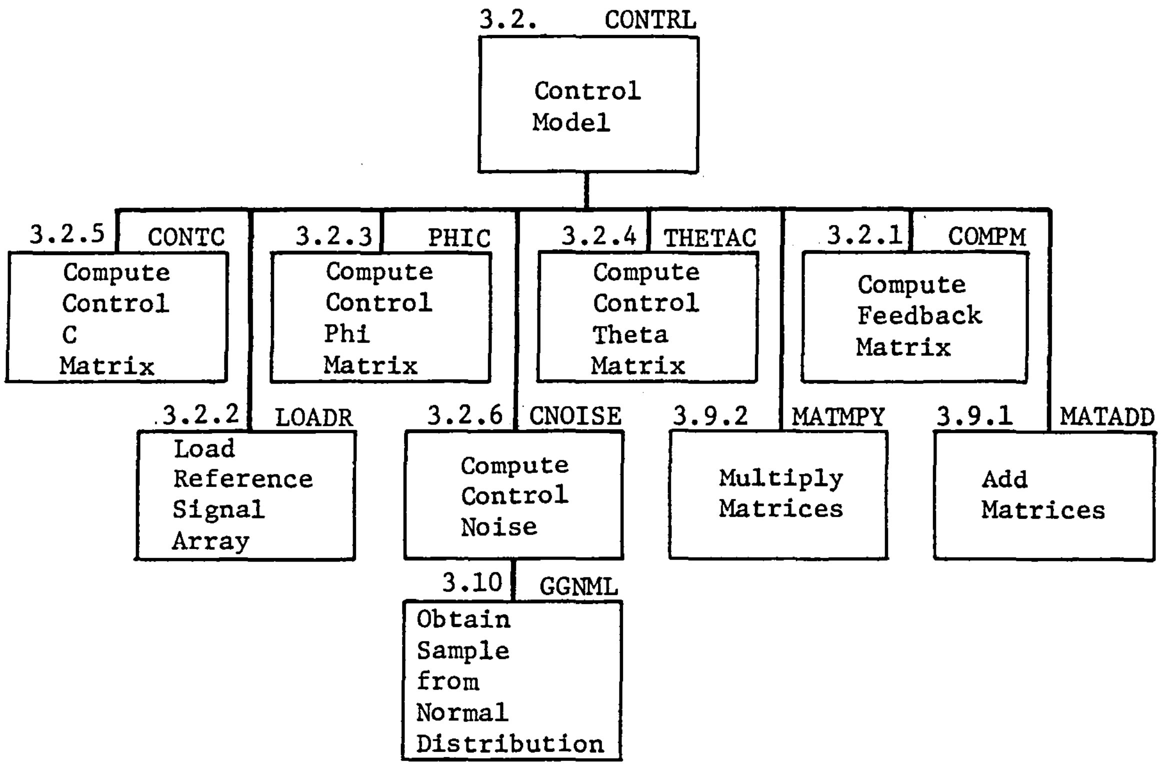


Figure A1-9 Control Model Hierarchy Diagram

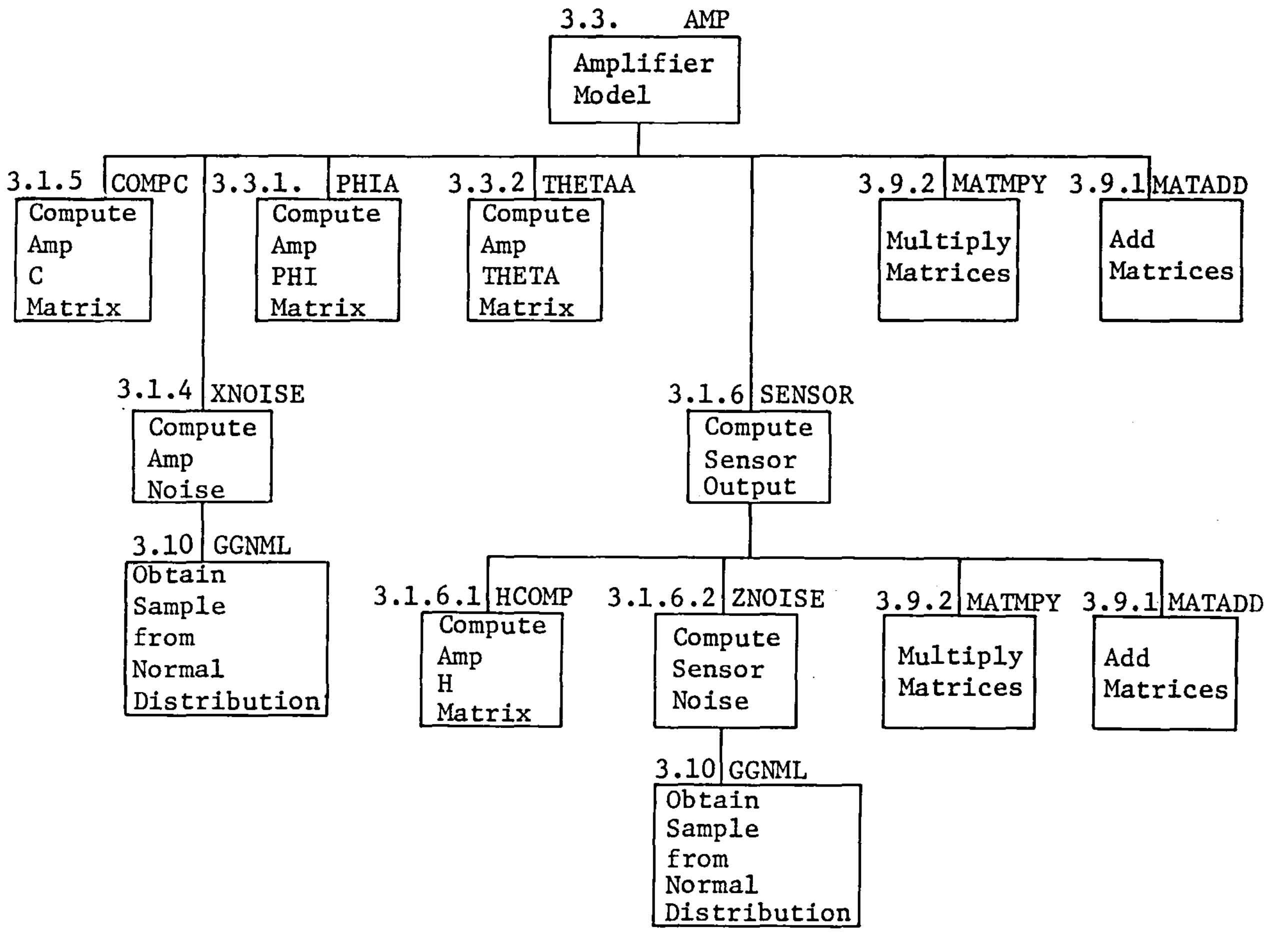


Figure A1-10 Amplifier Model Hierarchy Diagram

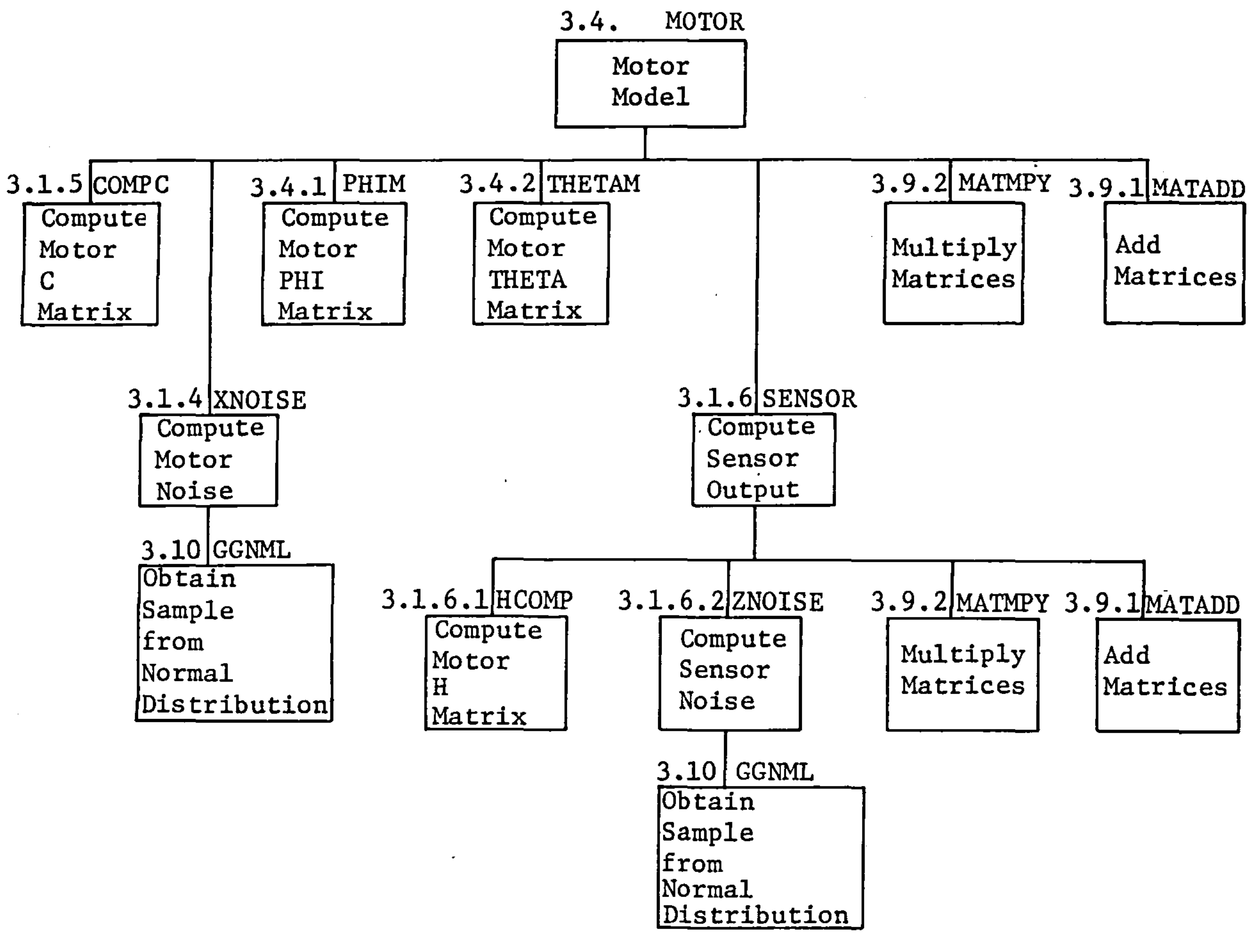


Figure A1-11 Motor Model Hierarchy Diagram

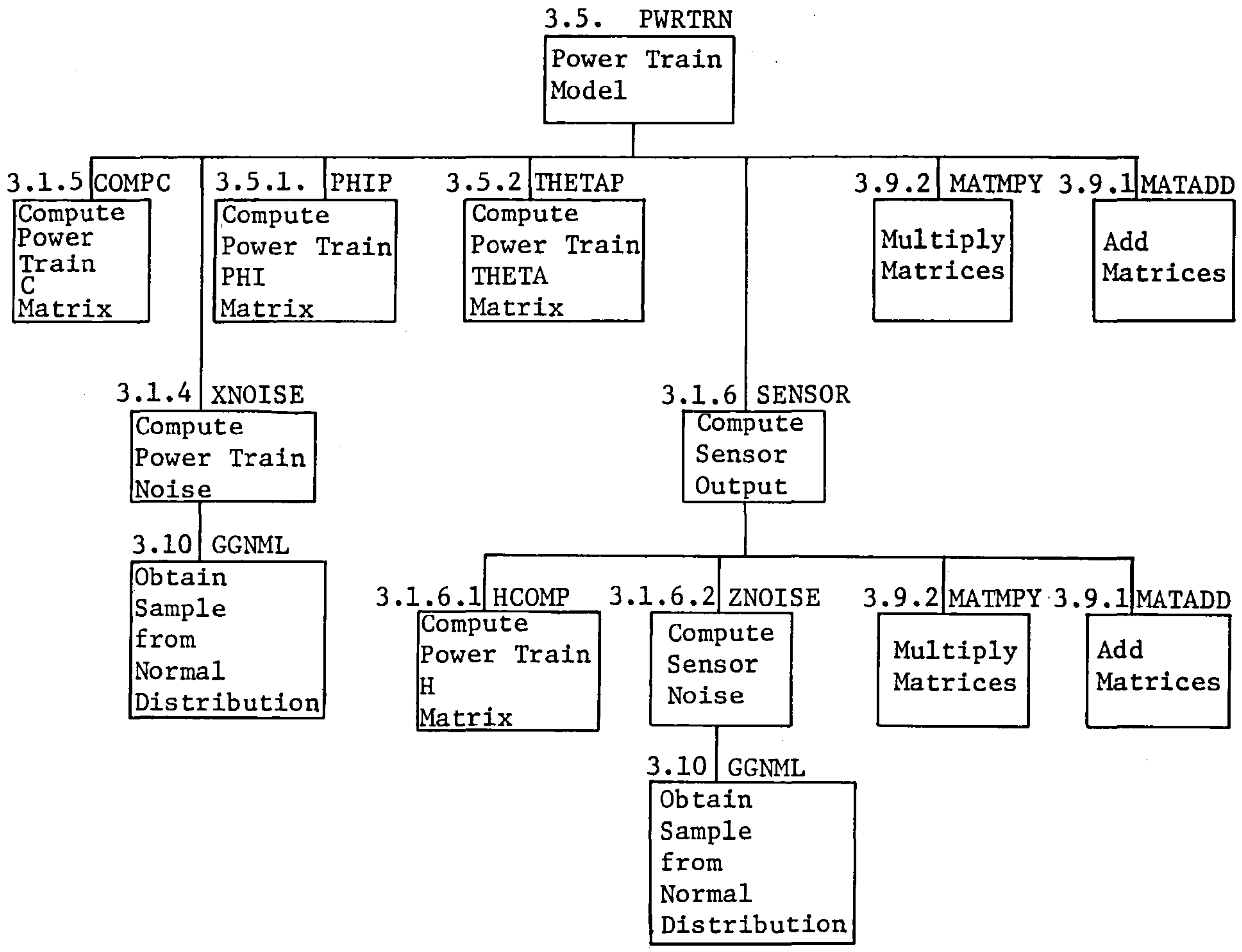


Figure A1-12 Power Train Model Hierarchy Diagram

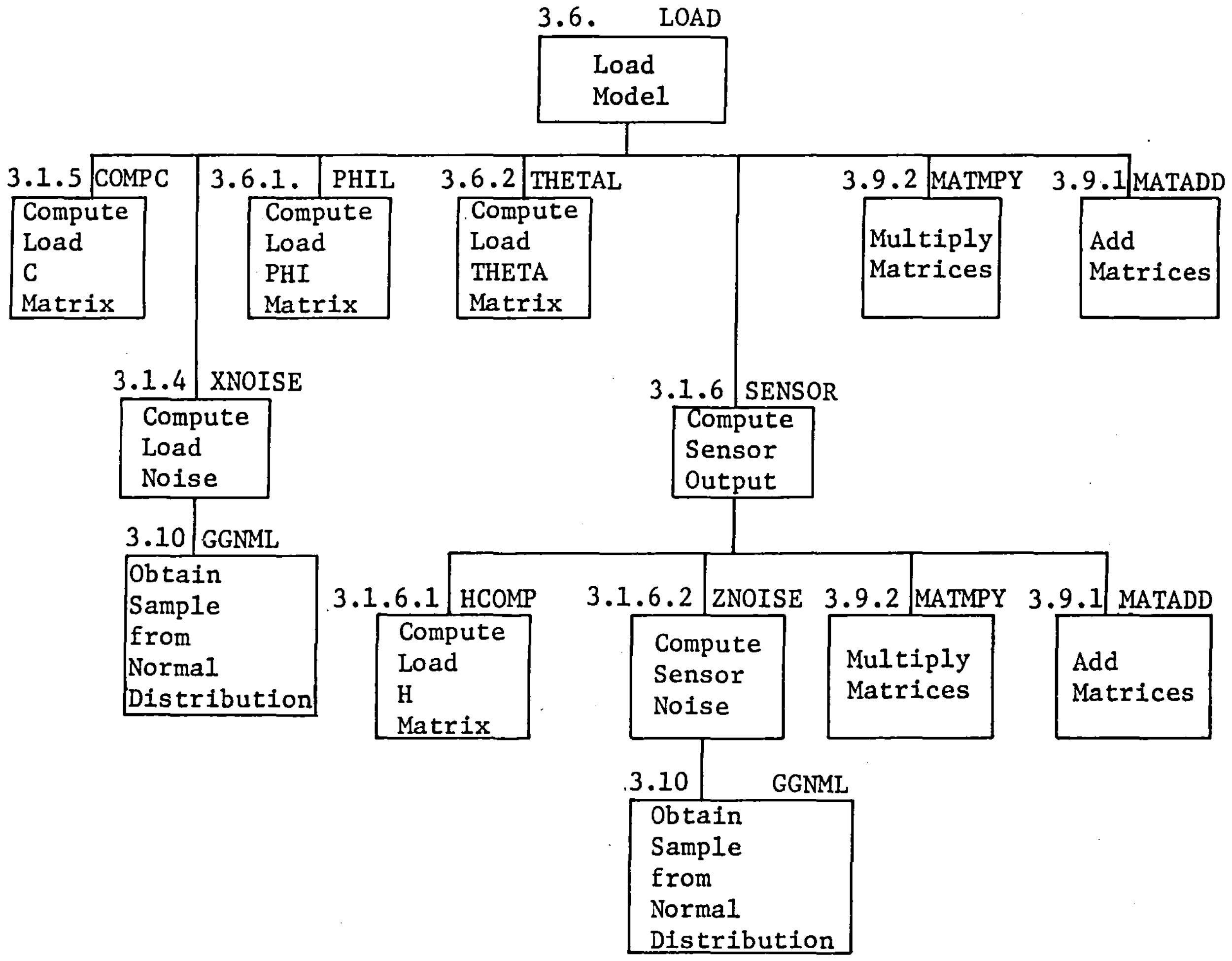


Figure A1-13 Load Model Hierarchy Diagram

1.3 VCLR FORMAT

VCLR diagrams present program logic flow that is compatible with structured programming. The use of VCLR diagrams offers many advantages over the use of flow charts:

1) Only the standard constructs are used;

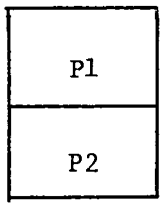
2) The total scope and impact of the logic can be seen and easily understood;

3) No extraneous symbols, connections, or notations are used.

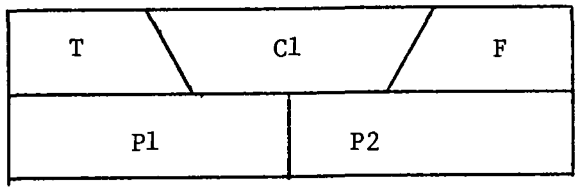
VCLR provides visible control logic representation, which is a picture of a software design. It enables software engineers to express their thinking visually and stresses the control logic of the design.

Standard constructs in visible control logic representations are the same as those for pseudo-code: SEQUENCE, IFTHENELSE, DOWHILE, DOUNTIL, and DOCASE; only the representations differ.

SEQUENCE - A SEQUENCE is simply one standard construct or one single statement followed by another. If P1 and P2 are standard constructs or single statements, the sequence would appear in a visible control logic representation as:



IFTHENELSE - IFTHENELSE consists of a true/false test and a path for each state. The true path appears on the left side, under the "T." One of the paths may be a "do nothing" or "NULL" path. One or both paths must consist of a standard construct or of a single statement. If "C1" is the condition being tested, "P1" is the true path, and "P2" is the false path, the IFTHENELSE construct would be written as:



DOWHILE - The DOWHILE is a loop with these characteristics:

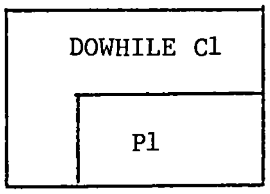
a) The counter or other item to be "incremented" is initialized before entering the loop.

b) The test is performed at the beginning of the loop. The conditions that must exist for the loop to be executed are the conditions that appear in the DOWHILE test.

c) The item to be executed must be a standard construct or a single statement.

d) The counter is incremented or other increment-like action is generally taken (e.g., another line is read) at the end of the loop.

If "C1" is the condition that must exist for the loop to be executed, and "P1" is a standard construct or single statement, the DOWHILE would be written as follows:



DOUNTIL - The DOUNTIL is a loop with these characteristics:

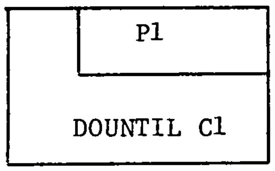
a) The counter or other item to be "incremented" is initialized before entering the loop.

b) The test is performed at the end of the loop. The conditions that must exist to exit from the loops are those that appear in the DOUNTIL test.

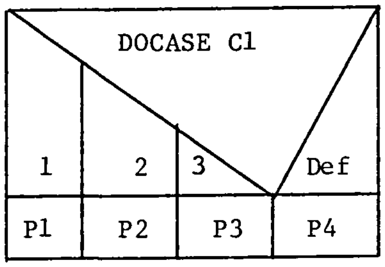
c) The item to be executed must be a standard construct or a **single** statement.

d) The counter is incremented or other increment-like action is generally taken (e.g., another line is read) at the beginning of the loop.

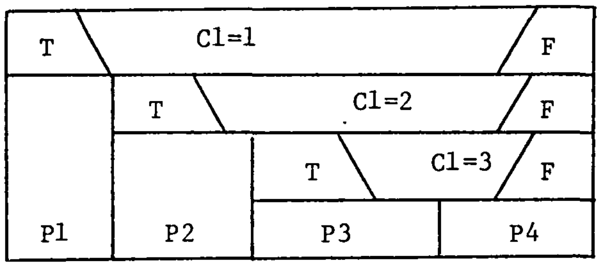
If "Cl" is the condition that must exist to exit from the loop and "Pl" is a standard construct or single statement, the DOUNTIL would be written as follows:



DOCASE - The DOCASE construct is for executing a different set of statements for each of several different values of a variable. If "Cl" is the variable being tested and if "Cl" may have values of 1, 2, or 3, the construct appears as follows:



Example A



Example B

Example A is equivalent to the nested IFTHENELSE form shown in B.

2.0 ROBSIM - EXECUTIVE PROGRAM

The executive routine controls the program execution through an interactive user prompt for the program function desired. Execution of the requested function is accomplished through a subroutine call to the appropriate function driver. The three program functions and the associated drivers are:

1) System definition (INITDRVR);

2) Analysis tools (SIMDRVR);

3) Postprocessing (POSTDRVR).

The System Definition function handles user input of system parameters and creates a disk file to be used as input to the Analysis Tools and Postprocessing functions. The Analysis Tools function handles the computational requirements of the ROBSIM program. The Postprocessing function allows for more detailed study of the results of the Analysis Tools function execution. Upon completion of the requested function execution, control is returned to the program executive. The program function prompt is then reissued to allow the user to either request another program function execution or request program termination.

Nonrecoverable errors encountered within any function return control to the executive program for display of the appropriate error message through a call to subroutine ERRMSG. Following a nonrecoverable error, the user may elect to terminate the program or reissue the program function prompt and attempt further program execution.

Figure A2-1 is the VCLR for the ROBSIM executive program.

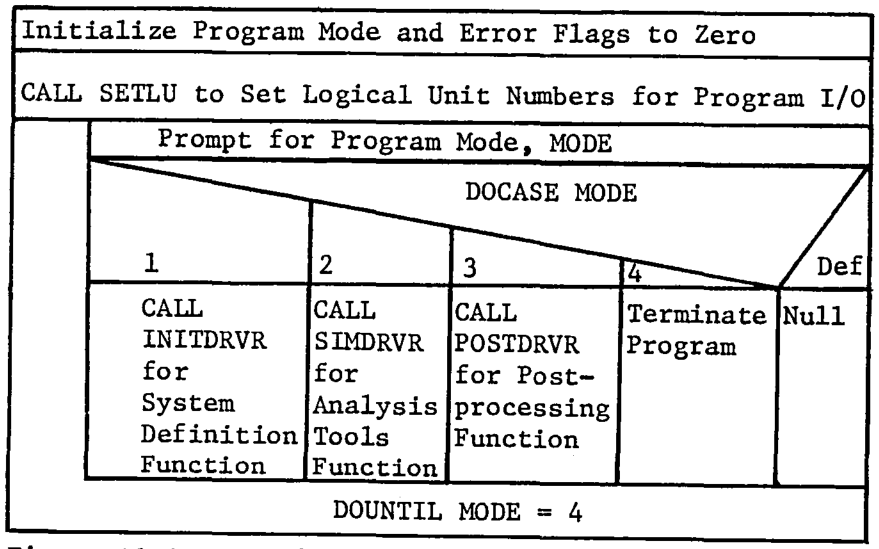

Initialize Program Mode and Error Flags to Zero
CALL SETLU to Set Logical Unit Numbers for Program I/O
Prompt for Program Mode, MODE
DOCASE MODE
1
2
3
4
Def
CALL INITDRVR for System Definition Function
CALL SIMDRVR for Analysis Tools Function
CALL POSTDRVR for Post-processing Function
Terminate Program
Null
DOUNTIL MODE = 4

Figure A2-1 VCLR for ROBSIM Executive Program

2.1 SYSTEM DEFINITION FUNCTION DRIVER (INITDRVR)

The System Definition function driver operates in an interactive mode and prompts the user for the system definition option desired. Valid options are:

1) Create a new basic data file;

2) Modify an existing basic data file;

3) Specify detailed environment geometry;

4) Specify detailed system geometry;

5) Return to the ROBSIM executive.

Option 1 provides for the input of data describing a robotic system not previously studied. All data required to describe the system must be input through terminal responses to interactive prompts issued by various routines within the System Definition function. The result of executing Option 1 will be a disk file containing all data input describing the robotic system. No data describing the geometry of the environment are requested within the prompts of Option 1. The data used to describe the geometry of the robotic system for graphics display will consist of simple cylinder representations. The simple cylinder representation was chosen for ease of data point computation, ease of modification, and acceptability of use as a coarse representation of most robotic system components.

Option 2 provides for the modification of an existing data file previously created by the System Definition function. Through interactive prompts issued by various routines within the System Definition function, the user selects the data to be modified. As in Option 1, geometric data describing the environment are not input within Option 2. The use of simple cylinder representations for the robotic system components allows the addition and deletion of links for quick study of various system configurations. Option 2 may be selected for modification of an existing data file that contains detailed geometric data describing the robotic system. However, modifications should be limited to data not pertaining to the system geometry or configuration of joints and links. Modifications in these areas will destroy the detailed data and replace it with simple cylinder data.

Option 3 allows the user to describe the geometry of the environment for graphics display. The data describing the environment are built up of components that are simple three-dimensional shapes. A data file generated with Option 1 or 2 must exist prior to selection of Option 3.

Option 4 allows the user to specify a detailed geometric representation of the robotic system used in Option 1 and 2. A data file generated with Option 1 or 2 must exist prior to selecting Option 4. Option 4 should be used only when the system configuration is stable because changes in the configuration require redefinition of the detailed geometry of the entire system.

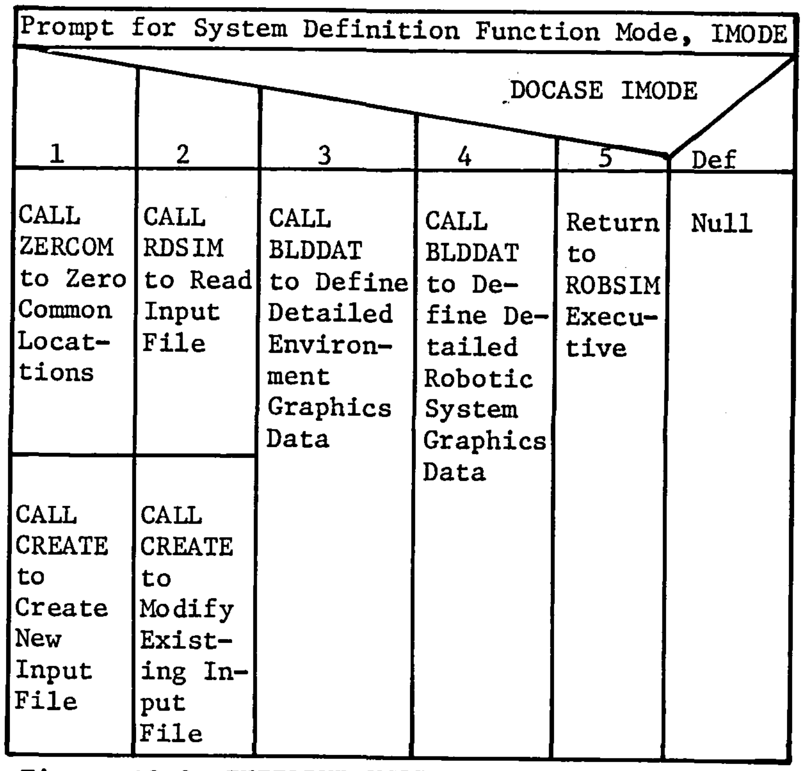
If Option 1 is requested, subroutine ZERCOM is called to zero all COMMON locations used for data storage during execution of the System Definition function. Subroutine CREATE is then called to control the program flow and the creation of the data file.

If Option 2 is requested, subroutine RDSIM is called to read the existing data file and load the data into the appropriate COMMON blocks. Subroutine CREATE is then called to control the program flow and the modifications of data as required.

If either Option 3 or 4 is requested, subroutine BLDDAT is called to control the input of the detailed geometric data.

Recoverable errors encountered within subroutine INITDRVR cause an error message to be written through a call to subroutine ERRMSG followed by appropriate recovery action. Nonrecoverable errors encountered within routines called by INITDRVR cause return of control to the ROBSIM executive program.

Figure A2-2 is the VCLR for subroutine INITDRVR.



Prompt for System Definition Function Mode, IMODE

DOCASE IMODE

1	2	3	4	5	Def
CALL ZERCOM to Zero Common Locat-tions	CALL RDSIM to Read Input File	CALL BLDDAT to Define Detailed Environ-ment Graphics Data	CALL BLDDAT to De-fine De-tailed Robotic System Graphics Data	Return to ROBSIM Execu-tive	Null
CALL CREATE to Create New Input File	CALL CREATE to Modify Exist-ing In-put File				

Figure A2-2 INITDRVR VCLR

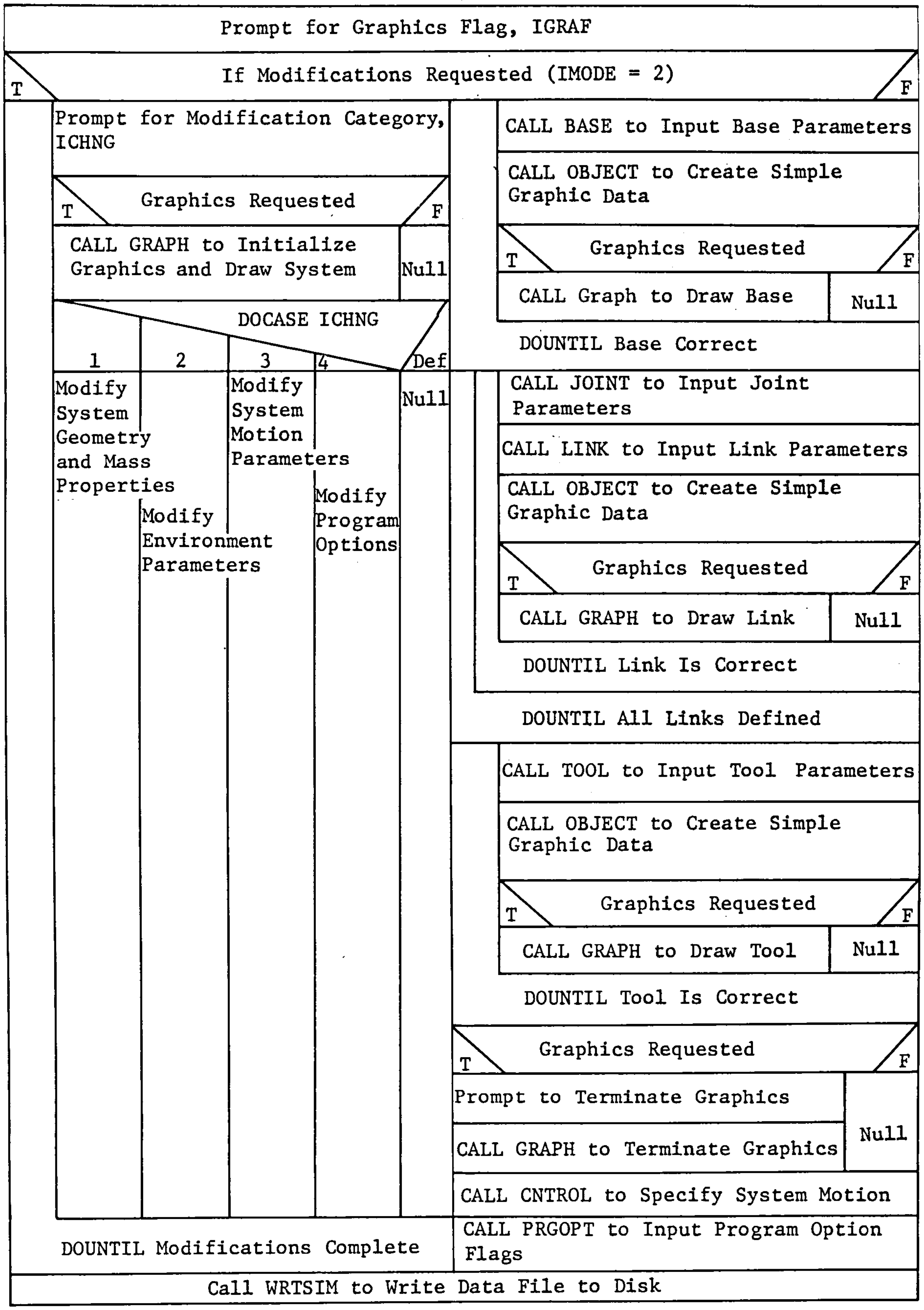
2.1.1 Create/Modify Data File (CREATE)

Subroutine CREATE controls the program flow during the creation or modification of the input data file under the System Definition function. Upon entering subroutine CREATE, the user turns on or off via interactive prompt the use of the graphics package. Subroutine CREATE is called in one of two modes, creation of a new data file, or modification of an existing file. In the create mode, the program logic flows sequentially through subroutine CREATE requiring input for all possible data. In the modify mode, the user is prompted to specify which data are to be changed. Program control is then sent directly to the routine responsible for those data.

The robotic system geometry and mass properties data are input through subroutines BASE, JOINT, LINK, and TOOL. The location orientation and size of the system base are defined in subroutine BASE. The location, orientation, size, and mass properties of each joint/link combination are defined in subroutines JOINT and LINK. Subroutine TOOL defines the location and orientation of the end effector. For the base, each link, and the end effector, subroutine OBJECT is called to generate the simple cylinder data for graphics representations. If graphics is requested, each system component is displayed as the data are input. In either the create or modify modes, the user may iterate on a particular component until it is correct before proceeding. Subroutine CNTROL allows the user to define a particular motion sequence for the robotic system. The program start time, stop time, time step, and other program option flags are set in subroutine PRGOPT. When all input is complete, subroutine WRTSIM is called to write the data file to disk.

Recoverable errors encountered within subroutine CREATE cause an error message to be written through a call to subroutine ERRMSG followed by appropriate recovery action. Nonrecoverable errors encountered within routines called by CREATE cause return of program control through the System Definition function routines back to the ROBSIM executive program.

Figure A2-3 is the VCLR for subroutine CREATE.



```
Prompt for Graphics Flag, IGRAF
If Modifications Requested (IMODE = 2)
T:
    Prompt for Modification Category, ICHNG
    Graphics Requested
    T:
        CALL GRAPH to Initialize Graphics and Draw System
    F:
        Null
    DOCASE ICHNG
    1:
        Modify System Geometry and Mass Properties
    2:
        Modify Environment Parameters
    3:
        Modify System Motion Parameters
    4:
        Modify Program Options
    Def:
        Null
    DOUNTIL Modifications Complete
F:
    CALL BASE to Input Base Parameters
    CALL OBJECT to Create Simple Graphic Data
    Graphics Requested
    T:
        CALL Graph to Draw Base
    F:
        Null
    DOUNTIL Base Correct
            CALL JOINT to Input Joint Parameters
            CALL LINK to Input Link Parameters
            CALL OBJECT to Create Simple Graphic Data
            Graphics Requested
            T:
                CALL GRAPH to Draw Link
            F:
                Null
        DOUNTIL Link Is Correct
    DOUNTIL All Links Defined
        CALL TOOL to Input Tool Parameters
        CALL OBJECT to Create Simple Graphic Data
        Graphics Requested
        T:
            CALL GRAPH to Draw Tool
        F:
            Null
    DOUNTIL Tool Is Correct
    Graphics Requested
    T:
        Prompt to Terminate Graphics
        CALL GRAPH to Terminate Graphics
    F:
        Null
    CALL CNTROL to Specify System Motion
    CALL PRGOPT to Input Program Option Flags
Call WRTSIM to Write Data File to Disk
```

Figure A2-3 CREATE VCLR

2.1.1.1 Define Base Data (BASE) - Subroutine BASE interactively prompts the user for location, orientation, and size data for the robotic system base. The calling argument MOD specifies whether subroutine BASE was called in the create mode or the modification mode. In the create mode, the user is prompted for all possible data. In the modification mode, the user is prompted to specify which data category is to be changed. The user is then prompted only for the requested data. Following input of the requested data, the modification category prompt is repeated allowing modification of other base data. Upon completion of all changes, the user requests termination of modifications and control is returned to the calling program.

The location of the base is specified as the Cartesian coordinates of the origin of the base coordinate system given in terms of the "world" coordinate system. Using the graphics screen as a reference, the "world" coordinate system is defined with origin at the center of the screen, x-axis positive to the right, y-axis positive upward, and z-axis positive out of the screen.

The orientation of the base is specified as a rotation sequence and corresponding set of rotation angles. This rotation sequence and the associated rotation angles relate the base coordinate system axes to the "world" coordinate system axes. Performing the rotation sequence on the "world" system produces the base system. The base system should be oriented so that the x-axis points toward the first joint in the robotic system. Orientation of the y-z plane is arbitrary.

The size parameters the user is prompted for in subroutine BASE are used by subroutine OBJECT to compute the simple cylinder representation for graphics. The base size is specified as the x-axis end points, the base radius, and the number of sides desired for the cylinder.

A recoverable error encountered within subroutine BASE causes an error message to be written through a call to subroutine ERRMSG followed by appropriate recovery action. There are no nonrecoverable error conditions in subroutine BASE.

Figure A2-4 is the VCLR for subroutine BASE.

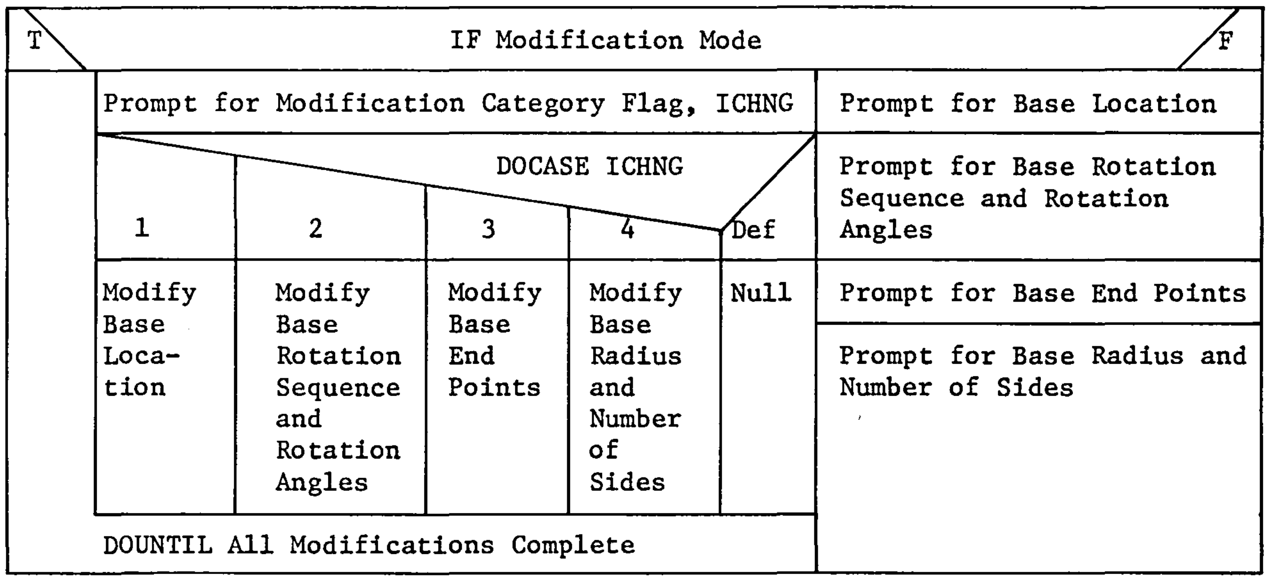

T
IF Modification Mode
F
Prompt for Modification Category Flag, ICHNG
DOCASE ICHNG
1
2
3
4
Def
Modify Base Loca- tion
Modify Base Rotation Sequence and Rotation Angles
Modify Base End Points
Modify Base Radius and Number of Sides
Null
DOUNTIL All Modifications Complete
Prompt for Base Location
Prompt for Base Rotation Sequence and Rotation Angles
Prompt for Base End Points
Prompt for Base Radius and Number of Sides

Figure A2-4 BASE VCLR

2.1.1.2 Define Joint Data (JOINT) - Subroutine JOINT interactively prompts the user for the type, location, orientation, and initial state of each joint in the robotic system. The calling argument MOD specifies whether subroutine JOINT was called in the create mode or the modification mode. In the create mode, the user is prompted for all possible data. In the modification mode, the user is prompted to specify which data category is to be changed. The user is then prompted only for the requested data. Following input of the requested data, the modification category prompt is repeated allowing modification of other joint data. Upon completion of all changes, the user requests termination of modifications, and control is returned to the calling program.

The joint type is specified as either hinge, swivel, or sliding. Hinge joints rotate about the joint y axis. Swivel joints rotate about the joint x axis. Sliding joints move along the joint x axis.

The location of the joint is specified as the Cartesian coordinates of the origin of the joint coordinate system given in terms of the coordinate system of the previous joint (or base if the current joint is joint 1). Note that the x axis of a joint coordinate system is directed along the centerline of the link between that joint and the next joint (or end effector if the current joint is the final joint in the system). The orientation of the y-z plane is user-defined but is usually determined by the joint type (i.e., orientation of the axis of rotation).

The orientation of the joint is specified as a rotation sequence and corresponding set of rotation angles that define the orientation of the current joint coordinate system with respect to the coordinate system of the previous joint (or the base if the current joint is joint 1). The joint-axis orientation conventions were discussed in the preceding paragraphs.

The initial state of each joint is specified as the initial joint angle for hinge or swivel joints and the initial length for sliding joints.

A recoverable error encountered within subroutine JOINT causes an error message to be printed through a call to subroutine ERRMSG. Appropriate recovery action is then taken. There are no nonrecoverable error conditions in subroutine JOINT.

Figure A2-5 is the VCLR for subroutine JOINT.

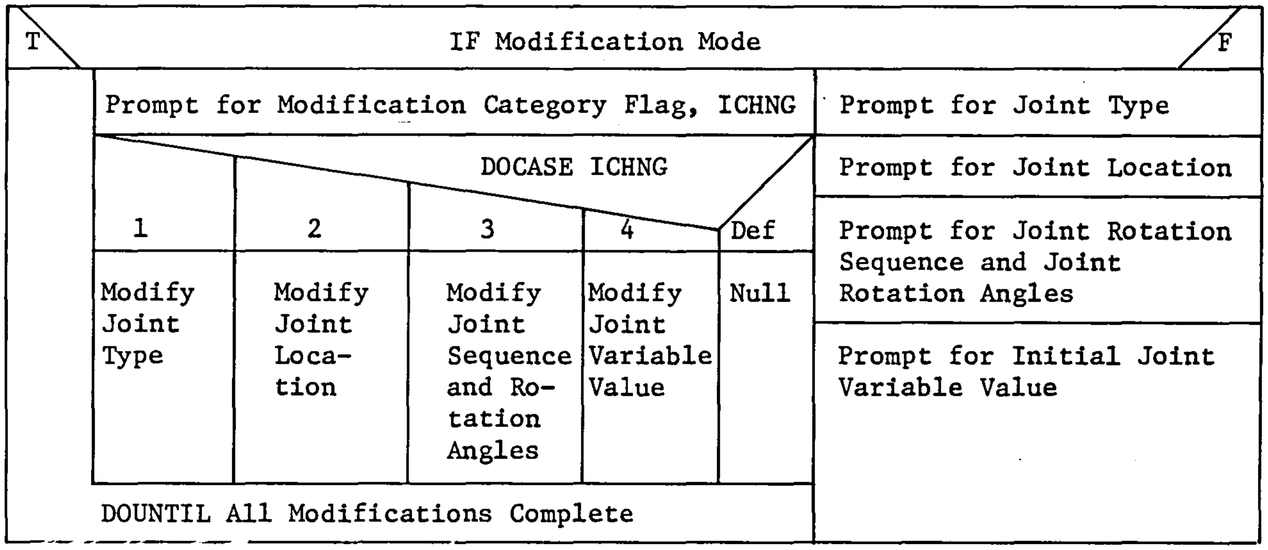

T
IF Modification Mode
F
Prompt for Modification Category Flag, ICHNG
DOCASE ICHNG
1
2
3
4
Def
Modify Joint Type
Modify Joint Loca-tion
Modify Joint Sequence and Ro-tation Angles
Modify Joint Variable Value
Null
DOUNTIL All Modifications Complete
Prompt for Joint Type
Prompt for Joint Location
Prompt for Joint Rotation Sequence and Joint Rotation Angles
Prompt for Initial Joint Variable Value

Figure A2-5 JOINT VCLR

2.1.1.3 Define Link Data (LINK) - Subroutine LINK interactively prompts the user for the size, location of the center of mass, the mass, and the inertia matrix of each link in the robotic system. The calling argument MOD specifies whether subroutine LINK was called in the create mode or the modification mode. In the create mode, the user is prompted for all possible data. In the modification mode, the user is prompted to specify which data category is to be changed. The user is then prompted only for the requested data. Following input of the requested data, the modification category prompt is repeated, allowing modification of other link data. Upon completion of all changes, the user requests termination of modifications, and control is returned to the calling program.

The size parameters the user is prompted for in subroutine LINK are used by subroutine OBJECT to compute the simple cylinder representation for graphics. The size of each link is specified as the x-axis end points, the link radius, and the number of sides desired for the cylinder.

The location of the center of mass of the link is specified as the Cartesian coordinates of the center of gravity (cg) in the coordinate system of the joint at the "base" end of the link. The location and orientation of that joint coordinate system were defined in a call to subroutine JOINT immediately preceding the current call to subroutine LINK.

The remaining link mass properties are specified by the link mass and the link inertia matrix. The inertia matrix is specified relative to the joint at the "base" end of the link.

A recoverable error encountered within subroutine LINK causes an error message to be printed through a call to subroutine ERRMSG. Appropriate recovery action is then taken. There are no nonrecoverable error conditions in subroutine LINK.

Figure A2-6 is the VCLR for subroutine LINK.

```
IF Modification Mode
T:
    Prompt for Modification Category Flag, ICHNG
    DOCASE ICHNG
        1:   Modify Link End Points
        2:   Modify Link Radius
        3:   Modify Number of Sides for Link
        4:   Modify Location of Center of Mass
        5:   Modify Link Mass
        6:   Modify Link Inertia Matrix
        Def: Null
    DOUNTIL All Modifications Complete
F:
    Prompt for Link End Points
    Prompt for Link Radius
    Prompt for Number of Sides for Link
    Prompt for Location of Link Center of Mass
    Prompt for Link Mass
    Prompt for Link Inertia Matrix
```

Figure A2-6 LINK VCLR

2.1.1.4 Define Tool Data (TOOL) - Subroutine TOOL interactively prompts the user for the location and orientation of the tool (or end effector) of the robotic system. The calling argument MOD specifies whether subroutine TOOL was called in the create mode or the modification mode. In the create mode, the user is prompted for all possible data. In the modification mode, the user is prompted to specify which data category is to be changed. The user is then prompted only for the requested data. Following input of the requested data, the modification category prompt is repeated, allowing modification of other tool data. Upon completion of all changes, the user requests termination of modifications, and control is returned to the calling program.

The location of the tool is specified as the Cartesian coordinates of the origin of the tool coordinate system given in terms of the coordinate system of the final joint in the robotic system. The location and orientation of the final joint was specified by the last call to subroutine JOINT.

The orientation of the tool is specified as a rotation sequence and corresponding set of rotation angles that define the orientation of the tool coordinate system with respect to the coordinate system of the final joint.

A recoverable error encountered within subroutine TOOL causes an error message to be printed through a call to subroutine ERRMSG. Appropriate recovery action is then taken. There are no nonrecoverable error conditions in subroutine TOOL.

Figure A2-7 is the VCLR for subroutine TOOL.

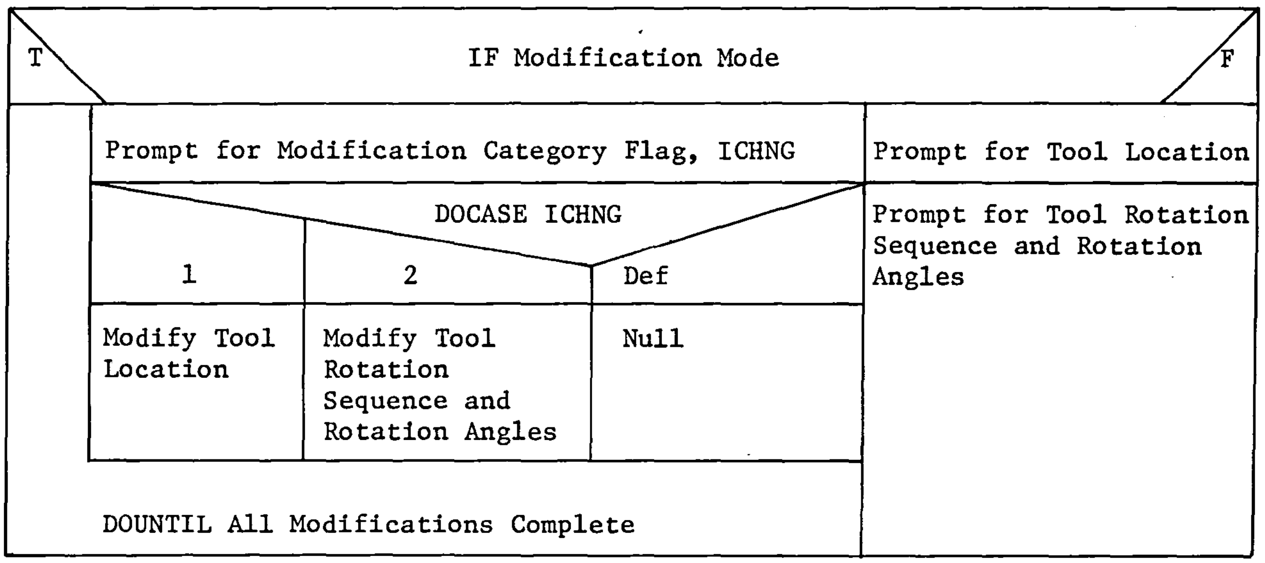

T
IF Modification Mode
F
Prompt for Modification Category Flag, ICHNG
Prompt for Tool Location
DOCASE ICHNG
1
2
Def
Prompt for Tool Rotation Sequence and Rotation Angles
Modify Tool Location
Modify Tool Rotation Sequence and Rotation Angles
Null
DOUNTIL All Modifications Complete

Figure A2-7 TOOL VCLR

2.1.1.5 Define Simple Graphic Representation (OBJECT) - Subroutine OBJECT creates simple cylinder graphic data used by the graphics package to draw the robotic system. The data created in subroutine OBJECT are stored in COMMON block IOBJ. The form of the data as stored in the common block is dictated by the requirements of the graphics routines. Data representing a right circular cylinder of the specified size are computed for each system component (the base and each link). For the tool (or end effector), data are computed to allow display of the tool coordinate system axes only.

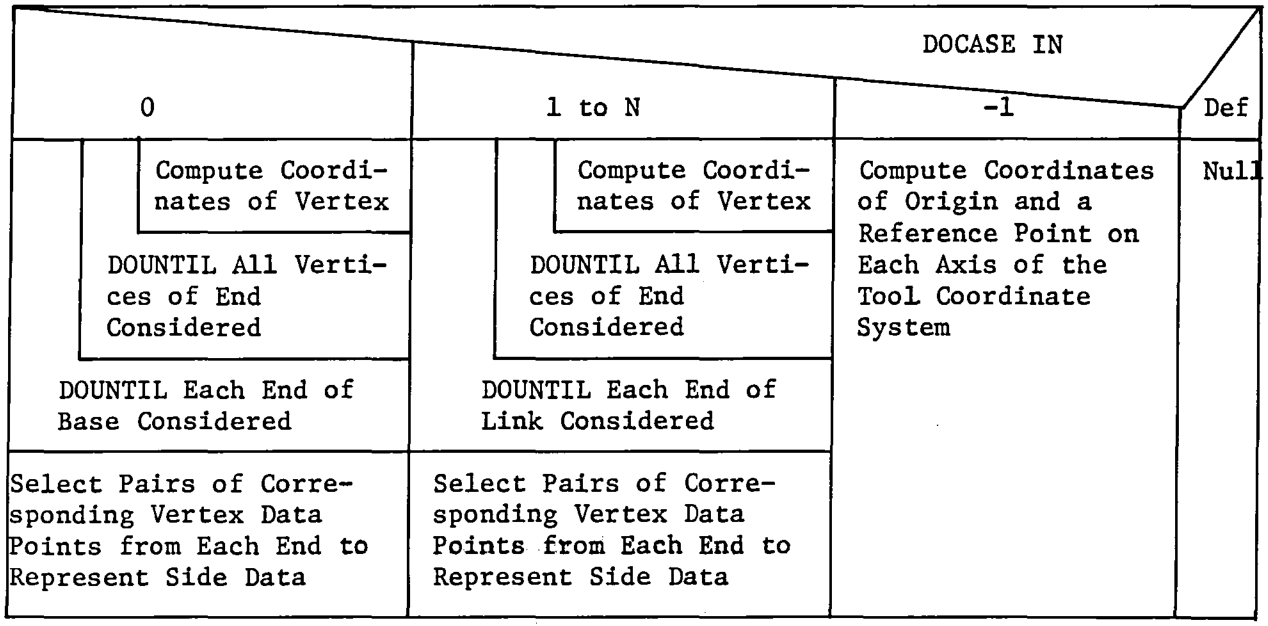
Two counter arrays are used in subroutine OBJECT and stored in common to keep track of the number of components and the starting location of each within the common block. These arrays are NUM and NSTRT respectively. These arrays are used by subroutine GRAPH to locate data in the common block for the various system components.

The simple cylinder representation used by subroutine OBJECT was chosen for ease of data point computation, ease of modification, and acceptability of use as a coarse representation of most robotic system components. The use of simple cylinder representations allows the addition and deletion of links for quick study of various system configurations.

The computation of the data points defining the cylinder for the base or each link is performed in two steps. First, the data defining the vertex points around the two end circles are computed. This is accomplished by computing the y and z coordinates around the x axis at one end of the cylinder. The coordinates for the other end of the cylinder are then specified by repeating the coordinates of the first end while replacing the x value with that of the second end. The second step in defining the data for the cylinder is to define the data required to represent the sides of the cylinder by connecting corresponding vertices in the two cylinder ends.

The computation of data points to define the tool coordinate system consists of specifying pairs of points from the origin to a specified distance out each axis. The distance used for the axis length is twice the radius of the final link in the system.

Figure A2-8 is the VCLR for subroutine OBJECT.



```
DOCASE IN
  0
    DOUNTIL Each End of Base Considered
      DOUNTIL All Vertices of End Considered
        Compute Coordinates of Vertex
    Select Pairs of Corresponding Vertex Data Points from Each End to Represent Side Data
  1 to N
    DOUNTIL Each End of Link Considered
      DOUNTIL All Vertices of End Considered
        Compute Coordinates of Vertex
    Select Pairs of Corresponding Vertex Data Points from Each End to Represent Side Data
  -1
    Compute Coordinates of Origin and a Reference Point on Each Axis of the Tool Coordinate System
  Def
    Null
```

Figure A2-8 OBJECT VCLR

2.1.1.6 System Definition Function Graphics (GRAPH) - Subroutine GRAPH provides the graphics capability in the System Definition function. Subroutine GRAPH displays the robotic system using the simple cylinder representation data computed by subroutine OBJECT. Subroutine GRAPH is called following definition of each system component (the base, each link, or the tool) and displays that component for user inspection. Capabilities exist for replacing modified components and for adding or deleting components. No provisions are made for displaying environment data within subroutine GRAPH.

Calling argument IFLAG specifies whether the base, a link, or the tool is to be displayed. The argument IFLAG also controls the initialization and termination of the graphics.

Creation and display of base data are controlled by subroutine CREATE through a sequence of calls to subroutines BASE, OBJECT, and GRAPH. If display of the base is selected, the graphics is initialized and the base is displayed in the proper position and orientation. Control is returned to subroutine CREATE where the user may elect to modify the base data through calls to subroutine BASE and OBJECT. If the base is modified, subroutine GRAPH is called to replace the current display with a display of the modified base data. The user may iterate on the base until satisfied before proceeding to definition of the system joints and links.

Creation and display of the data for each link are controlled by subroutine CREATE through a sequence of calls to subroutines JOINT, LINK, OBJECT, and GRAPH. If display of the link is selected, the new link is added to the display in the proper position and orientation. Control is returned to subroutine CREATE where the user may elect to modify the link data through calls to subroutines JOINT, LINK, and OBJECT. If the link is modified, subroutine GRAPH is called to replace the current link display with a display of the modified link data. The user may iterate on the link data until satisfied before proceeding to the next link or to the tool. The user is allowed to add or delete links even after the tool data have been defined and displayed.

Creation and display of the tool data are controlled by subroutine CREATE through a sequence of calls to subroutines TOOL, OBJECT, and GRAPH. If display of the tool is selected, the tool coordinate system is added to the display in the proper position and orientation. Control is then returned to subroutine CREATE where the user may elect to modify the tool data through calls to subroutines TOOL and OBJECT. If the tool data are modified, subroutine GRAPH is called to replace the current display of the tool data with a display of the modified tool data. The user may iterate on the tool data until satisfied before terminating the graphics display.

Subroutine GRAPH uses Evans and Sutherland graphics routines designed for use with the Evans and Sutherland Multi-Picture System.

Figure A2-9 is the VCLR for subroutine GRAPH.

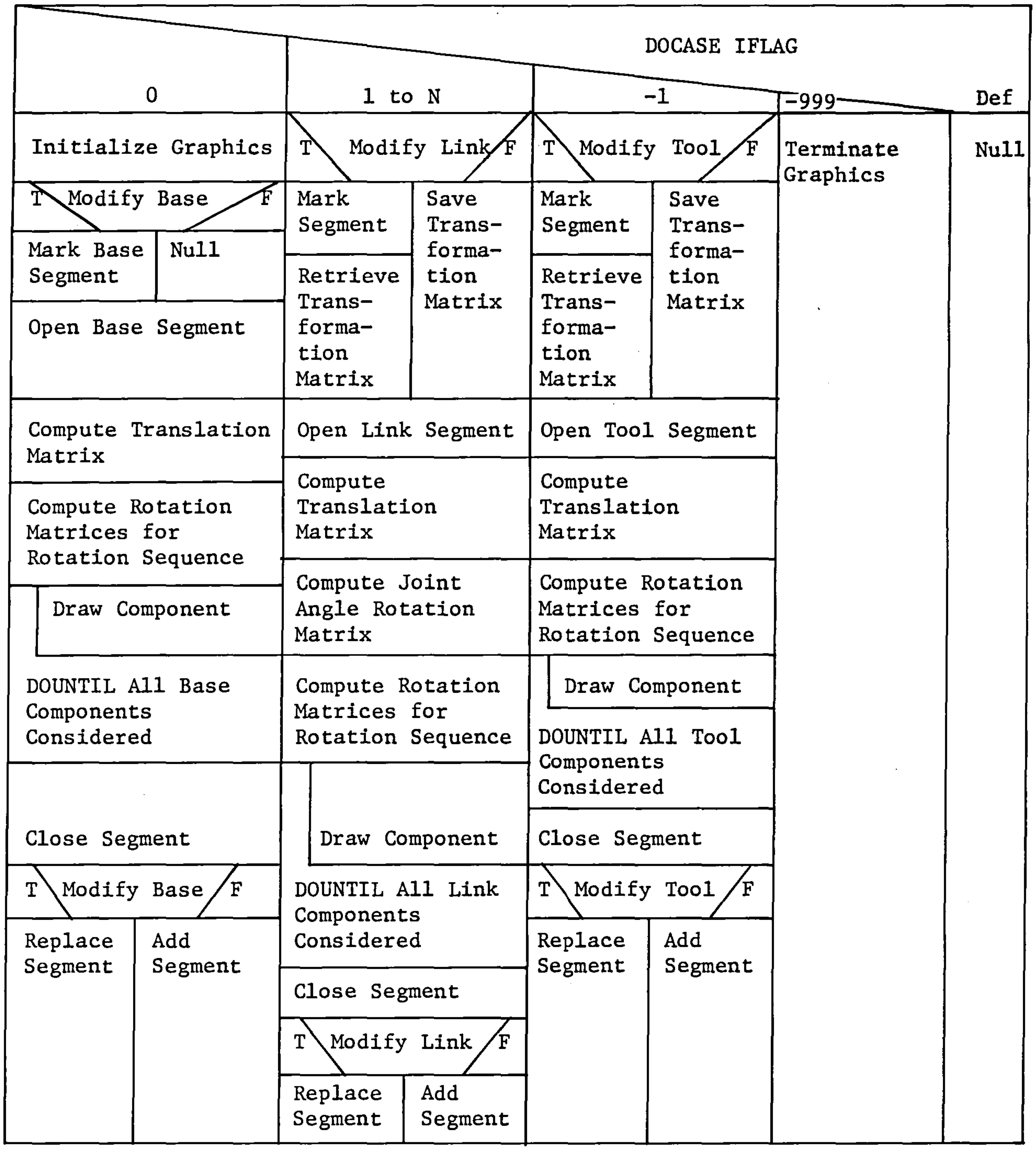

DOCASE IFLAG
0
1 to N
-1
-999
Def
Initialize Graphics
T Modify Base F
Mark Base Segment
Null
Open Base Segment
Compute Translation Matrix
Compute Rotation Matrices for Rotation Sequence
Draw Component
DOUNTIL All Base Components Considered
Close Segment
T Modify Base F
Replace Segment
Add Segment
T Modify Link F
Mark Segment
Retrieve Trans-forma-tion Matrix
Save Trans-forma-tion Matrix
Open Link Segment
Compute Translation Matrix
Compute Joint Angle Rotation Matrix
Compute Rotation Matrices for Rotation Sequence
Draw Component
DOUNTIL All Link Components Considered
Close Segment
T Modify Link F
Replace Segment
Add Segment
T Modify Tool F
Mark Segment
Retrieve Trans-forma-tion Matrix
Save Trans-forma-tion Matrix
Open Tool Segment
Compute Translation Matrix
Compute Rotation Matrices for Rotation Sequence
Draw Component
DOUNTIL All Tool Components Considered
Close Segment
T Modify Tool F
Replace Segment
Add Segment
Terminate Graphics
Null

Figure A2-9 GRAPH VCLR

2.1.1.7 Define Desired Motion (CNTROL) - Subroutine CNTROL interactively prompts the user for coefficients of quadratic functions of time that are used to control the motion of the robotic system. The calling argument MOD specifies whether subroutine CNTROL was called in the create mode or the modification mode. In the create mode, the user is prompted for all possible data. In the modification mode, the user is prompted to specify which data category is to be changed. The user is then prompted only for the requested data. Following input of the requested data, the modification category prompt is repeated, allowing modification of other data within subroutine CNTROL. Upon completion of all changes, the user requests termination of modifications and control is returned to the calling program.

Subroutine CNTROL prompts the user for control option flag, IHIST, which indicates whether control of the system motion will be through time histories or through Evans and Sutherland analog devices. Control of the system motion through the Evans and Sutherland analog devices is not currently implemented.

For control of the system through time histories, the user may specify up to 20 time segments within which the system motion will be specified. For each time segment, the user is prompted for the segment start time, whether control is of the end-effector motion or the motion of the individual joints, and whether the time functions specify rates or positions, and the coefficients for the time functions. The use of the time functions to specify position is not currently implemented. If end-effector control is requested for the current segment, coefficients must be supplied for functions describing the end-effector translation along each axis and the end-effector rotation about each axis. If control of the individual joints is requested for the current segment, coefficients must be supplied for functions describing the motion of each joint in the system.

A recoverable error encountered within subroutine CNTROL causes an error message to be written through a call to subroutine ERRMSG followed by appropriate recovery action. There are no nonrecoverable error conditions in subroutine CNTROL.

Figure A2-10 is the VCLR for subroutine CNTROL.

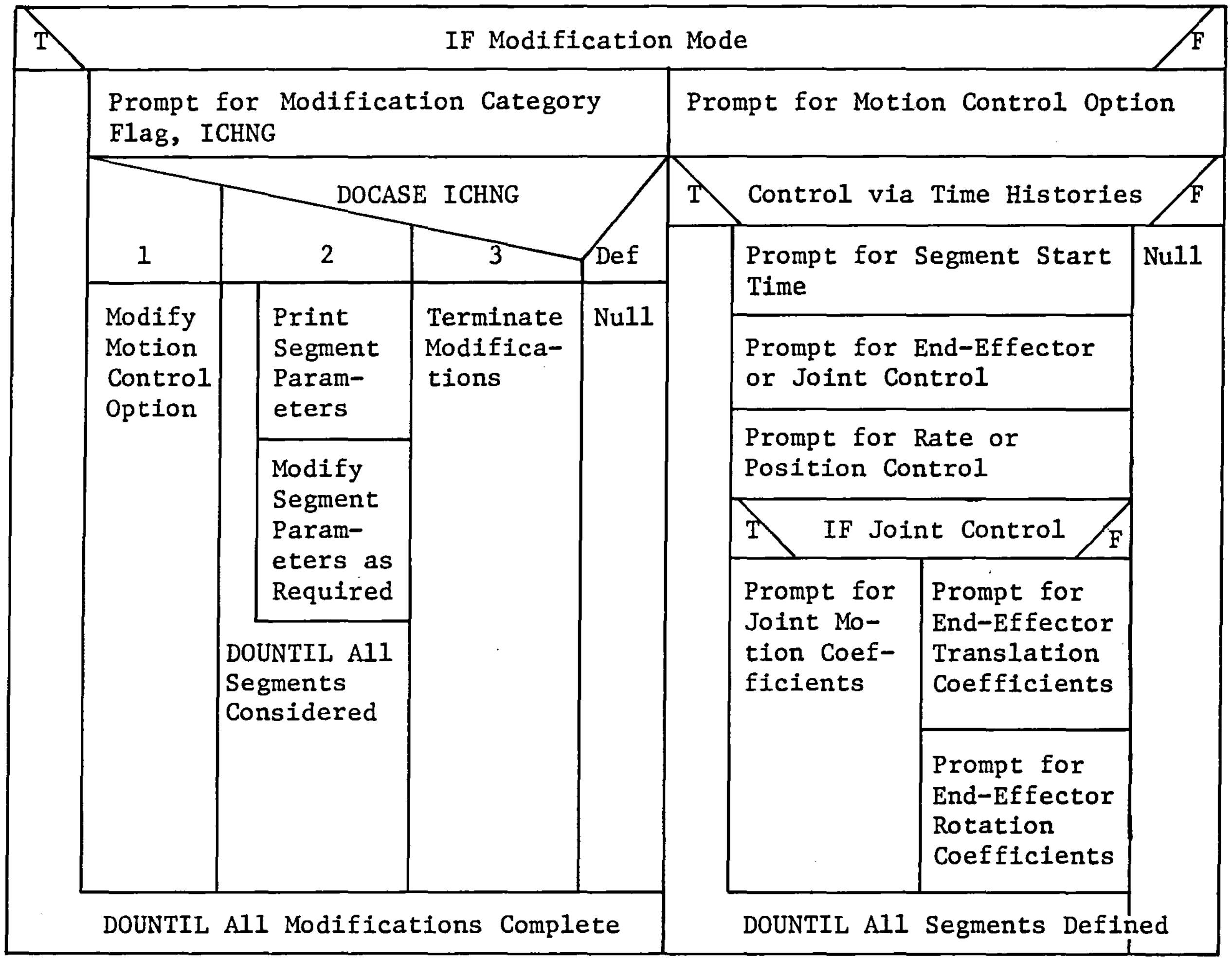

T
IF Modification Mode
F
Prompt for Modification Category Flag, ICHNG
DOCASE ICHNG
1
2
3
Def
Modify Motion Control Option
Print Segment Parameters
Modify Segment Parameters as Required
DOUNTIL All Segments Considered
Terminate Modifications
Null
DOUNTIL All Modifications Complete
Prompt for Motion Control Option
T
Control via Time Histories
F
Prompt for Segment Start Time
Prompt for End-Effector or Joint Control
Prompt for Rate or Position Control
T
IF Joint Control
F
Prompt for Joint Motion Coefficients
Prompt for End-Effector Translation Coefficients
Prompt for End-Effector Rotation Coefficients
Null
DOUNTIL All Segments Defined

Figure A2-10 *CNTROL VCLR*

2.1.1.8 Specify Program Options (PRGOPT) - Subroutine PRGOPT interactively prompts the user for the program start time, stop time, time step, and several flags for the control of output and the selection of some computational capabilities. The calling argument MOD specifies whether subroutine PRGOPT was called in the create mode or the modification mode. In the create mode, the user is prompted for all possible data. In the modification mode, the user is prompted to specify which data category is to be changed. The user is then prompted only for the requested data. Following input of the requested data, the modification category prompt is repeated, allowing modification of other data within subroutine PRGOPT. Upon completion of all changes, the user requests termination of modifications, and control is returned to the calling program.

Subroutine PRGOPT allows the user to request the generation of an output file from the Analysis Tools function. The file will contain all data required by the Postprocessing function for further and more detailed study of the results of the execution of the particular analysis tool requested. The time frequency of output of data to the file is also specified.

Subroutine PRGOPT allows the user to request printed output during the Analysis Tools function execution. The content and format of the data to be printed are provided within each of the analysis tools. The flag set within subroutine PRGOPT is used only to turn on the print routines. The time frequency of the printed output is also specified.

Subroutine PRGOPT allows the user to request that dynamics computations not be performed. This flag is used within the requirements analysis tool to turn off dynamics computations to greatly speed up the execution. If the dynamics computations are turned off, no force or torque data will be available.

A recoverable error encountered within subroutine PRGOPT causes an error message to be written through a call to subroutine ERRMSG followed by appropriate recovery action. There are no nonrecoverable error conditions in subroutine PRGOPT.

Figure A2-11 is the VCLR for subroutine PRGOPT.

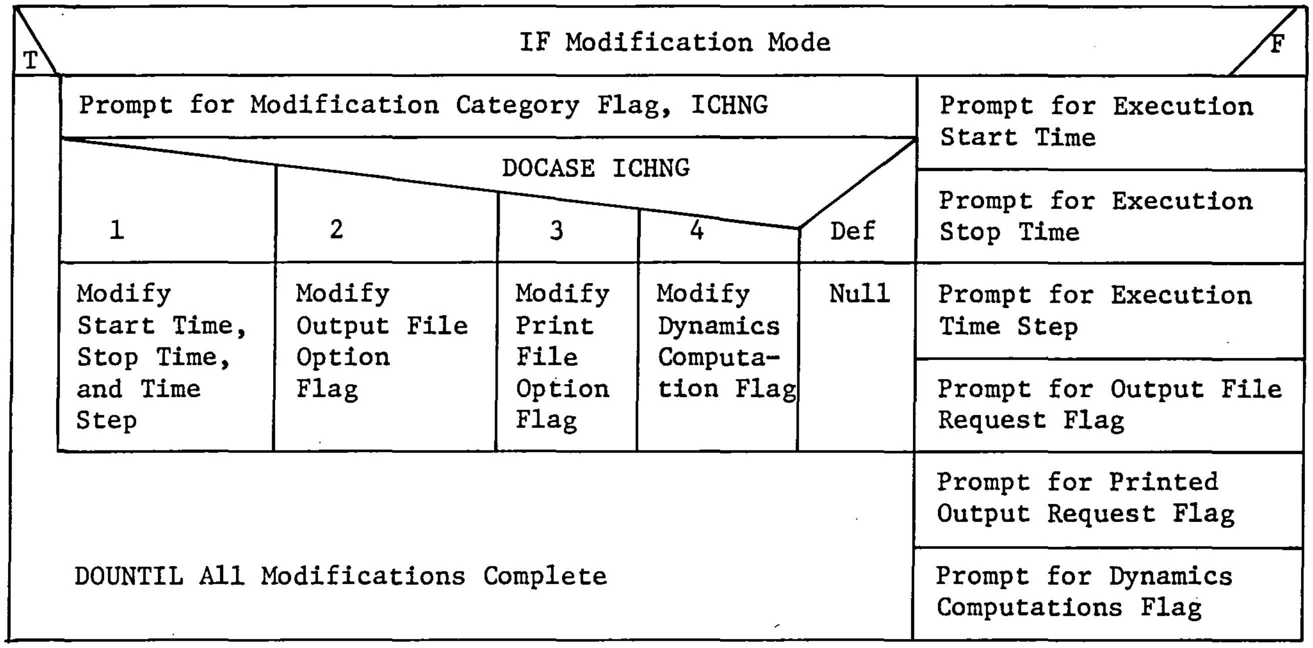

IF Modification Mode
T
F
Prompt for Modification Category Flag, ICHNG
DOCASE ICHNG
1
2
3
4
Def
Modify Start Time, Stop Time, and Time Step
Modify Output File Option Flag
Modify Print File Option Flag
Modify Dynamics Computation Flag
Null
DOUNTIL All Modifications Complete
Prompt for Execution Start Time
Prompt for Execution Stop Time
Prompt for Execution Time Step
Prompt for Output File Request Flag
Prompt for Printed Output Request Flag
Prompt for Dynamics Computations Flag

Figure A2-11 PRGOPT VCLR

2.1.2 Define Detailed Graphics Representation Data (BLDDAT)

Subroutine BLDDAT controls the program flow during the creation of the detailed graphics representation data used to display either the robotic system or the physical environment. The basic input data file generated by the System Definition function must already exist prior to calling subroutine BLDDAT. Subroutine RDSIM is called to read the input data file and load the required COMMON blocks. Subroutine DRAW is then called to initialize the graphics and draw the reference coordinate system. If subroutine BLDDAT was called to define the environment representation, the robotic system base coordinate system is used as the reference system. If the robotic system representation is being defined, the coordinate system for the appropriate section of the system is used (base, each joint/link, or tool).

Each section of the detailed representation is made up of a number of components, which are themselves simple three-dimensional solid shapes. The user is prompted for a shape type. Currently, the shapes include cylinder, cone, rectangular solid, symmetric and nonsymmetric trapezoidal solids, and a triangular cross-section beam. Additional shapes can be added as required. Based on the shape selected, an appropriate subroutine is called to prompt the user for the shape dimensions and compute the data points for that shape. Subroutine CYL is called for cylinders and cones. Subroutine RECT is called for rectangular or trapezoidal solids. Subroutine TRISTR is called for the triangular cross-section beam.

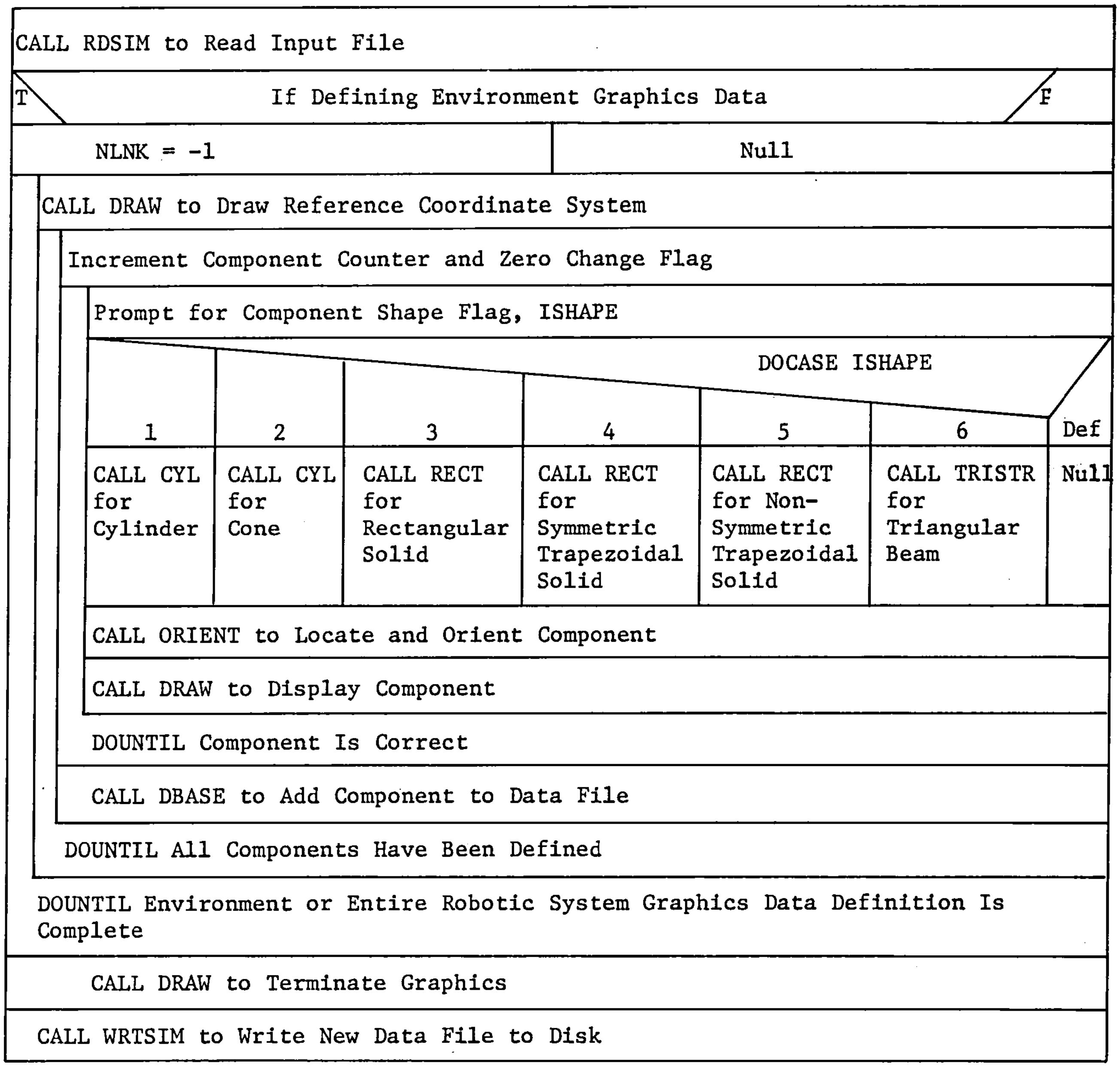
Following selection of a shape and the computation of the data points defining that shape, subroutine ORIENT is called to prompt the user for the position and orientation of the shape within the reference coordinate system. Subroutine DRAW is then called to display the component on the graphics screen for user inspection. The user may then elect to accept the component as defined or change the component. If the user elects to change the component, the shape selection prompt is reissued and the component selection and definition process is repeated. Subroutine DRAW is then called to replace the rejected component with the modified component. The user may continue to iterate on a component until satisfied. Once the user elects to accept a component, that component may no longer be modified.

After the component is satisfactory, subroutine DBASE is called to add that component to the data defining the representation of the environment or of the section of the robotic system under consideration. The user then specifies through prompt response whether another component is to be defined. When defining the environment representation, components are defined until the entire environment representation is complete. When defining the robotic system representation, each major section of the system is defined in turn (base, each link, tool). Components for each section are defined until that section is complete before continuing to the next section.

After all input is complete, subroutine DRAW is called to terminate the graphics. Subroutine WRTSIM is then called to write the new data file containing the detailed graphics representation data.

A recoverable error encountered within subroutine BLDDAT causes an error message to be written through a call to subroutine ERRMSG. Appropriate recovery action is then taken. Nonrecoverable errors encountered within routines called by BLDDAT cause return of program control through the System Definition function routines to the ROBSIM executive program.

Figure A2-12 is the VCLR for subroutine BLDDAT.



```
CALL RDSIM to Read Input File
If Defining Environment Graphics Data
  T: NLNK = -1
  F: Null
    CALL DRAW to Draw Reference Coordinate System
        Increment Component Counter and Zero Change Flag
            Prompt for Component Shape Flag, ISHAPE
            DOCASE ISHAPE
              1:   CALL CYL for Cylinder
              2:   CALL CYL for Cone
              3:   CALL RECT for Rectangular Solid
              4:   CALL RECT for Symmetric Trapezoidal Solid
              5:   CALL RECT for Non-Symmetric Trapezoidal Solid
              6:   CALL TRISTR for Triangular Beam
              Def: Null
            CALL ORIENT to Locate and Orient Component
            CALL DRAW to Display Component
        DOUNTIL Component Is Correct
        CALL DBASE to Add Component to Data File
    DOUNTIL All Components Have Been Defined
DOUNTIL Environment or Entire Robotic System Graphics Data Definition Is Complete
CALL DRAW to Terminate Graphics
CALL WRTSIM to Write New Data File to Disk
```

Figure A2-12 BLDDAT VCLR

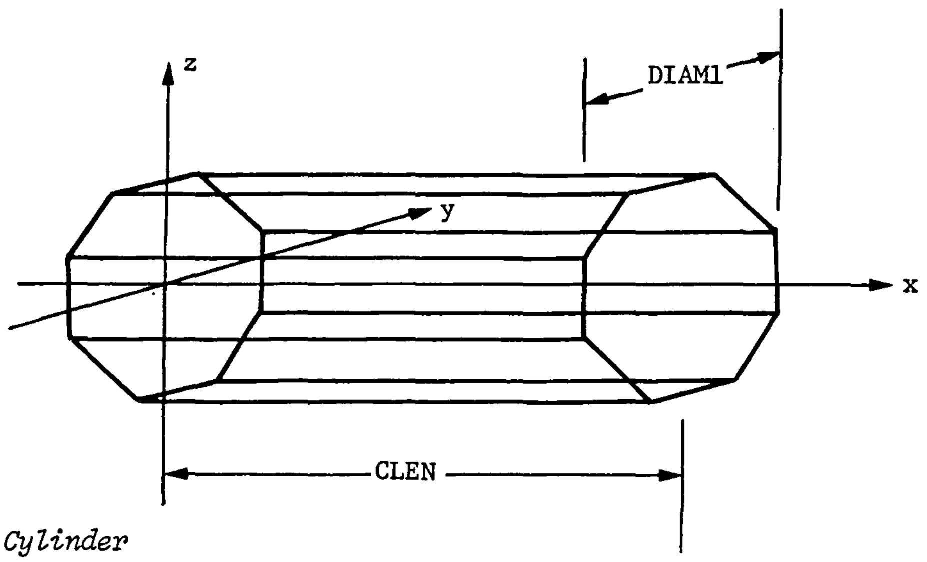
2.1.2.1 Define Cylinder Shape (CYL) - Subroutine CYL is called from subroutine BLDDAT during the definition of detailed graphic representations for the environment or the robotic system. Subroutine CYL is called if the requested component is a cylinder or a cone.

The user is prompted for the shape diameter, DIAM1 (diameter for a cylinder, base diameter for a cone). If the shape is a cone, the user is then prompted for the top diameter of the cone, DIAM2. The user is then prompted for the shape length, CLEN.

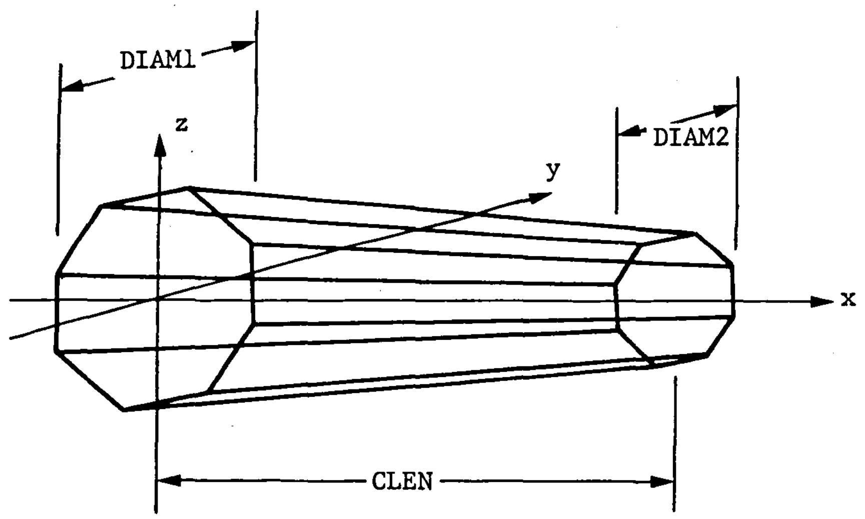
Using the shape size parameters, the data points describing the shape are computed. The data defining the shape are computed in a shape coordinate system. Figure A2-13 shows the coordinate systems used for cylinders and cones. For a cylinder or cone, the x axis is along the shape centerline. The shape length is measured from x = 0 to x = CLEN. The orientation of the y-z plane is arbitrary for the cylinder or cone shapes. The vertex points for the shape base (at x = 0) are computed using eight sides and the shape diameter DIAM1. The vertex points for the shape end at x = CLEN are computed using eight sides and either DIAM1 for a cylinder or DIAM2 for a cone. The data points used to define the shape sides are computed by selecting pairs of corresponding vertex points.

The data computed by subroutine CYL are stored in the array ARRAY as Cartesian coordinates in the shape coordinate system. The counter N1 contains the number of points describing the two shape ends. These points are connected sequentially by the graphics routines. The counter N2 contains the number of points describing the shape sides. These points are connected in alternating pairs by the graphics routines.

Figure A2-14 is the VCLR for subroutine CYL.



Cylinder



Cone

Figure A2-13 Cylinder and Cone Shape Coordinate Systems

```
Prompt for Cylinder Diameter (or Cone Diameter at x = 0), DIAM1
IF Cone Requested
  T: Prompt for Cone Diameter at X = CLEN, DIAM2
  F: Null
Prompt for Shape Length, CLEN
    Set End Radius to DIAM1/2.0
    IF Second End and Cone
      T: Set End Radius to DIAM2/2.0
      F: Null
        Compute y and z Location of Vertex
        IF Second End
          T: X = CLEN
          F: X = 0.0
        Store Current Vertex Coordinates in ARRAY
    DOUNTIL All Vertices Computed
DOUNTIL Both Ends Considered
    Store in ARRAY Pairs of Corresponding Vertex Points from Each End to
    Define Shape Side Data
DOUNTIL All Sides Considered
```

Figure A2-14 CYL VCLR

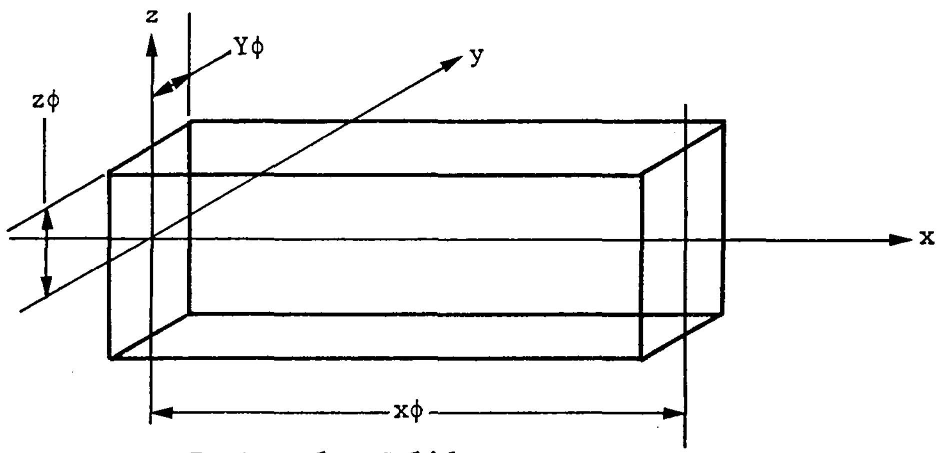
2.1.2.2 <u>Define Rectangular Shape (RECT)</u> - Subroutine RECT is called from subroutine BLDDAT during the definition of detailed graphic representations for the environment or the robotic system. Subroutine RECT is called if the requested component is a rectangular solid, a symmetric trapezoidal solid, or a nonsymmetric trapezoidal solid.

The user is prompted for the shape length (x-axis dimension, X0), the shape width ($\pm$y-axis dimension, Y0), and the appropriate z-axis dimensions. For a rectangular solid, the user is prompted for the shape height ($\pm$z-axis dimension, Z0). For a symmetric trapezoidal solid, the user is prompted for the height of each end of the trapezoid (x = 0 end z-axis dimension, Z1; and x = X0 end z-axis dimension, Z2). For a nonsymmetric trapezoidal solid, the user is prompted for the height of each end of the trapezoid (x = 0 end z-axis dimension, Z1, and x = X0 end z-axis dimension, Z2).

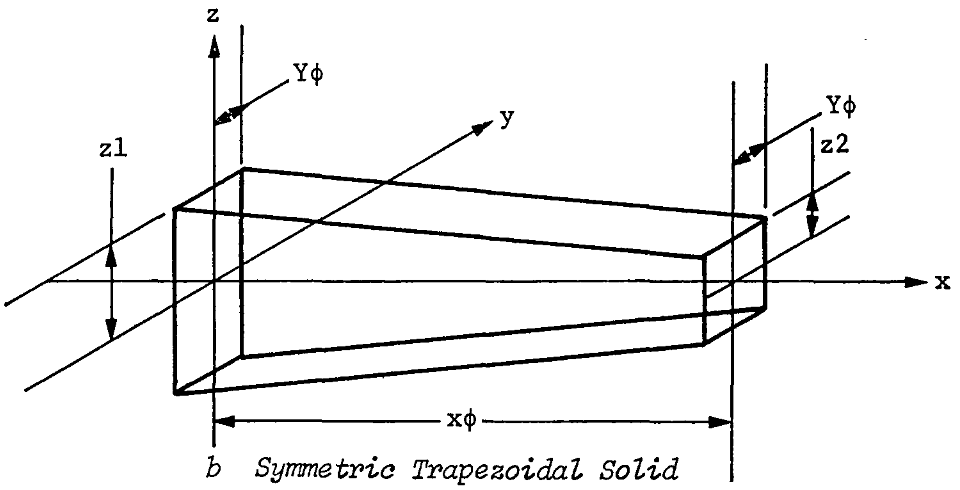
Using the shape size parameters, the data points describing the shape are computed. The data defining the shape are computed in a shape coordinate system. Figure A2-15 shows the coordinate systems used for rectangular or trapezoidal solids. The x axis is along the shape centerline. The shape length is measured from x = 0 to x = X0. The rectangular and symmetric trapezoidal solid shapes are symmetric about both the y axis and the z axis. The nonsymmetric trapezoidal solid is symmetric about the y axis but not the z-axis. The vertex points for the shape base (at x = 0) are computed using $\pm$Y0 and either $\pm$Z0, $\pm$Z1, or 0 and -Z1 for the rectangle, the symmetric trapezoid, or the nonsymmetric trapezoid, respectively. The vertex points for the shape end at x = X0 are com- puted using $\pm$Y0 and either $\pm$Z0, $\pm$Z2, or 0 and -Z2 for the rectangle, the symmetric trapezoid, or the nonsymmetric trapezoid, respectively. The data points used to define the shape sides are computed by select- ing pairs of corresponding vertex points.

The data computed by subroutine RECT are stored in the array ARRAY as Cartesian coordinates in the shape coordinate system. The counter N1 contains the number of points describing the two shape ends. These points are connected sequentially by the graphics routines. The counter N2 contains the number of points describing the shape sides. These points are connected in alternating pairs by the graphics routines.

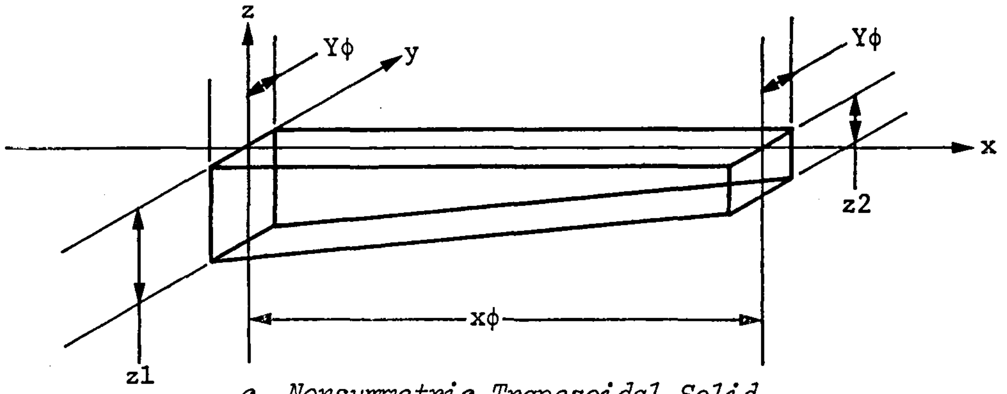
Figure A2-16 is the VCLR for subroutine RECT.



a Rectangular Solid



b Symmetric Trapezoidal Solid



c Nonsymmetric Trapezoidal Solid

Figure A2-15 Rectangular and Trapezoidal Shape Coordinate Systems

```
Prompt for Shape Length, xϕ
Prompt for Shape Width, yϕ
IF Shape is Rectangular Solid
T   Prompt for Shape Height, zϕ
F   Prompt for Trapezoid Height
    at x = 0, z1
    Prompt for Trapezoid Height at
    x = xϕ, z2
    Using Shape Size Parameters, Compute Coordinates of Each Vertex
DOUNTIL Both Ends Considered
    Select Pairs of Corresponding Vertex Points from Each End to
    Define Shape Side Data
DOUNTIL All Sides Considered
```

Figure A2-16 RECT VCLR

2.1.2.3 Define Triangular Beam Shape (TRISTR) - Subroutine TRISTR is called from subroutine BLDDAT during the definition of detailed graphic representations for the environment or the robotic system. Subroutine TRISTR is called if the requested component is a triangular cross-section beam.

The user is prompted for the length of the base (also used as the triangle height) of the triangular cross section of the beam, TRIL. The user is then prompted for the length of a segment of the beam, SEGL. Finally, the user is prompted for the number of segments in the beam, NSEG.

Using the beam size parameters, the data points describing the beam are computed. The data defining the beam are computed in a shape coordinate system. Figure A2-17 shows the coordinate system used for beams. The beam length is measured along the x axis from x = 0 to x = NSEG*SEGL. One side of the triangular cross section lies on the y axis from y = -TRIL/2.0 to y = +TRIL/2.0. One vertex of the triangular cross section lies on the line defined by x = 0 to x = NSEG*SEGL, y = 0, and z = -TRIL. The vertex points for a triangle are computed at the base (x = 0) of the beam and at the end of each segment along the beam length. The data points used to define the beam sides are computed by selecting pairs of corresponding vertex points from the two ends of the beam.

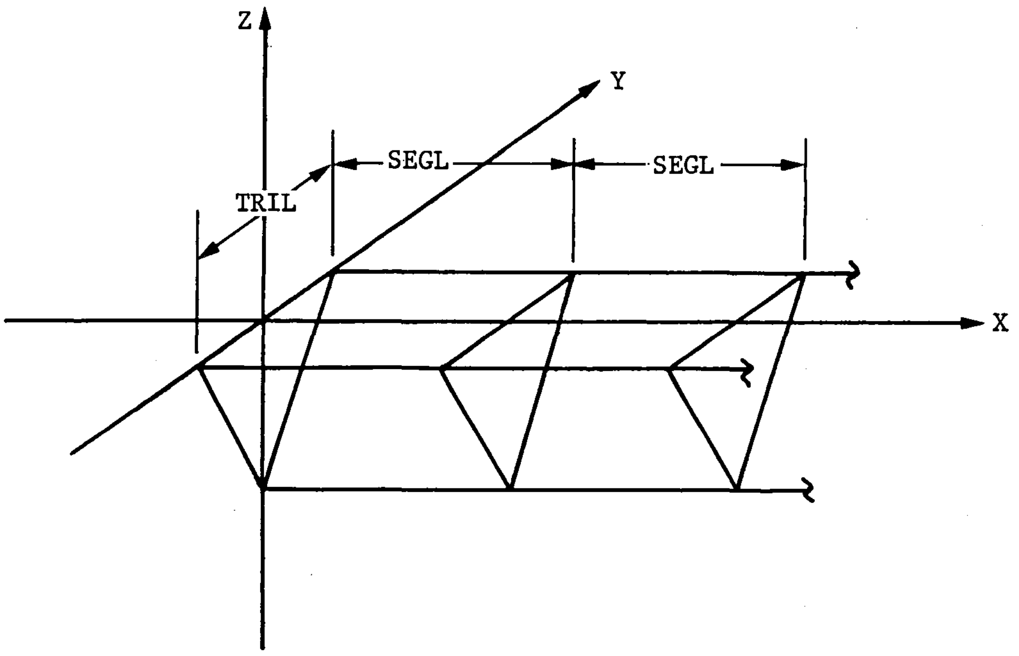


Figure A2-17 Triangular Cross-Section Beam Coordinate System

The data computed by subroutine TRISTR are stored in ARRAY as Cartesian coordinates in the shape coordinate system. The counter N1 contains the number of points describing the triangles along the beam and at each beam end. These points are connected sequentially by the graphics routines. The counter N2 contains the number of points describing the beam sides. These points are connected in alternating pairs by the graphics routines.

Figure A2-18 is the VCLR for subroutine TRISTR.

```
Prompt for Length of Side of Triangular
Cross Section
Prompt for Length of Segment of Beam
Prompt for Number of Segments in Beam
        Compute Coordinates of Vertices of
        Triangle at Segment End
    DOUNTIL All Segments Considered
        Select Pairs of Corresponding Vertex
        Points from Each End of the Beam to Define
        the Beam Sides
    DOUNTIL All Sides Considered
```

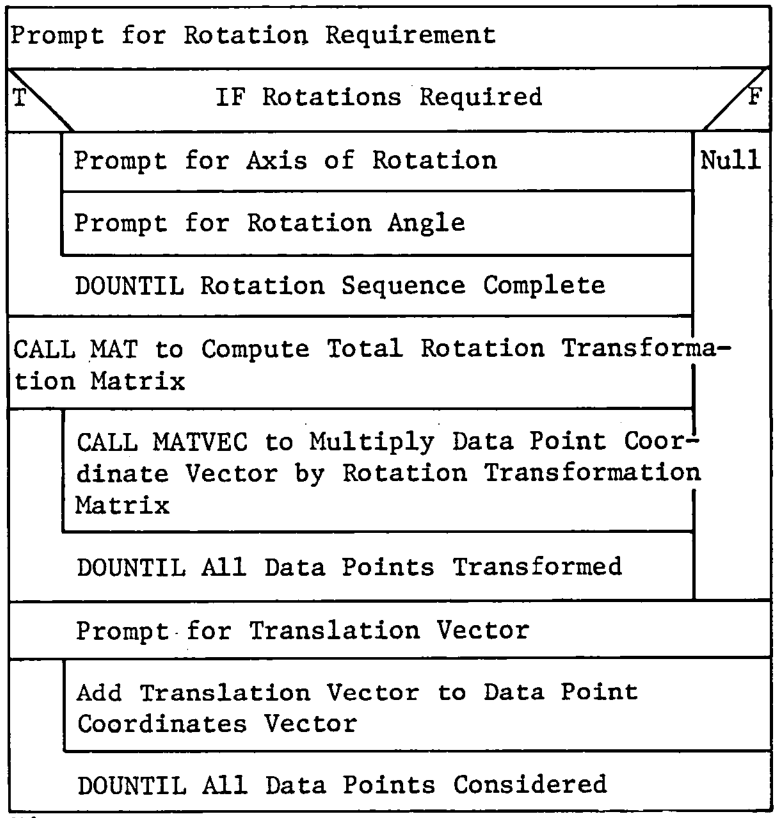
Figure A2-18 TRISTR VCLR

2.1.2.4 Orient Component (ORIENT) - Subroutine ORIENT is called from subroutine BLDDAT during the definition of detailed graphic representations for the environment or the robotic system. Subroutine ORIENT is called to position the current component properly within the reference coordinate system.

The user can request input of a rotation sequence via prompt response. If rotations are required, the user is prompted for an axis of rotation and corresponding rotation angle for each desired rotation. After all rotations have been defined, subroutine MAT is called to compute the total rotation transformation matrix corresponding to the requested rotation sequence. Each set of coordinates in ARRAY is then transformed from the shape coordinate system to the reference coordinate system through calls to subroutine MATVEC using the rotation transformation matrix.

The user is then prompted for a translation vector to position the origin of the component within the reference coordinate system. This translation vector is then added to each set of coordinates in ARRAY.

Figure A2-19 is the VCLR for subroutine ORIENT.



```
Prompt for Rotation Requirement
IF Rotations Required                                          T / F
  T:
      Prompt for Axis of Rotation
      Prompt for Rotation Angle
    DOUNTIL Rotation Sequence Complete
    CALL MAT to Compute Total Rotation Transformation Matrix
      CALL MATVEC to Multiply Data Point Coordinate Vector by Rotation Transformation Matrix
    DOUNTIL All Data Points Transformed
  F:
    Null
Prompt for Translation Vector
    Add Translation Vector to Data Point Coordinates Vector
DOUNTIL All Data Points Considered
```

Figure A2-19 ORIENT VCLR

2.1.2.4.1 Rotation Matrix (MAT) - Subroutine MAT is called from subroutine ORIENT to compute the total rotation transformation matrix defined by the input rotation sequence and angles.

The rotation sequence and corresponding angles input from subroutine ORIENT describe rotations from the reference system to the desired component system. The transformation matrix desired from subroutine MAT is from the component system to the reference system. Therefore, the transpose (inverse) of the normal x, y, and z-axis rotation matrices are used.

For each rotation in the input rotation sequence, the axis rotation matrix is loaded and premultiplied with the current total transformation matrix. The axis rotation matrices used are:

For x-axis rotation

$$\begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & \cos(ang) & -\sin(ang) \\ 0.0 & \sin(ang) & \cos(ang) \end{bmatrix}$$

For y-axis rotation

$$\begin{bmatrix} \cos(ang) & 0.0 & \sin(ang) \\ 0.0 & 1.0 & 0.0 \\ -\sin(ang) & 0.0 & \cos(ang) \end{bmatrix}$$

For z-axis rotation

$$\begin{bmatrix} \cos(ang) & -\sin(ang) & 0.0 \\ \sin(ang) & \cos(ang) & 0.0 \\ 0.0 & 0.0 & 1.0 \end{bmatrix}$$

Figure A2-20 is the VCLR for subroutine MAT.

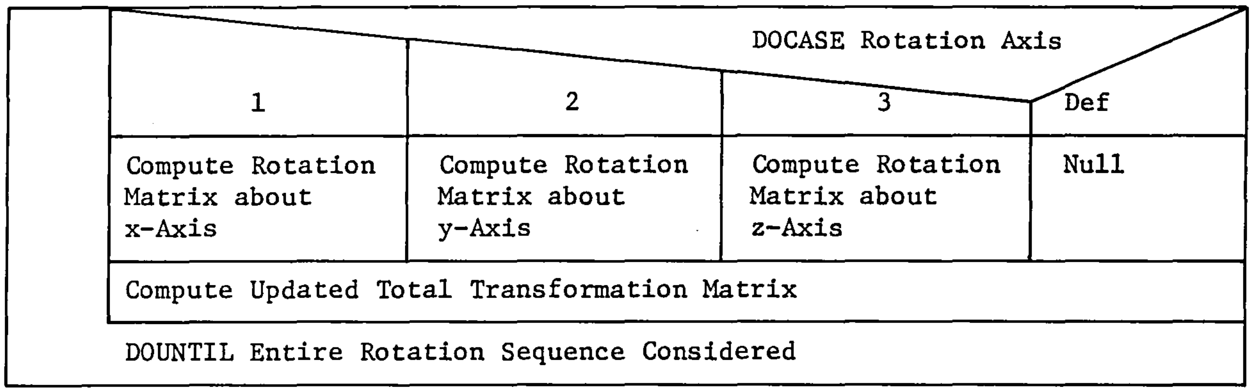

DOCASE Rotation Axis
1
2
3
Def
Compute Rotation Matrix about x-Axis
Compute Rotation Matrix about y-Axis
Compute Rotation Matrix about z-Axis
Null
Compute Updated Total Transformation Matrix
DOUNTIL Entire Rotation Sequence Considered

Figure A2-20 MAT VCLR

2.1.2.4.2 Matrix/Vector Multiplication (MATVEC) - Subroutine MATVEC is called from subroutine ORIENT to provide matrix/ vector multiplication. .Input Vector A is multiplied by input matrix TRANS to produce output Vector B.

$$\begin{bmatrix} B(1) \\ B(2) \\ B(3) \end{bmatrix} = \begin{bmatrix} TRANS(1,1) & TRANS(1,2) & TRANS(1,3) \\ TRANS(2,1) & TRANS(2,2) & TRANS(2,3) \\ TRANS(3,1) & TRANS(3,2) & TRANS(3,3) \end{bmatrix} \begin{bmatrix} A(1) \\ A(2) \\ A(3) \end{bmatrix}$$

Figure A2-21 is the VCLR for subroutine MATVEC.

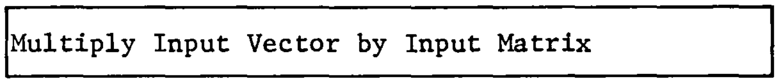


Figure A2-21 MATVEC VCLR

2.1.2.5 Draw Component (DRAW) - Subroutine DRAW is called from subroutine BLDDAT to provide graphics display during the definition of detailed graphic representations for the environment or the robotic system. Subroutine DRAW is called to display each successive component as it is defined.

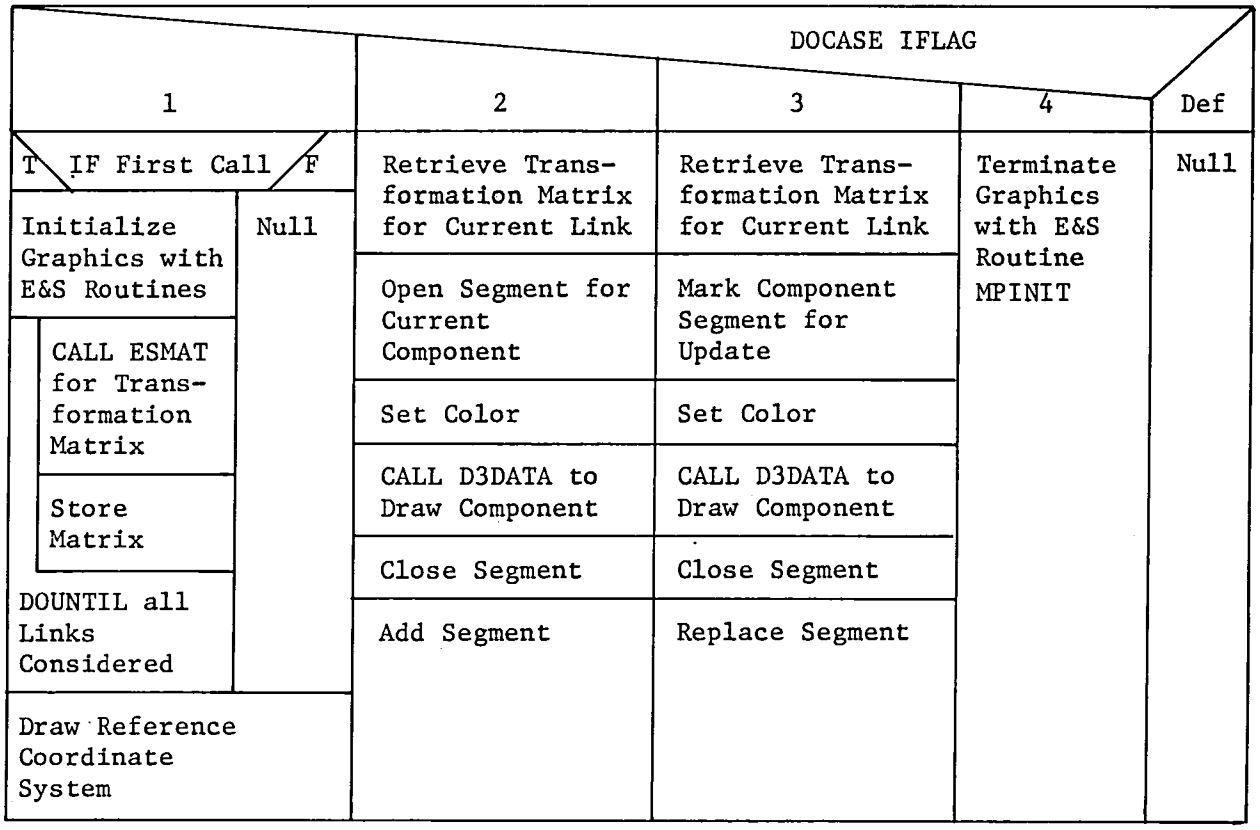
Input argument IFLAG controls the routine logic. A value of IFLAG = 1 indicates the start of a new definition section. Sections are specified by input argument M. If the current section is the first section considered (M = 1), then the graphics system is initialized and subroutine ESMAT is called to compute transformation matrices for all sections that will be required. The reference coordinate system for the current section is then drawn.

A value of IFLAG = 2 indicates that the component under consideration be displayed for the first time. The current component number is specified by input argument NC. A new display segment is opened, the component is drawn, and the segment is added to the current display.

A value of IFLAG = 3 indicates that the component under consideration has been modified and the modified version is to be displayed. The component display segment is marked for update, the segment opened, and the component drawn. The segment is then replaced in the current display.

A value of IFLAG = 4 indicates that all display is complete and termination of the graphics is requested.

Figure A2-22 is the VCLR for subroutine DRAW.



```
DOCASE IFLAG
  1:
    IF First Call
      T:
        Initialize Graphics with E&S Routines
        DOUNTIL all Links Considered
          CALL ESMAT for Transformation Matrix
          Store Matrix
      F:
        Null
    Draw Reference Coordinate System
  2:
    Retrieve Transformation Matrix for Current Link
    Open Segment for Current Component
    Set Color
    CALL D3DATA to Draw Component
    Close Segment
    Add Segment
  3:
    Retrieve Transformation Matrix for Current Link
    Mark Component Segment for Update
    Set Color
    CALL D3DATA to Draw Component
    Close Segment
    Replace Segment
  4:
    Terminate Graphics with E&S Routine MPINIT
  Def:
    Null
```

Figure A2-22 DRAW VCLR

2.1.2.5.1 Graphics Transformation Matrix (ESMAT) - Subroutine ESMAT is called from subroutine DRAW to compute the transformation matrix from each system section coordinate system to the graphics coordinate system. The environment data have only one section. The environment is defined in the robotic system base coordinate system. The robotic system has section coordinate systems for the base, each joint/link, and the end effector.

Subroutine ESMAT uses Evans and Sutherland graphics routines to construct the required transformation matrices. Input argument K specifies which system section is under consideration.

A value of K = 1 indicates the robotic system base or the environment. The transformation matrix is composed of a translation matrix based on the base location and rotation matrices constructed using the base orientation parameters.

A value of K from 2 to the number of links in the system (N) plus 1 (N+1) indicates the (K-1)th joint/link. The transformation matrix computed by each call to subroutine ESMAT is automatically concatenated to the previous matrix, thereby forming the total transformation from the current section coordinate system to the graphics coordinate system. The joint/link transformation matrix is composed of a translation matrix based on the joint position, a rotation matrix based on the initial joint angular displacement, and rotation matrices constructed using the joint orientation parameters. Joint position and orientation are specified relative to the coordinate system of the previous joint (base if the current joint is the first joint in the system).

A value of K = N+2 indicates the end-effector system. The transformation matrix for the end-effector is composed of a translation matrix based on the end-effector position and rotation matrices constructed from the end-effector orientation parameters. The end-effector location and orientation are specified relative to the coordinate system of the final joint in the system.

Figure A2-23 is the VCLR for subroutine ESMAT.

		DOCASE K	
1	2	3	Def
Compute Translation Matrix for Base	Compute Translation Matrix for Current Link	Compute Translation Matrix for Tool	Null
Decode Rotation Axis Sequence	Convert Current Joint Angle to Graphics Units	Decode Rotation Axis Sequence	
Convert Rotation Angles to Graphics Units	Compute Rotation Matrix for Joint Angle	Convert Rotation Angles to Graphics Units	
Compute Rotation Matrix for Third Rotation of Sequence	Decode Rotation Axis Sequence	Compute Rotation Matrix for Third Rotation of Sequence	
Compute Rotation Matrix for Second Rotation of Sequence	Convert Rotation Angles to Graphics Units	Compute Rotation Matrix for Second Rotation of Sequence	
Compute Rotation Matrix for First Rotation of Sequence	Compute Rotation Matrix for Third Rotation of Sequence	Compute Rotation Matrix for First Rotation of Sequence	
Retrieve Total Translation-Rotation Transformation Matrix	Compute Rotation Matrix for Second Rotation of Sequence	Retrieve Total Translation-Rotation Transformation Matrix	
	Compute Rotation Matrix for First Rotation of Sequence		
	Retrieve Total Translation-Rotation Transformation Matrix		

Figure A2-23 ESMAT VCLR

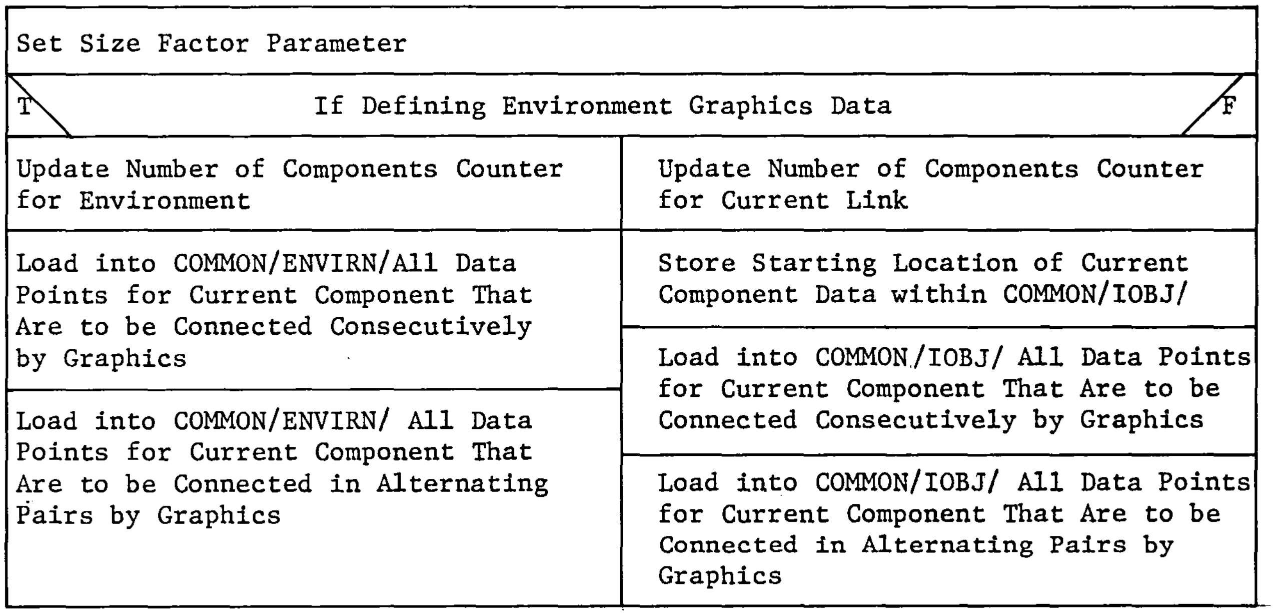
2.1.2.6 Load Graphics Data to COMMON (DBASE) - Subroutine DBASE is called from subroutine BLDDAT during definition of detailed graphics representations for the environment or the robotic system. Subroutine DBASE is called to load the data for a component into the appropriate graphics data COMMON. Input argument IMAN specifies whether the component data are part of the environment or part of the robotic system.

If the component is part of the robotic system, the data are loaded into COMMON/IOBJ/. The parameter NUM contains the number of components that make up the current robotic system section. The parameter NSTRT contains the locations within COMMON/IOBJ/ at which the data for each component start.

If the component is part of the environment, the data are loaded into COMMON/ENVIRN/. The parameter NUME contains the number of components that make up the environment data.

The manner in which the data are stored in the COMMON blocks is dictated by the data format used in Evans and Sutherland graphics routine D3DATA. It should be noted that the graphics routines require INTEGER*2 data.

Figure A2-24 is the VCLR for subroutine DBASE.


Set Size Factor Parameter

T If Defining Environment Graphics Data F

T:
Update Number of Components Counter for Environment
Load into COMMON/ENVIRN/All Data Points for Current Component That Are to be Connected Consecutively by Graphics
Load into COMMON/ENVIRN/ All Data Points for Current Component That Are to be Connected in Alternating Pairs by Graphics

F:
Update Number of Components Counter for Current Link
Store Starting Location of Current Component Data within COMMON/IOBJ/
Load into COMMON/IOBJ/ All Data Points for Current Component That Are to be Connected Consecutively by Graphics
Load into COMMON/IOBJ/ All Data Points for Current Component That Are to be Connected in Alternating Pairs by Graphics

Figure A2-24 DBASE VCLR

2.2 ANALYSIS TOOLS FUNCTION DRIVER (SIMDRVR)

The Analysis Tools function driver operates in an interactive mode and prompts the user for the analysis tool option desired. Currently valid options are (1) requirements analysis without graphics; (2) requirements analysis with graphics; and (3) return to the ROBSIM executive.

The requirements analysis tool is the only analysis tool currently implemented within the ROBSIM program. The simulation tool has been developed outside the ROBSIM framework and is documented in Section 3.0 of this appendix. Additional analysis tools will be added as program capabilities are expanded.

If Option 2 is selected, the system motion is displayed during program execution. An output file of joint variable time histories can be generated that allows replay of the system motion in the Postprocessing function.

The requirements analysis tool allows the user to specify a desired system motion and computes the forces and torques necessary to produce that motion. The motion may be specified as individual joint rates or as desired end-effector rates. If end-effector rates are given, the requirements analysis tool computes the corresponding individual joint rates required.

If either Option 1 or 2 is selected, subroutine RDSIM is called to read the input file created by the System Definition function. Subroutine REQUIR is then called to perform the requirements analysis.

A recoverable error encountered within subroutine SIMDRVR causes an error message to be written through a call to subroutine ERRMSG. Appropriate recovery action is then taken. Nonrecoverable errors encountered within routines called by SIMDRVR cause return of control to the ROBSIM executive program.

Figure A2-25 is the VCLR for subroutine SIMDRVR.

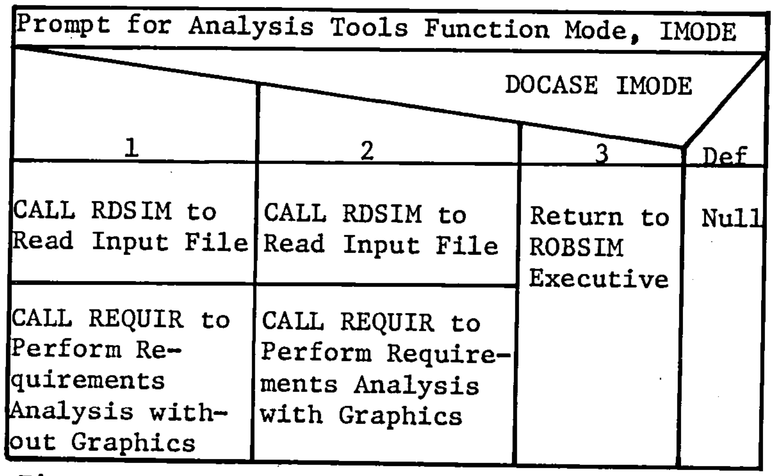

Prompt for Analysis Tools Function Mode, IMODE
DOCASE IMODE
1
2
3
Def
CALL RDSIM to Read Input File
CALL RDSIM to Read Input File
Return to ROBSIM Executive
Null
CALL REQUIR to Perform Requirements Analysis without Graphics
CALL REQUIR to Perform Requirements Analysis with Graphics

Figure A2-25 SIMDRVR VCLR

2.2.1 Requirements Analysis Tool (REQUIR)

Subroutine REQUIR controls the program logic flow for the requirements analysis capability. Subroutine REQUIR is called from subroutine SIMDRVR within the Analysis Tools function.

If printed output is desired, the user is prompted for the name of the file to be opened for printed output. The requested file is then opened. If dynamics computations are requested, the user is prompted for the name of the file to be opened for the dynamics output. The requested file is then opened. If a data file for postprocessing is desired, the user is prompted for the name of the file to be opened for postprocessing data. The requested file is then opened. Subroutine LDCOM is then called to load the COMMON parameters required by subroutine CNTRLR, which handles the motion and dynamics computations. If graphics are requested, subroutine GRAFIX is called to initialize the graphics system and the display.

Subroutine REQUIR executes a time loop from the specified start time to the specified stop time using the user-requested time increment. Within the time loop, subroutine SEGMNT is called to load the proper coefficients specifying the required system motion. Subroutine CNTRLR is called to compute the system motion and dynamics for each time step. The calls to the graphics routines are handled by subroutine CNTRLR, if required.

After completion of the time loop, any open files are closed. If graphics were requested, subroutine GRAFIX is called to terminate the graphics display.

Figure A2-26 is the VCLR for subroutine REQUIR.

```
IF Printed Output Requested
  T: Prompt for File Name for Printed Output File
     Open Printed Output File
  F: Null
IF Dynamics Computations Requested
  T: Prompt for File Name for Dynamics Output File
     Open Dynamics Output File
  F: Null
IF Data File for Postprocessing Requested
  T: Prompt for File Name for Postprocessing Data File
     Open Postprocessing Data Output File
  F: Null
CALL LDCOM to Interface Common Structure for CNTRLR
IF Graphics Requested
  T: Initialize Graphics and Display
  F: Null
Set Time to Start Time
  Time Equals Time Plus Time Step
  IF Motion Control via Time Histories
    T: CALL SEGMNT to Load Proper Motion Coefficients
       CALL CNTRLR to Compute System Motion from Time Histories
    F: Null
DOUNTIL Stop Time
IF Printed Output Requested
  T: Close Printed Output File
  F: Null
IF Dynamics Computations Requested
  T: Close Dynamics Output File
  F: Null
IF Data File for Postprocessing Requested
  T: Close Postprocessing Data Output File
  F: Null
IF Graphics Requested
  T: Terminate Graphics
  F: Null
```

Figure A2-26 REQUIR VCLR

2.2.1.1 Load COMMON (LDCOM) - Subroutine LDCOM is called from subroutine REQUIR to load COMMON parameters used by subroutine CNTRLR, which handles motion and dynamics computations within the requirements analysis tool. The data considered in subroutine LDCOM come from the COMMON structures used to store the data input from the file created in the System Definition function.

The data include joint type, location, and initial joint angular displacement. Some program option flags and similar data are also loaded.

Figure A2-27 is the VCLR for subroutine LDCOM.

```
    Load Joint Location Array
    Load Initial Joint Variable Array
    Load Joint Type Array
DOUNTIL All Joints Considered
Load End-Effector Location Array
Load Number of Joints Variable
Load Logical Units Variables
Load Output Options Flags
Load Stop Time and Time Step Variables
```

Figure A2-27 LDCOM VCLR

2.2.1.2 <u>System Motion Graphics (GRAFIX)</u> - Subroutine GRAFIX provides the motion graphics capability in the Analysis Tools and Postprocessing functions. Subroutine GRAFIX displays the environment and the robotic system motion within the environment. Input argument IFLAG controls the logic flow in subroutine GRAFIX.

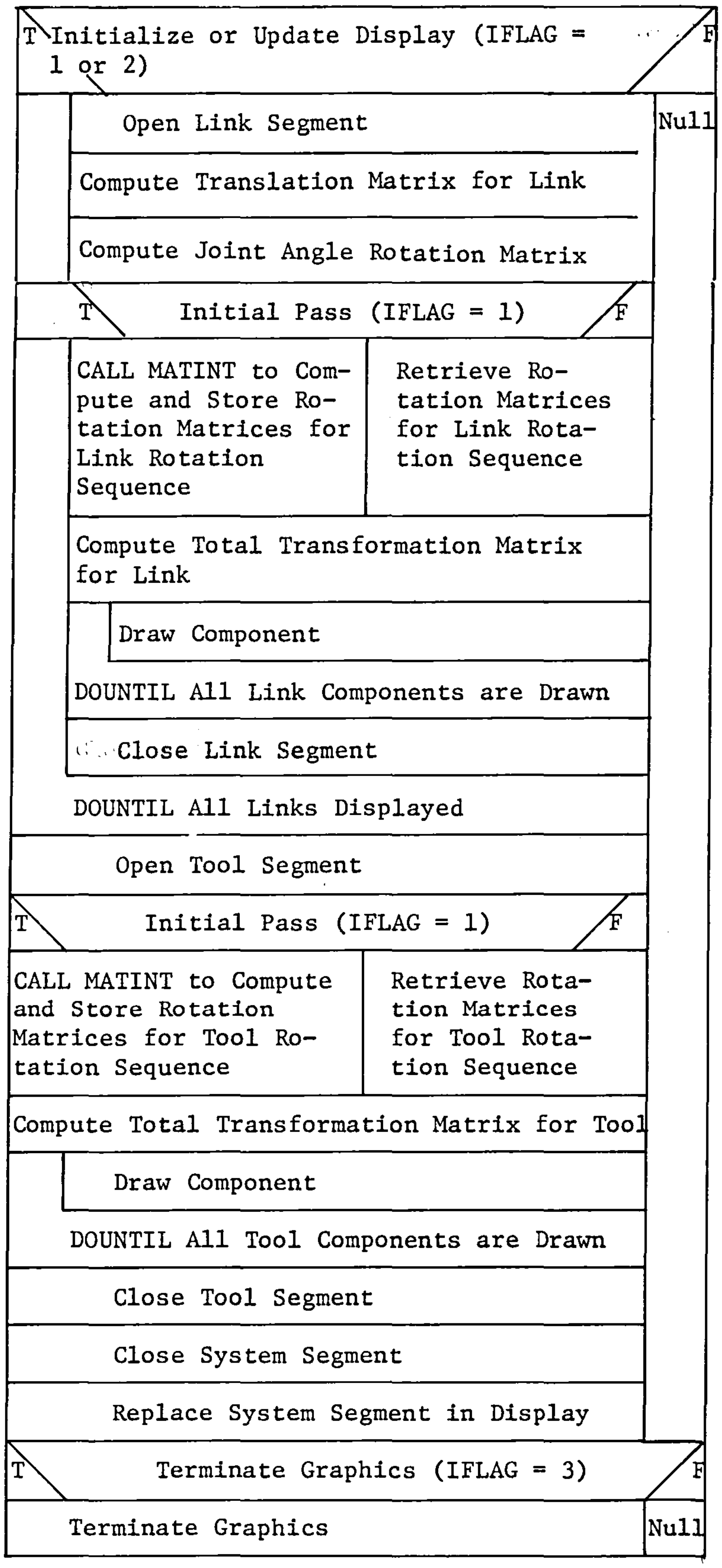
If IFLAG = 1, the graphics system is initialized and the environment and robotic system are displayed in the initial condition. If IFLAG = 2, the display is updated to the current time step condition. In the update mode, the environment and the system base are constant and therefore, are not updated. If IFLAG = 3, the motion is complete and the graphics display is terminated.

Evans and Sutherland graphics routines are used to provide all graphics capabilities.

Figure A2-28 is the VCLR for subroutine GRAFIX.

```
Update System Display (IFLAG = 2)
  T:
    Mark and Open System Segment
  F:
    Null
Initialize Display (IFLAG = 1)
  T:
    Initialize Graphics
    Open Base Segment
    Compute Translation Matrix for Base
    Compute Rotation Matrices for Base Rotation Sequence
    Prompt for Environment Data Display
    Display Environment
      T:
        Draw Component
        DOUNTIL All Environment Components Drawn
      F:
        Null
    Draw Component
    DOUNTIL All Base Components Drawn
    Close Base Segment
    Add Base Segment to Display
    Open System Segment
        Open Link Segment
        Close Link Segment
    DOUNTIL All Link Segments Nested in System Segment
    Close System Segment
    Add System Segment
    Mark System Segment for Update
    Open System Segment
  F:
    Null
```

Figure A2-28 GRAFIX VCLR



```
T  Initialize or Update Display (IFLAG = 1 or 2)  F
T:
        Open Link Segment
        Compute Translation Matrix for Link
        Compute Joint Angle Rotation Matrix
        T  Initial Pass (IFLAG = 1)  F
        T:
            CALL MATINT to Compute and Store Rotation Matrices for Link Rotation Sequence
        F:
            Retrieve Rotation Matrices for Link Rotation Sequence
        Compute Total Transformation Matrix for Link
            Draw Component
        DOUNTIL All Link Components are Drawn
        Close Link Segment
    DOUNTIL All Links Displayed
    Open Tool Segment
    T  Initial Pass (IFLAG = 1)  F
    T:
        CALL MATINT to Compute and Store Rotation Matrices for Tool Rotation Sequence
    F:
        Retrieve Rotation Matrices for Tool Rotation Sequence
    Compute Total Transformation Matrix for Tool
        Draw Component
    DOUNTIL All Tool Components are Drawn
    Close Tool Segment
    Close System Segment
    Replace System Segment in Display
F:
    Null
T  Terminate Graphics (IFLAG = 3)  F
T:
    Terminate Graphics
F:
    Null
```

Figure A2-28 (concluded)

Graphics Matrix Initialization (MATINT) - Subroutine MATINT is called from subroutine GRAFIX to provide initial computation of certain constant matrices, which are then stored for later use by subroutine GRAFIX. The computation and storage of the matrices decrease execution time for system display.

Subroutine MATINT is called once for each joint/link in the robotic system and once for the end effector. In each case, the matrix representing the total of the translation and the rotation sequence defining the location and orientation of that part of the robotic system is computed.

Evans and Sutherland graphics routines are used to perform the matrix computations and concatenations.

Figure A2-29 is the VCLR for subroutine MATINT.

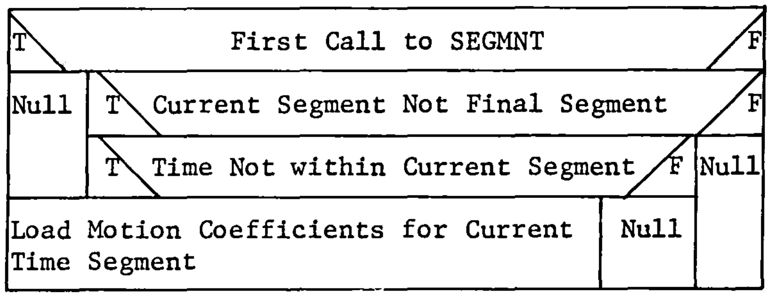
T Link Data Requested	F
Decode Link Rotation Sequence	Compute Translation Matrix for Tool
Convert Rotation Angles to Graphics Units	Decode Tool Rotation Sequence
Compute Rotation Matrix for Third Rotation of Link Rotation Sequence	Convert Rotation Angles to Graphics Units
Compute Rotation Matrix for Second Rotation of Link Rotation Sequence	Compute Rotation Matrix for Third Rotation of Tool Rotation Sequence
Compute Rotation Matrix for First Rotation of Link Rotation Sequence	Compute Rotation Matrix for Second Rotation of Tool Rotation Sequence
Retrieve Total Link Rotation Transformation Matrix	Compute Rotation Matrix for First Rotation of Tool Rotation Sequence
	Retrieve Total Tool Translation - Rotation Transformation Matrix

Figure A2-29 MATINT VCLR

2.2.1.3 Load Time Segment Coefficients (SEGMNT) - Subroutine SEGMNT loads the appropriate coefficients for the time functions that define the desired system motion. The coefficients were specified during the System Definition function. A maximum of 20 time segments is allowed with coefficients specified for each segment. The coefficients are stored in COMMON/CONTRL/. The coefficients required for the current time segment are selected from the stored data and loaded into the current working array VELPRO.

At each time step, subroutine SEGMNT is called to ensure that the proper coefficients are loaded. If a new segment has begun, the proper coefficients are loaded from COMMON/CONTRL/ to array VELPRO.

Figure A2-30 is the VCLR for subroutine SEGMNT.



T
First Call to SEGMNT
F
Null
T
Current Segment Not Final Segment
F
T
Time Not within Current Segment
F
Null
Load Motion Coefficients for Current Time Segment
Null

Figure A2-30 SEGMNT VCLR

2.2.1.4 Requirements Function Motion Controller (CNTRLR) - Subroutine CNTRLR controls the motion of manipulator models during requirements analysis. CNTRLR is called at every time step and supervises computations that describe both the position and velocity of manipulator components during requirements analysis. CNTRLR also operates on user input to activate the following ROBSIM program options:

1) Print out a detailed file describing the motion of the manipulator model;

2) Perform dynamics computations to determine forces and torques acting at the joints of the model as a result of input motion;

3) Display a graphics representation of the manipulator model during motion;

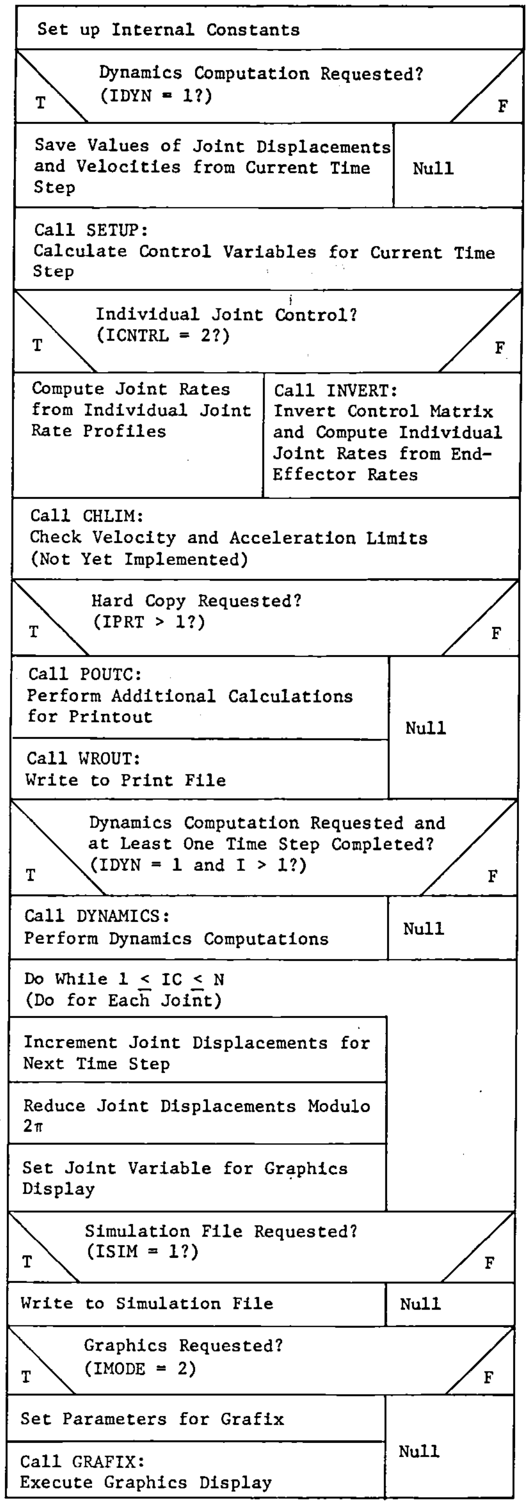
4) Save a file describing the motion of the model for later graphics display.

CNTRLR can use either of two methods of motion control, depending on the user's selection:

1) Individual Joint Rate Control - The user inputs a rate profile for each joint that specifies the rotation rate of the joint as a function of time. Using this form of motion control, CNTRLR directly computes the rotation rate of each joint.

2) Coordinated End Effector (Tool) Control - The user inputs a set of six rate profiles that specify tool velocity as a function of time. Using this form of motion control, CNTRLR first computes the specified tool velocity, then calculates the set of individual joint rates that yield the best approximation to the desired tool velocity.

Figure A2-31 is the VCLR for subroutine CNTRLR.



```
Set up Internal Constants
Dynamics Computation Requested?
(IDYN = 1?)
  T: Save Values of Joint Displacements
     and Velocities from Current Time
     Step
  F: Null
Call SETUP:
Calculate Control Variables for Current Time
Step
Individual Joint Control?
(ICNTRL = 2?)
  T: Compute Joint Rates
     from Individual Joint
     Rate Profiles
  F: Call INVERT:
     Invert Control Matrix
     and Compute Individual
     Joint Rates from End-
     Effector Rates
Call CHLIM:
Check Velocity and Acceleration Limits
(Not Yet Implemented)
Hard Copy Requested?
(IPRT > 1?)
  T: Call POUTC:
     Perform Additional Calculations
     for Printout
     Call WROUT:
     Write to Print File
  F: Null
Dynamics Computation Requested and
at Least One Time Step Completed?
(IDYN = 1 and I > 1?)
  T: Call DYNAMICS:
     Perform Dynamics Computations
  F: Null
Do While 1 ≤ IC ≤ N
(Do for Each Joint)
    Increment Joint Displacements for
    Next Time Step
    Reduce Joint Displacements Modulo
    2π
    Set Joint Variable for Graphics
    Display
Simulation File Requested?
(ISIM = 1?)
  T: Write to Simulation File
  F: Null
Graphics Requested?
(IMODE = 2)
  T: Set Parameters for Grafix
     Call GRAFIX:
     Execute Graphics Display
  F: Null
```

Figure A2-31 CNTRLR VCLR

2.2.1.4.1 Set Up Computations (SETUP) - SETUP is called at each time step during requirements analysis and computes quantities needed in other subroutines under CNTRLR. Hence, SETUP acts to "set up" succeeding calculations.

The quantities computed by SETUP include the following:

1) The transformation matrices between neighboring joint coordinate systems and between joint and base coordinate systems;

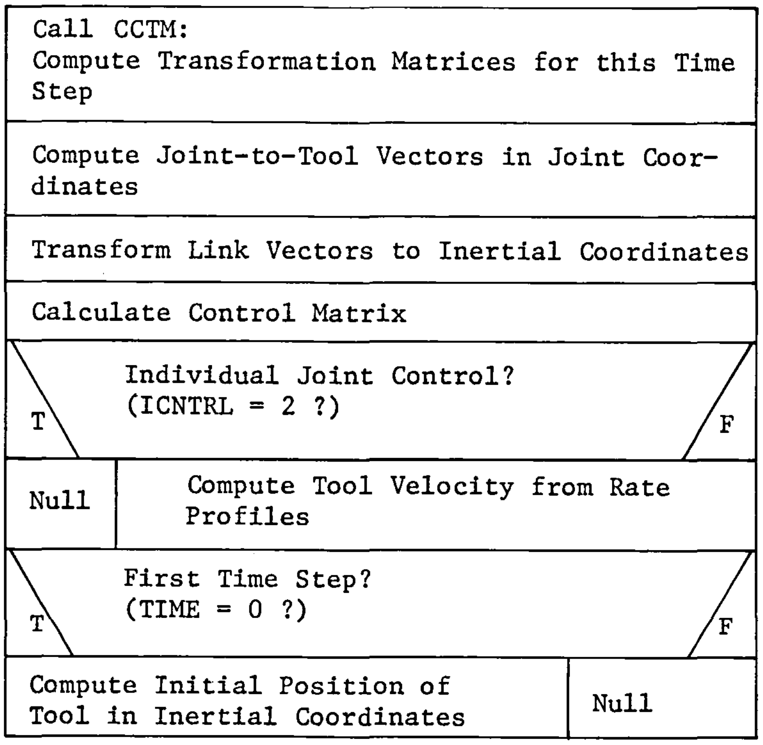
2) The vectors describing tool location with respect to each joint (the vectors are expressed in joint coordinates);

3) Transformation of vectors representing links into base coordinates;

4) The control matrix used to compute tool velocity given individual joint rates (see Appendix D);

5) The specified tool velocity from the input rate profiles (only performed when coordinated tool rate control is specified).

Figure A2-32 is the VCLR for subroutine SETUP.


Call CCTM:
Compute Transformation Matrices for this Time Step
Compute Joint-to-Tool Vectors in Joint Coordinates
Transform Link Vectors to Inertial Coordinates
Calculate Control Matrix
Individual Joint Control?
(ICNTRL = 2 ?)
T
F
Null
Compute Tool Velocity from Rate Profiles
First Time Step?
(TIME = 0 ?)
T
F
Compute Initial Position of Tool in Inertial Coordinates
Null
Figure A2-32 SETUP VCLR

2.2.1.4.2 Perform Output Calculations (POUTC) - POUTC is only called if a detailed printout of manipulator model motion data is requested by the user. If such a request has been made, POUTC performs at each time step computations of quantities that appear in the printout but are not required elsewhere in the ROBSIM program. The quantities computed by POUTC are:

1) Tool position in base coordinates at the end of the time step;

2) Transformation of all joint-to-tool vectors to base coordinates;

3) Ideal tool position (coordinated tool rate control only);

4) Tool velocity resulting from individual joint rates.

Figure A2-33 is the VCLR for subroutine POUTC.

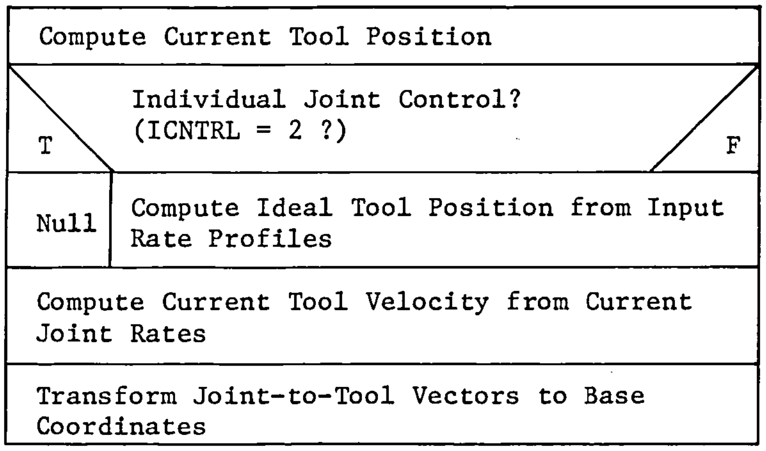

Compute Current Tool Position
Individual Joint Control? (ICNTRL = 2 ?)
T
F
Null
Compute Ideal Tool Position from Input Rate Profiles
Compute Current Tool Velocity from Current Joint Rates
Transform Joint-to-Tool Vectors to Base Coordinates

Figure A2-33 POUTC VCLR

2.2.1.4.3 Write out Motion Calculations (WROUT) - WROUT produces a file to be printed that contains details on the computed motion of the manipulator model. WROUT is only called if the user requests a printed output.

On the first time step only, WROUT lists the initial conditions of the manipulator model. The data output includes:

1) For each joint

   - Free axis of rotation,

   - Joint rate profile (if applicable*),

   - Vector describing location of next joint,

   - Initial joint displacement;

2) Tool rate profiles (if applicable*);

3) Analysis stop time;

4) Analysis time increment step size.

On every time step, WROUT lists:

1) Time;

2) Ideal tool velocity (if applicable*);

3) Tool velocity resulting from joint rates;

4) Ideal tool position (if applicable*);

5) Current tool position;

6) Position error as vector and magnitude (if applicable*);

7) For each joint

   - Current joint rotation rate,

   - Current joint displacement (degrees and radians),

   - Current joint-to-base transformation matrix,

   - Current joint-to-tool vector (joint and base coordinates),

   - Current location of joint in base coordinates.

---

*This step is applicable only if coordinated tool rate control was used.

Figure A2-34 is the VCLR for subroutine WROUT.

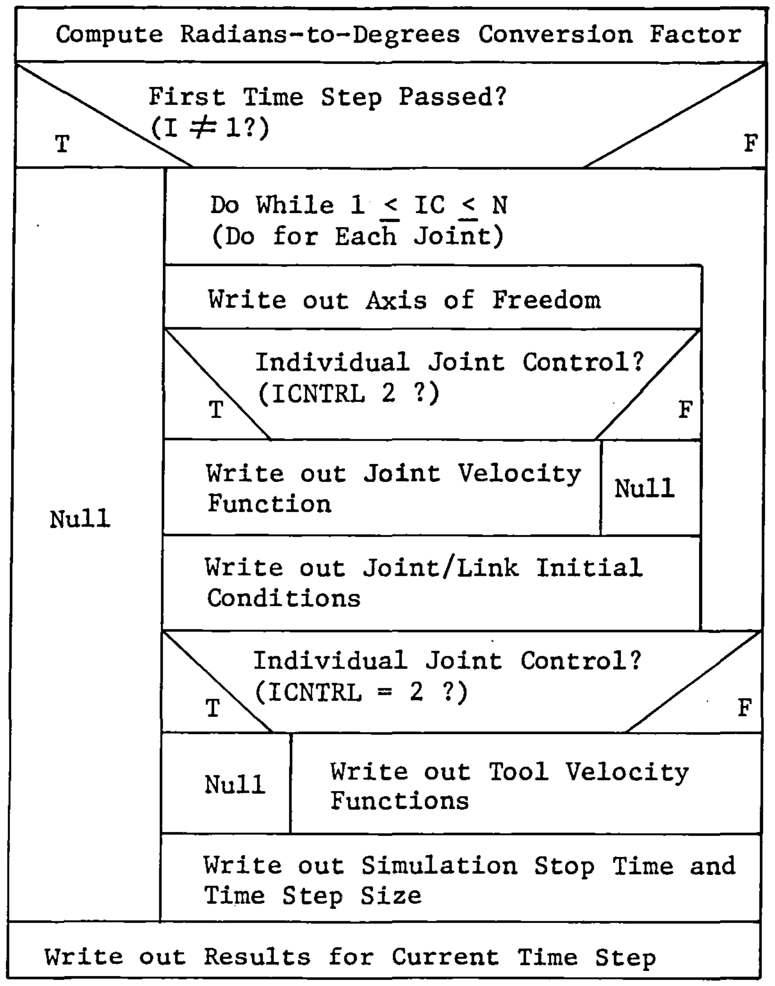

Compute Radians-to-Degrees Conversion Factor
First Time Step Passed? (I ≠ 1?)
T
F
Null
Do While 1 ≤ IC ≤ N (Do for Each Joint)
Write out Axis of Freedom
Individual Joint Control? (ICNTRL 2 ?)
T
F
Write out Joint Velocity Function
Null
Write out Joint/Link Initial Conditions
Individual Joint Control? (ICNTRL = 2 ?)
T
F
Null
Write out Tool Velocity Functions
Write out Simulation Stop Time and Time Step Size
Write out Results for Current Time Step

Figure A2-34 WROUT VCLR

2.2.1.4.4 Dynamics Computation Function (DYNAMICS) - Subroutine DYNAMICS controls the solution of the dynamics equations derived in Appendix B. DYNAMICS is called only if the user has requested dynamics output; in this case, DYNAMICS is called every time step.

For input into the dynamics equations, DYNAMICS calculates the average angular displacement, angular velocity, and angular acceleration for each joint over an entire time step. Average displacement and velocity are obtained by averaging values from the beginning and end of each time step. The average velocities are computed by taking the difference of the velocities from the beginning and end of each time step and dividing by the step size.

DYNAMICS then calls the subroutines that perform the following functions:

1) Computation of transformation matrices for the average joint displacements;

2) Transformation of all quantities to base coordinates;

3) Computation of total velocity and acceleration of each joint/link system;

4) Computation of dynamic reactions;

5) Writing of results to print file.

Figure A2-35 is the VCLR for subroutine DYNAMICS.

Initialize All Variables to Zero
Average Position and Velocity Over Time Step
Compute Average Acceleration by Differences
Call CCTM: Compute Transformation Matrices for Average Position
Call TQBASE: Transform All Quantities to Base Coordinates
Call CABSM: Compute Absolute Velocities and Accelerations
Call FORCE: Compute Reaction Forces
Call TORQUE: Compute Reaction Torques
Call DYNOUT: Write Results to Print File

Figure A2-35 DYNAMICS VCLR

2.2.1.4.4.1 Transform Quantities to Base Coordinates (TQBASE) - The purpose of subroutine TQBASE is to transform the vector quantities describing manipulator motion and the link inertia matrices into base coordinates.

The formula for transforming vectors from joint i coordinates to base coordinates is

$${}_bV = {}_bT_i\,{}_iV$$

where

${}_iV$ = Vector, V, expressed in joint i coordinates;
${}_bV$ = Same vector V, expressed in base coordinates;
${}_bT_i$ = Joint i-to-base transformation matrix.

The formula for transforming inertia matrices from joint coordinates to base coordinates is

$${}_bI = ({}_bT_i)({}_iI)({}_bT_i)^{-1}$$

where

${}_iI$ = Inertia matrix, I, expressed in joint i coordinates;
${}_bI$ = Same inertia matrix, I, expressed in base coordinates;
${}_bT_i$ = Joint i-to-base transformation matrix.

For a more detailed discussion of the transformation, see Appendix B.

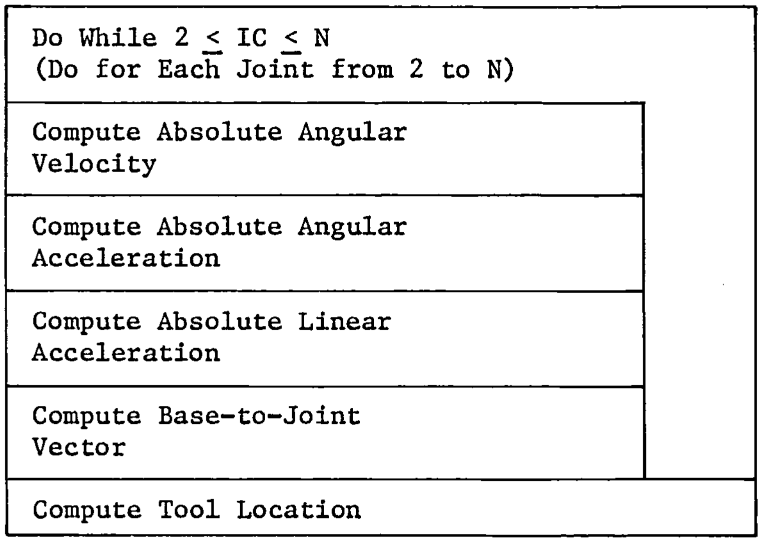
Figure A2-36 is the VCLR for subroutine TQBASE.

Transform Vector Quantities to Base Coordinates
Transform Inertia Matrices to Base Coordinates

Figure A2-36 TQBASE VCLR

2.2.1.4.4.2 <u>Compute Absolute Motion (CABSM)</u> - CABSM uses a recursive technique (see Appendix B) to compute the absolute angular velocity, angular acceleration, and linear acceleration for each joint/link system. CABSM also computes the location of each joint and the tool in base coordinates.

Figure A2-37 is the VCLR for subroutine CABSM.



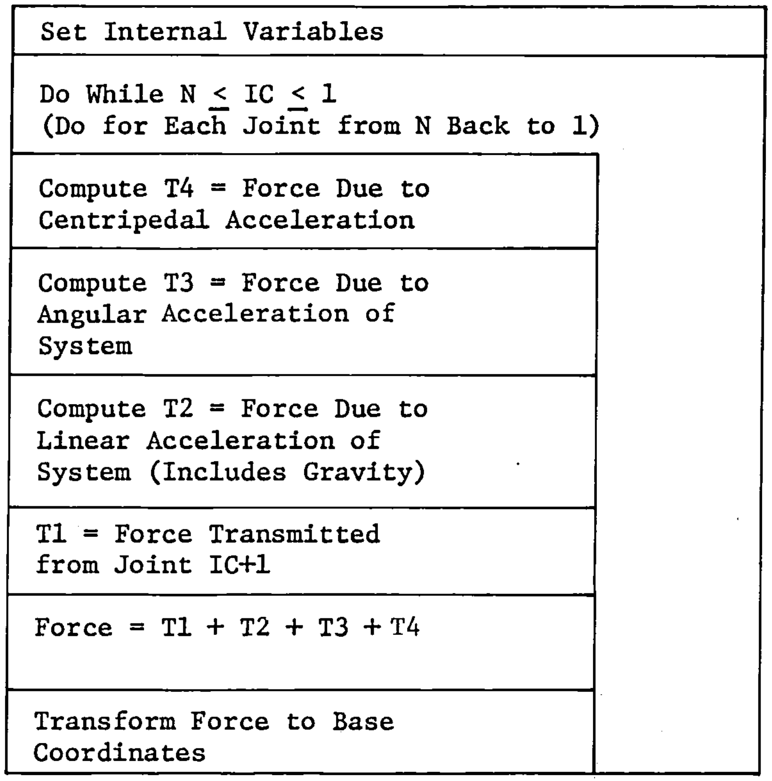
```
Do While 2 ≤ IC ≤ N
(Do for Each Joint from 2 to N)
    Compute Absolute Angular Velocity
    Compute Absolute Angular Acceleration
    Compute Absolute Linear Acceleration
    Compute Base-to-Joint Vector
Compute Tool Location
```

Figure A2-37 CABSM

2.2.1.4.4.3 <u>Compute Reaction Forces (FORCE)</u> - FORCE computes the reaction forces at each joint using the recursive technique derived in Appendix B. In particular, FORCE implements Equation B-12.

FORCE also transforms the joint reaction forces into base coordinates.

Figure A2-38 is the VCLR for subroutine FORCE.



```
Set Internal Variables
Do While $N \leq IC \leq 1$
(Do for Each Joint from N Back to 1)
    Compute T4 = Force Due to
    Centripedal Acceleration
    Compute T3 = Force Due to
    Angular Acceleration of
    System
    Compute T2 = Force Due to
    Linear Acceleration of
    System (Includes Gravity)
    T1 = Force Transmitted
    from Joint IC+1
    Force = T1 + T2 + T3 + T4
    Transform Force to Base
    Coordinates
```

Figure A2-38 FORCE VCLR

2.2.1.4.4.4 Compute Reaction Torque (TORQUE) - TORQUE computes the reaction torques at each joint using the recursive technique derived in Appendix B. In particular, TORQUE implements Equation B-13.

TORQUE also transforms the joint reaction forces into base coordinates.

Figure A2-39 is the VCLR for subroutine TORQUE.

```
Set Internal Variables
Do While $N \geq IC \geq 1$
(Do for Each Joint from N to 1)
    S1 = Torque Transmitted from Joint IC + 1
    Compute $S2 = I\alpha$
    Compute $S3 = w \times Iw$
    Compute S4 = Moment of Force Transmitted from Joint IC + 1
    S5 = Any External Torques
    Compute $S6 = m\{ r \times [w \times (x \times r)]\}$
    Torque = S1 + S2 + S3 + S4 + S5 + S6
    Transform Torque to Base Coordinates
```

Figure A2-39 TORQUE VCLR

2.2.1.4.4.5 Write Dynamics Output (DYNOUT) - DYNOUT writes a detailed record of the dynamic input and output to a print file.

In addition to the dynamics output, at the end of the first time step, before any dynamics output has been written, DYNOUT writes a record of the model initial conditions. This initial record includes:

1) The number of joints in the manipulator model;

2) The analysis start time, stop time, and step size;

3) For each joint

   - The joint type,

   - Link dimensions in inches and meters,

   - Location of link center-of-gravity in inches and meters,

   - Mass of link in kilograms,

   - Link inertia matrix.

At the end of every time step, DYNOUT writes a record of the dynamics input and output. For each joint, this record includes:

1) Joint angular displacement (degrees and radians);

2) Joint location in base coordinates (inches and meters);

3) Link vector (inches and meters, i-joint and base coordinates);

4) Relative angular velocity in radians/second (joint and base coordinates);

5) Relative angular acceleration in radians/second^2 (joint and base coordinates);

6) Absolute angular velocity in radians/second (joint and base coordinates);

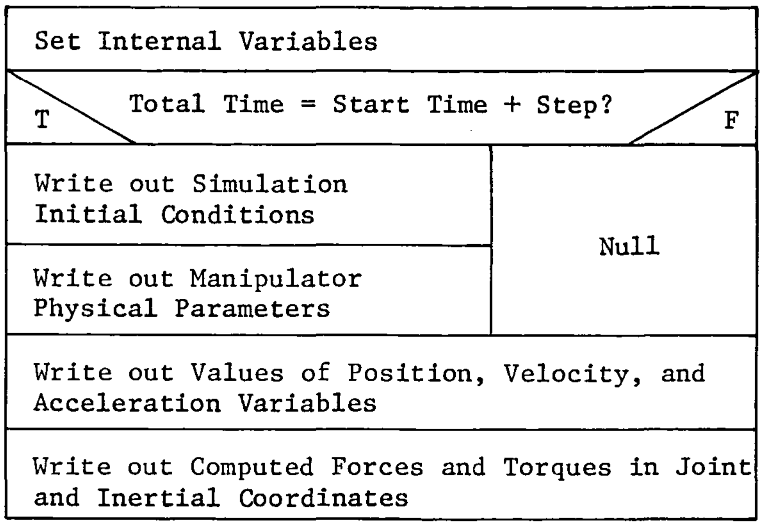
7) Relative angular acceleration in radians/second^2 (joint and base coordinates);

8) Absolute linear acceleration in inches/second^2 and meters/second^2 (joint and base coordinates);

9) Reaction force in kilogram-inches/second^2 and kilogram-meters/second^2 (joint and base coordinates);

10) Reaction torque in kilogram-inches^2/second^2 and kilogram-meters^2/second^2 (joint and base coordinates).

Figure A2-40 is the VCLR for subroutine DYNOUT.



Set Internal Variables
Total Time = Start Time + Step?
T
F
Write out Simulation Initial Conditions
Write out Manipulator Physical Parameters
Null
Write out Values of Position, Velocity, and Acceleration Variables
Write out Computed Forces and Torques in Joint and Inertial Coordinates

Figure A2-40 DYNOUT VCLR

2.3 POSTPROCESSING FUNCTION DRIVER (POSTDRVR)

The Postprocessing function driver operates in an interactive mode and prompts the user for the postprocessing option desired. Currently valid options are:

1) Replay robotic system motion;

2) Parameter versus parameter plots;

3) Return to the ROBSIM executive.

Additional postprocessing functions will be added as program capabilities are expanded.

If Option 1 is selected, subroutine MOTION is called to provide a replay of the system motion computed during the Analysis Tools function execution. If Option 2 is selected, subroutine GENPLT is called to provide parameter versus parameter plots of any of the data computed and written to a plot file during the Analysis Tools function execution.

A recoverable error encountered within subroutine POSTDRVR causes an error message to be written through a call to subroutine ERRMSG. Appropriate recovery action is then taken. Nonrecoverable errors encountered within routines called by POSTDRVR cause return of control to the ROBSIM executive program.

Figure A2-41 is the VCLR for subroutine POSTDRVR.

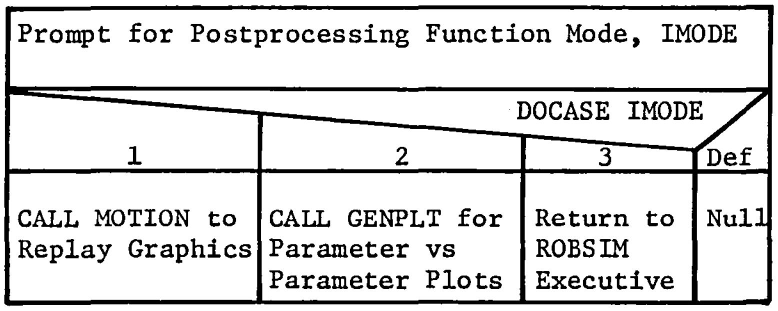

Prompt for Postprocessing Function Mode, IMODE
DOCASE IMODE
1
2
3
Def
CALL MOTION to Replay Graphics
CALL GENPLT for Parameter vs Parameter Plots
Return to ROBSIM Executive
Null

Figure A2-41 POSTDRVR VCLR

2.3.1 Replay Motion (MOTION)

Subroutine MOTION is called from subroutine POSTDRVR to provide a replay of the robotic system motion produced during the Analysis Tools function execution. The user is prompted for the name of the file containing the data generated during the Analysis Tools function execution. The file is then opened. Subroutine GRAFIX is called to initialize the graphics system and display.

The postprocessing data file is read for each time step to obtain the individual joint displacements. Subroutine GRAFIX is called with the joint displacements at each time step to update the display producing the system motion.

Upon completion of the motion display, the postprocessing data file is closed and subroutine GRAFIX is called to terminate the graphics display.

Figure A2-42 is the VCLR for subroutine MOTION.

```
CALL RDSIM to Read System Definition File
Prompt for File Name of Analysis Tool Output
file
Open Analysis Tool Output File
Initialize Graphics and Display
    Read Current Joint Variables for System
    CALL GRAFIX to Update Display
DOUNTIL All Records Read from File
Terminate Graphics
Close Analysis Tool Output File
```

Figure A2-42 MOTION VCLR

2.3.2 General Plotting (GENPLT)

Subroutine GENPLT is called from subroutine POSTDRVR to provide parameter versus parameter plots of the data generated during the Analysis Tools function execution. A plot file must have been requested with the Analysis Tools function execution.

Subroutine GENPLT provides the capability to plot the data for any variable on the plot file against any other variable on the plot file. User interface with subroutine GENPLT is through interactive prompts. Plotting may be requested on an HP7221 plotter, Tektronix 4010, Tektronix 4014, or Retrographics terminal. Plotting is done using the DISSPLA plot package.

The user is prompted for the file name of the plot file, which is then opened. Subroutine RDPLT is called to prompt the user for the variables to be plotted. The user may then specify a variety of options or use defaults as desired. The user has complete control of plot format. Once all plot characteristics are specified, subroutine RDPLT is called to read the plot file and extract the data to be plotted.

Following plotting of the data, subroutine LOGO may be called to plot the Martin Marietta logo if desired.

Figure A2-43 is the VCLR for subroutine GENPLT.

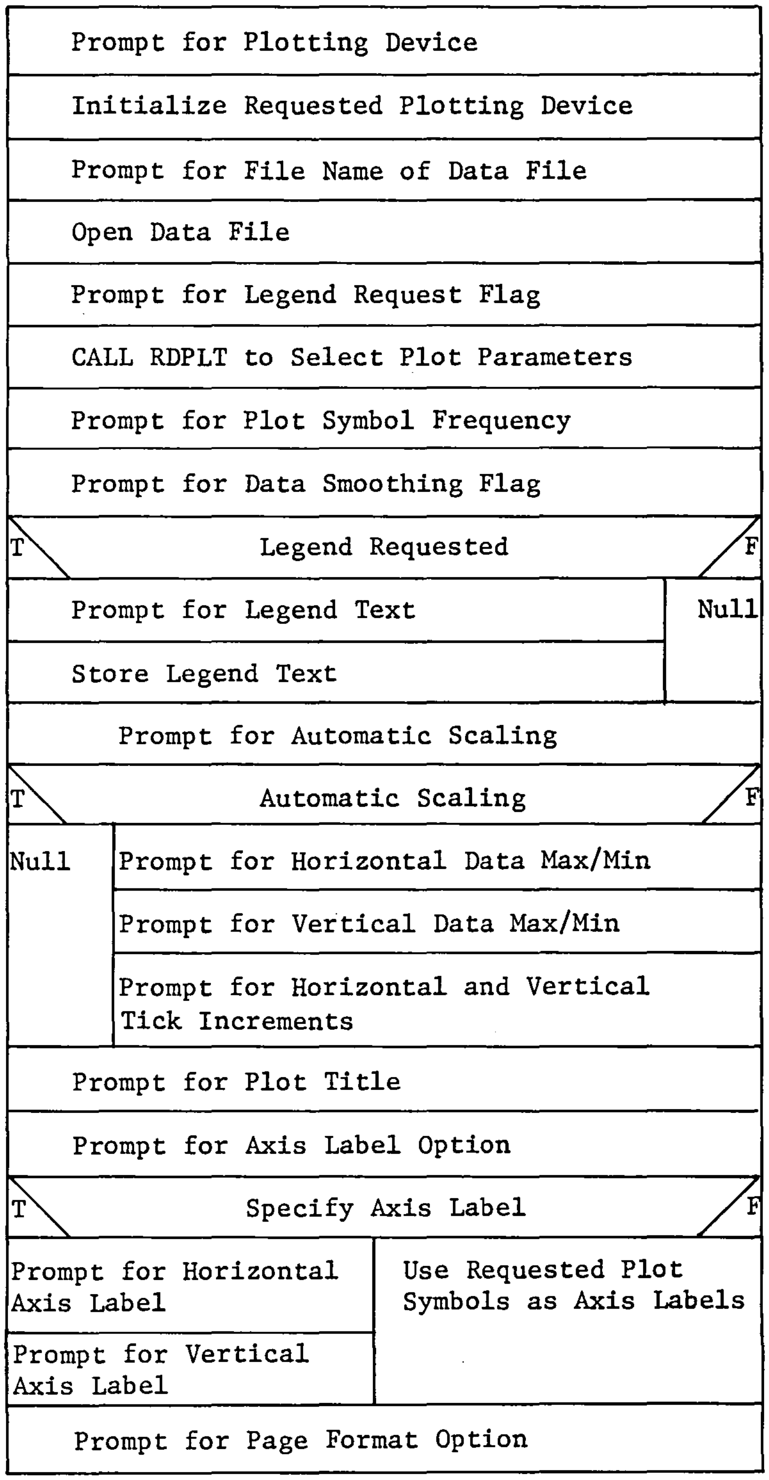

Prompt for Plotting Device
Initialize Requested Plotting Device
Prompt for File Name of Data File
Open Data File
Prompt for Legend Request Flag
CALL RDPLT to Select Plot Parameters
Prompt for Plot Symbol Frequency
Prompt for Data Smoothing Flag
T
Legend Requested
F
Prompt for Legend Text
Store Legend Text
Null
Prompt for Automatic Scaling
T
Automatic Scaling
F
Null
Prompt for Horizontal Data Max/Min
Prompt for Vertical Data Max/Min
Prompt for Horizontal and Vertical Tick Increments
Prompt for Plot Title
Prompt for Axis Label Option
T
Specify Axis Label
F
Prompt for Horizontal Axis Label
Prompt for Vertical Axis Label
Use Requested Plot Symbols as Axis Labels
Prompt for Page Format Option

Figure A2-43 GENPLT VCLR

```
Specify Page Format
  T:
    Prompt for Page Dimensions
    Prompt for Origin Location
    Prompt for Axis Lengths
    Logo Requested
      T:
        Prompt for Logo Position
        Prompt for Logo Size
      F:
        Null
  F:
    Set Parameters for 11.0x8.5 Format
    Logo Required
      T:
        Set Logo Parameters
      F:
        Null
Automatic Scaling
  T:
    Compute Horizontal Tick Mark Increment
    Compute Horizontal Axis Max/Min Values
    Compute Vertical Tick Mark Increment
    Compute Vertical Axis Max/Min Values
  F:
    Null
Draw Axes
Label Horizontal Axis
Label Vertical Axis
Draw Plot Title
Draw Axes Tick Marks and Label
CALL RDPLT to Read Plot File and Load Plot Data
Smooth Data
  T:
    Spline Fit Data
  F:
    Null
Plot Data
Legend Required
  T:
    Plot Legend
  F:
    Null
Logo Requested
  T:
    Plot Logo
  F:
    Null
Terminate Plotting Device
```

Figure A2-43 (concluded)

2.3.2.1 <u>Read Plot File (RDPLT)</u> - Subroutine RDPLT is called from subroutine GENPLT to prompt the user for the variables to be plotted and to read the plot file and extract the data to be plotted.

The input argument IFLAG is used to specify selection of plot parameters or extraction of plot data. If IFLAG = 1, first the plot file symbol record is read. The user is then prompted for the symbol of the parameter desired as the horizontal axis parameter. The symbol record is searched to locate the requested symbol and determine the position of the data corresponding to that symbol in the plot file records. This process is repeated for the vertical axis parameter. The plot file header record is then read to obtain the maximum and minimum values for the plot parameters selected.

If IFLAG = 2, the plot file data records are read to extract and store the parameter values to be plotted. A maximum of 5000 data values can be stored at one time. If more data than that are required, they will be plotted in blocks of 5000 points.

Figure A2-44 is the VCLR for subroutine RDPLT.

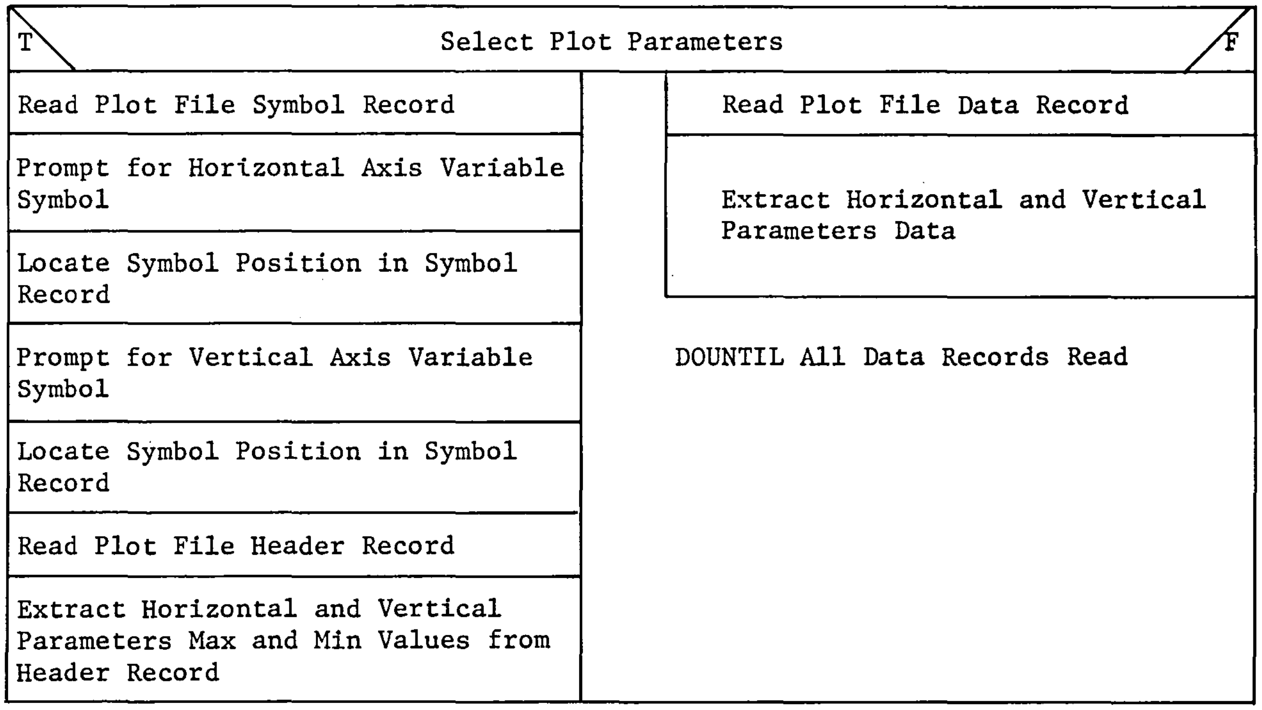

T
Select Plot Parameters
F
Read Plot File Symbol Record
Prompt for Horizontal Axis Variable Symbol
Locate Symbol Position in Symbol Record
Prompt for Vertical Axis Variable Symbol
Locate Symbol Position in Symbol Record
Read Plot File Header Record
Extract Horizontal and Vertical Parameters Max and Min Values from Header Record
Read Plot File Data Record
Extract Horizontal and Vertical Parameters Data
DOUNTIL All Data Records Read

Figure A2-44 RDPLT VCLR

2.3.2.2 Plot Logo (LOGO) - Subroutine LOGO is called from subroutine GENPLT to plot the Martin Marietta logo. The logo can be placed anywhere on the plot and can be drawn any size.

Figure A2-45 is the VCLR for subroutine LOGO.

```
Open Logo Data File
Read Logo Data
Close Logo Data File
    Draw Logo Segment
    DOUNTIL All Logo Segments Complete
```

Figure A2-45 LOGO VCLR

2.4 ROBSIM UTILITIES

This section contains the description of ROBSIM subroutines that provide utility functions and are used throughout the program. The routines described in this section are:

1) ERRMSG - Searches the error message file and prints the current error message;

2) RDSIM - Reads the data file created by the System Definition function;

3) SETLU - Sets logical units for all program input and output;

4) WRTSIM - Writes to disk the data file generated by the System Definition function;

5) ZERCOM - Zeros all locations in the common blocks used for data storage in the System Definition function.

2.4.1 Error Message Routine (ERRMSG)

The subroutine ERRMSG prints error messages for any errors occurring during execution of the ROBSIM program. Error conditions have been defined throughout the program and error messages stored in an error message file with unique error numbers used to identify each error message. When an error occurs, subroutine ERRMSG is called with the appropriate error number. Subroutine ERRMSG opens the error message file and locates and prints the appropriate error message. The error message file is then closed and control is returned to the calling program for appropriate action.

A recoverable error encountered within subroutine ERRMSG causes an error message to be written followed by appropriate recovery action. A nonrecoverable error encountered within subroutine ERRMSG causes an error message to be written and control to be returned through the sequence of calling routines back to the ROBSIM executive program for further user action.

Figure A2-46 is the VCLR for subroutine ERRMSG.

Open Error Message File
Locate Text of Message Corresponding to Input Error Number
Write Error Message
Close Error Message File

Figure A2-46 ERRMSG VCLR

2.4.2 Read Input File (RDSIM)

The subroutine RDSIM reads the data file created by the System Definition function. The data file is an unformatted file containing the contents of the following COMMON blocks:

1) COMMON/AMASPR/ - Mass properties data;

2) COMMON/CONSTR/ - Constraint data;

3) COMMON/CONTRL/ - Prescribed motion data;

4) COMMON/ENVIRN/ - Environment graphics representation data;

5) COMMON/GEOM/ - System geometry data;

6) COMMON/IOBJ/ - System graphics representation data;

7) COMMON/IOPT/ - Program options data.

The user is prompted for the file name under which the data have been stored on disk. The file is opened and read, loading all data into the appropriate COMMON locations. The user is then prompted to specify whether the file is to be saved or deleted. The file is then closed with the proper disposition option.

An error encountered within subroutine RDSIM causes an error message to be written through a call to subroutine ERRMSG. If the error is a recoverable error, appropriate recovery action is taken. If the error is nonrecoverable, control is returned through the sequence of calling routines to the ROBSIM executive program for further user action.

Figure A2-47 is the VCLR for subroutine RDSIM.

```
Prompt for File Name of Input File
Open Requested File
Read Mass Properties Data
Read Constraints Data
Read Motion Specification Data
Read Environment Graphics Data
Read Robotic System Geometry Data
Read Robotic System Graphics Data
Read Program Options Data
Prompt for Disposition of Input File
T  IF Deletion of File Requested  F
    T: Close and Delete File
    F: Close and Save File
```

Figure A2-47 RDSIM VCLR

2.4.3 Set Logical Units (SETLU)

The subroutine SETLU sets the logical units used within the ROBSIM program for all program input and output. Default logical units are set in a DATA statement in subroutine SETLU. The user may accept the default logical unit assignments or may request modifications. The capability to modify the default logical unit assignments is not currently implemented. The logical unit data are stored in COMMON block/LUNIT/for use by the rest of the ROBSIM program.

Figure A2-48 is the VCLR for subroutine SETLU.

$$\boxed{\text{Set Logical Unit Numbers Required for Program I/O Operations}}$$

Figure A2-48 SETLU VCLR

2.4.4 Write Input File (WRTSIM)

The subroutine WRTSIM writes to disk the data file created by the System Definition function. The data file is an unformatted file containing the contents of the following COMMON blocks:

1) COMMON/AMASPR/ - Mass properties data;

2) COMMON/CONSTR/ - Constraint data;

3) COMMON/CONTRL/ - Prescribed motion data;

4) COMMON/ENVIRN/ - Environment graphics representation data;

5) COMMON/GEOM/ - System geometry data;

6) COMMON/IOBJ/ - System graphics representation data;

7) COMMON/IOPT/ - Program options data.

The user is prompted for the file name under which the data are to be stored on disk. The file is opened and the data from each COMMON block are written to the file. The file is then closed with a disposition option of "SAVE."

An error encountered within subroutine WRTSIM causes an error message to be written through a call to subroutine ERRMSG. If the error is a recoverable error, appropriate recovery action is taken. If the error is nonrecoverable, control is returned through the sequence of calling routines to the ROBSIM executive program for further user action.

Figure A2-49 is the VCLR for subroutine WRTSIM.

Prompt for File Name To Be Used
Open Requested File
Write Mass Properties Data from Common /AMASPR/ to Disk File
Write Constraints Data from Common /CONSTR/ to Disk File
Write Motion Specification Data from Common /CONTRL/ to Disk File
Write Environment Graphics Data from Common /ENVIRN/ to Disk File
Write Robotic System Geometry Data from Common /GEOM/ to Disk File
Write Robotic System Graphics Data from Common /IOBJ/ to Disk File
Write Program Options Data from Common /IOPT/ to Disk File
Close File

Figure A2-49 WRTSIM VCLR

2.4.5 Zero COMMON (ZERCOM)

The subroutine ZERCOM zeros COMMON locations used to store the data that are input during the System Definition function. Subroutine ZERCOM is called from subroutine CREATE prior to defining a new data file and zeros the contents of the following COMMON blocks:

1) COMMON/AMASPR/ - Mass properties data;

2) COMMON/CONSTR/ - Constraint data;

3) COMMON/CONTRL/ - Prescribed motion data;

4) COMMON/ENVIRN/ - Environment graphics representation data;

5) COMMON/GEOM/ - System geometry data;

6) COMMON/IOBJ/ - System graphics representation data;

7) COMMON/IOPT/ - Program options data.

Figure A2-50 is the VCLR for subroutine ZERCOM.

Zero Fill Mass Properties Common /AMASPR/
Zero Fill Constraints Common /CONSTR/
Zero Fill Motion Specification Common /CONTRL/
Zero Fill Environment Graphics Data Common /ENVIRN/
Zero Fill Robotic System Geometry Common /GEOM/
Zero Fill Robotic System Graphics Data Common /IOBJ/
Zero Fill Program Options Common /IOPT/

Figure A2-50 ZERCOM VCLR

2.5 MATH UTILITIES

This section describes several matrix math routines used within the ROBSIM program.

2.5.1 Compute Complete Transformation Matrix (CCTM)

CCTM is a utility routine that computes the complete transformation matrices needed to transform vectors in the coordinate system of joint i into terms of either the joint i-1 or the base coordinate systems.

CCTM is called at each time step. CCTM multiplies the transformation matrices resulting from initial orientation and current joint displacement to obtain the transformation matrix between joint i and joint i-1. The joint-to-joint transformation matrices are then multiplied to yield the joint-to-base transformation matrices.

Figure A2-51 is the VCLR for subroutine CCTM.

```
Compute Degrees-to-Radians Conversion Factor
Set All Transformation Matrices to Identity
Do While $1 \leq IC \leq N$
(Do for Each Joint from Base to Tool)
    Set Scratch Matrix to Identity
    Compute Transformation Matrix to Joint
    IC-1 Coordinates Resulting from Initial
    Orientation
    Compute Transformation Matrix from
    Current Displacement of Joint IC to
    Initial Displacement
    Multiply Matrices to Obtain Complete
    Joint IC to IC-1 Transformation
    Matrix
    Multiply Matrices to Obtain Complete
    Joint IC to Base Transformation
    Matrix
```

Figure A2-51 CCTM VCLR

2.5.2 Solve Linear System (SLVLIN)

Subroutine SLVLIN is a routine designed to solve the matrix equation $AX = B$ by computing A^+, the psuedo-inverse of A. Details of the calculation of A^+, as well as a general discussion of the pseudo-inverse can be found in Appendix D.

Figure A2-52 is the VCLR for subroutine SLVLIN.

Set Internal Variables $Ax = B$
IMAX = MAX {No. of Rows, No. of Columns}
Call GAUSS: Reduce Augmented System to Row-echelon Form
Compute C in $A = C \cdot D$, a Rank Factorization
Compute Pseudo - Inverse $A^+ = D^t (DD^t)^{-1} C^t$
Compute Best Solution $\hat{x} = A^+B$

Figure A2-52 SLVLIN VCLR

Perform Gaussian Elimination (GAUSS) - GAUSS is a routine that performs Gauss-Jordan elimination with partial pivoting on an augmented matrix system to reduce the system to row-echelon form. More on the Gauss-Jordan method, pivoting, and row-echelon forms can be found in Appendix D and in Matrices and Linear Transformation.*

Figure A2-53 is the VCLR for subroutine GAUSS.

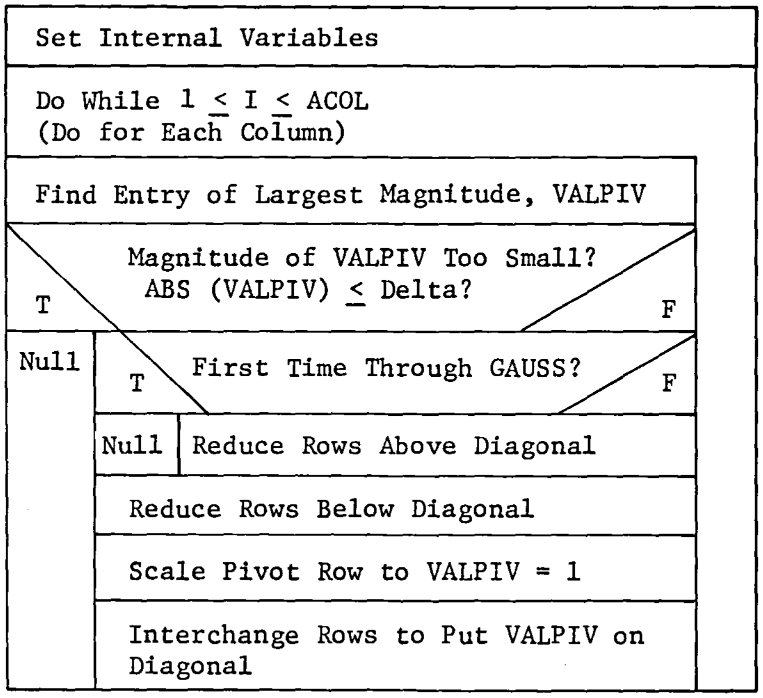

Set Internal Variables
Do While $1 \leq I \leq$ ACOL
(Do for Each Column)
Find Entry of Largest Magnitude, VALPIV
Magnitude of VALPIV Too Small?
ABS (VALPIV) $\leq$ Delta?
T
F
Null
First Time Through GAUSS?
T
F
Null
Reduce Rows Above Diagonal
Reduce Rows Below Diagonal
Scale Pivot Row to VALPIV = 1
Interchange Rows to Put VALPIV on Diagonal

Figure A2-53 GAUSS VCLR

---

*Charles G. Cullen: Matrices and Linear Transformations. Addison-Wesley Publishing Company, 1972

2.5.3 Matrix Multiplication Function (MATMPY)

MATMPY is a utility routine that performs matrix multiplication. The maximum dimension of any of the matrices is 10x10. When MATMPY is called, the maximum dimension of the calling arguments must be passed to MATMPY.

Figure A2-54 is the VCLR for subroutine MATMPY.

```
Compute     C = A • B
  Where     A is i x j
            B is j x k
     and
            C is i x k
```

Figure A3-54 MATMPY VCLR

2.5.4 Form Skew-Symmetric Matrix (SKEW)

SKEW is a utility routine used to form a 3x3 skew-symmetric matrix given a 3x1 vector as input. The resulting skew-symmetric matrix can be used to evaluate a vector cross product by using matrix multiplication.

Figure A2-55 is the VCLR for subroutine SKEW.

Set Diagonal to Zero
Form Skew-Symmetric Matrix for Cross-Product Operator

Figure A2-55 SKEW VCLR

2.5.5 Compute Elementary Transformation Matrix (CETM)

CETM is a utility routine that is used to calculate the elementary transformation matrix resulting from a rotation about a single coordinate axis. If is the angle of rotation and T is the resulting transformation matrix, then

$$T = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \text{ if } \phi \text{ is a rotation about the x axis;}$$

$$= \begin{bmatrix} \cos\phi & 0 & \sin\phi \\ 0 & 1 & 0 \\ -\sin\phi & 0 & \cos\phi \end{bmatrix} \text{ if } \phi \text{ is a rotation about the y axis;}$$

$$= \begin{bmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ if } \phi \text{ is a rotation about the z axis;}$$

Figure A2-56 is the VCLR for subroutine CETM.

Set Matrix to Zero		
Do Case (IAXIS - 2)		
IAXIS - 2 < 0	IAXIS - 2 = 0	IAXIS - 2 > 0
Compute Transformation Matrix for Rotation about the X - Axis	About the Y - Axis	About the Z - Axis

Figure A2-56 CETM VCLR

2.6 EVANS AND SUTHERLAND GRAPHICS ROUTINES

The computer-generated motion representations in the ROBSIM program are produced on Evans and Sutherland (E&S) Multi-Picture System (MPS) line drawing graphics hardware. Picture System 2 (PS-2) equipment and MPS FORTRAN callable graphics routines are used. All graphics programming has been confined to a small number of ROBSIM routines to facilitate conversion to another graphics package if required. The new E&S Picture System 300 (PS-300) would be well suited for ROBSIM use. Conversion of the current MPS code would be required to execute ROBSIM on the PS-300 system.

This section briefly describes each of the E&S MPS routines used in ROBSIM. Complete descriptions can be found in the Evans and Sutherland Multi-Picture System Users Manual (document number E&S #901141-052 NC), Chapter 6, "Multi-Picture System Graphics Software Package."

2.6.1 Initialization and Setup

1) CALL LSPEED - Set line generator refresh speed;
2) CALL MPINIT - Attach MPS Picture Station to user task and initialize;
3) CALL SINIT - Clear refresh display file and initialize segment namestack;
4) CALL TINIT - Initialize transformation stack and set Picture Processor transformation to identify;
5) CALL TWINDP - Set three-dimensional perspective window;
6) CALL VBOUND - Set viewport boundaries;
7) CALL VINTEN - Set intensity levels.

2.6.2 Segment Control

1) CALL SADD - Add segment to refresh display file;
2) CALL SCLOSE - Close most recently opened segment;
3) CALL SMARK - Mark specified segment for update;
4) CALL SOPEN - Open specified segment;
5) CALL SREMOV - Remove specified segment from refresh display file;
6) CALL SREP - Replace the marked segment in the refresh display file with the set of outstanding segments.

2.6.3 Matrix Manipulation

1) CALL TCON - Concatenate the specified matrix with the current Picture Processor transformation;

2) CALL TGET - Load into the specified matrix the current Picture Processor transformation;

3) CALL TPOP - Pop the top element of the Picture Processor transformation stack making it the Picture Processor transformation;

4) CALL TPUSH - Push the current Picture Processor transformation onto the transformation stack;

5) CALL TROTX - Concatenate with the Picture Processor transformation an x-axis rotation matrix for the specified angle;

6) CALL TROTY - Concentrate with the Picture Processor transformation a y-axis rotation matrix for the specified angle;

7) CALL TROTZ - Concatenate with the Picture Processor transformation a z-axis rotation matrix for the specified angle;

8) CALL TSCALE - Concatenate with the Picture Processor transformation a scaling matrix for the specified scale values;

9) CALL TSET - Set the Picture Processor transformation to the specified matrix;

10) CALL TTRAN - Concatenate with the Picture Processor transformation a translation matrix for the specified translation values.

2.6.4 Line Drawing

1) CALL D3DATA - Process three-dimensional data array according to line drawing mode selected;

2) CALL LCOLOR - Set line-generator color and saturation values.

2.6.5 Termination

CALL MPSTOP - Detach the MPS Picture Station from the user task.

2.7 DISSPLA PLOT ROUTINES

The requirement for x-y type parameter plots is met in the ROBSIM program by the use of the Integrated Software Systems Corporation (ISSCO) DISSPLA plotting package. Conversion to another plot package could be easily accomplished.

This section provides a brief description of the DISSPLA routines used in ROBSIM. Complete descriptions of these routines can be found in the Display Integrated Software System and Plotting Language (DISSPLA) Users Manual, Version 9.0.

2.7.1 Device Initialization

1) CALL HP7221 - Initialize Hewlett Packard HP7221 plotter;

2) CALL TK4010 - Initialize Tektronix 4010 terminal or Retrographics terminal;

3) CALL TK4014 - Initialize Tektronix 4014 terminal.

2.7.2 Plot Layout

1) CALL AREA2D - Define the subplot area based on input axis lengths;

2) CALL GRAF - Primary graph setup routine that establishes relationship between physical axis length and plot units and draws axes;

3) CALL HEADIN - Write plot heading (title);

4) CALL NOBRDR - Suppress drawing of border around graph layout;

5) CALL PAGE - Set page size in inches;

6) CALL PHYSOR - Define location of origin on page;

7) CALL SETCLR - Set pen color;

8) CALL XNAME - Label x axis;

9) CALL YNAME - Label y axis.

2.7.3 Curve Plotting

1) CALL CURVE - Plot input x and y data;

2) CALL LINEAR - Plot data linearly connected point to point;

3) CALL RASPLN - Smooth data with rational spline fit.

2.7.4 Point-to-Point Plotting

1) CALL CONNPT - Draw line from current location to input location;

2) CALL STRTPT - Move to input location.

2.7.5 Legend

1) CALL LEGEND - Draw legend;

2) CALL LINES - Load legend text;

3) Function LINEST - Set line length for legend text.

2.7.6 Termination

1) CALL DONEPL - Terminate plot device;

2) CALL ENDPL - Terminate current plot.

3.0 JNTMOD - MAIN PROGRAM

The basis of what will become the simulation tool within the ROBSIM program is being developed outside the ROBSIM framework as the Joint Model (JNTMOD) program. The JNTMOD program models a single typical joint using the state-variable formulation. The single joint model allows demonstration of the state-variable concept and will be extended first to a two-link case and ultimately to an N-link capability. The joint model consists of controller, amplifier, motor, power train, and load models. A Kalman filter is also provided.

The basic state-variable formulation equations used in each model block are:

$$X(k+1) = \phi(k+1,k)X(k) + \theta(k+1,k)U(k) + W(k)$$

$$Y(k+1) = C(k+1)X(k+1)$$

$$Z(k+1) = H(k+1)Y(k+1) + V(K)$$

where

U = Control function;

X = State-variable array;

W = Process noise;

Y = Observable array;

Z = Sensor output array;

V = Sensor noise.

Figure A3-1 shows a typical model block.

When the individual model blocks are combined to form the joint model, a system of equations in the state-variable formulation is formed. Figure A3-2 shows the joint model configuration. A complete discussion of the simulation tool formulation is given in Subsection IV.C of the ROBSIM final report. This document describes the individual subroutines that make up the JNTMOD program. It assumes that the reader is familiar with the notation and equations used.

The Joint Model program main routine, JNTMOD, controls the logic flow through the program. Subroutine INPUT is called to provide input of the parameters necessary within each of the model blocks. Most program options are input through subroutine INPUT as well. Subroutine INIT provides initialization for the joint model system. Subroutine KFINIT is called to handle initialization required if the Kalman filter has been requested. The remainder of the JNTMOD code is within a time loop from the user-requested simulation start time to the user-requested simulation stop time.

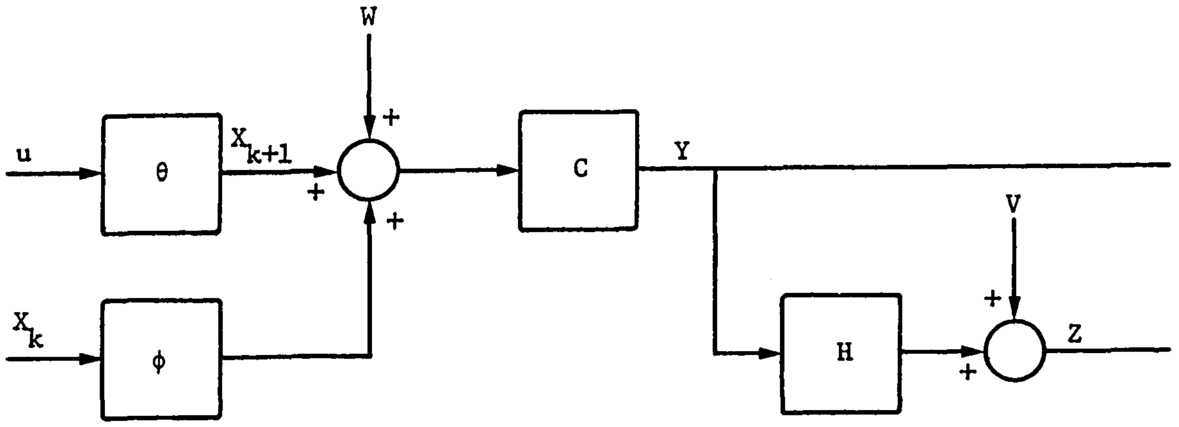


Figure A3-1 Typical Model Block

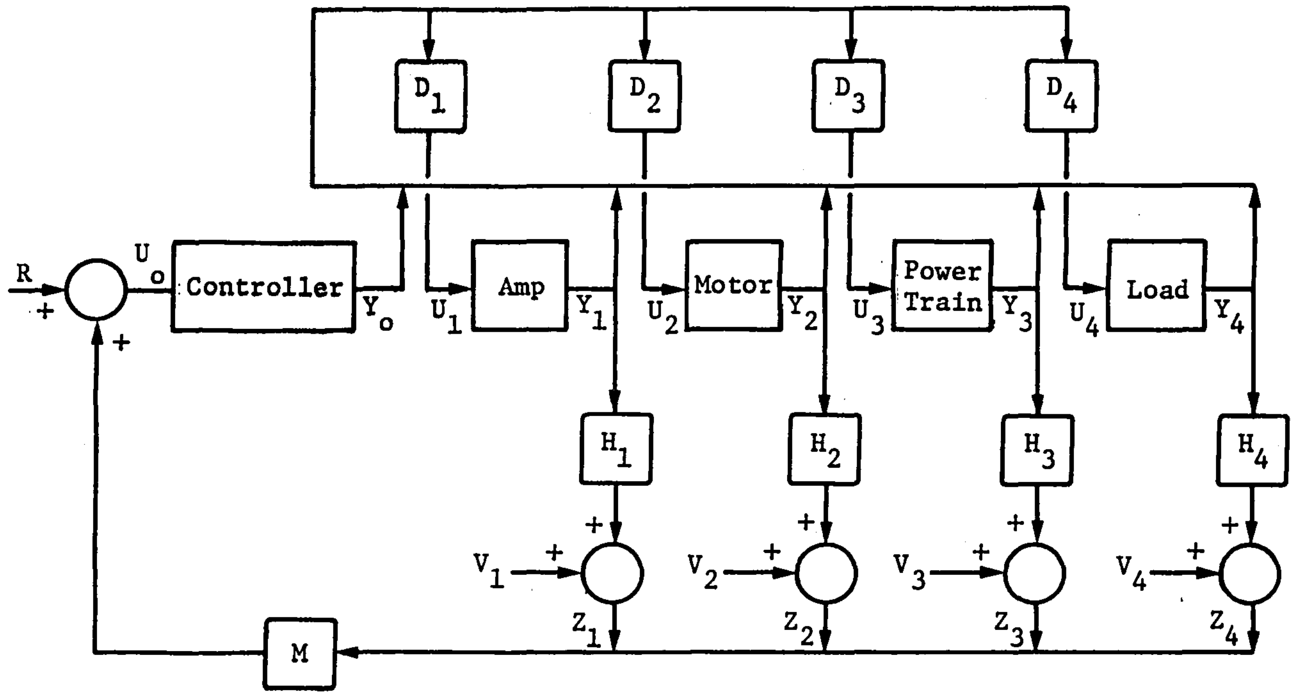


Figure A3-2 Joint Model

The controller is modeled in subroutine CONTRL using the state-variable formulation. If plot file output is requested, the controller parameters are loaded in the plot file data record through calls to subroutine LDVALU.

The logic sequence for each of the remaining joint model blocks (amplifier, motor, power train, and load) is identical. Subroutine UVEC is called to load the control array. The appropriate block model subroutine is then called (AMP, MOTOR, PWRTRN, or LOAD). Each block model uses the state-variable formulation. If plot file output is requested, subroutine LDVALU is called to load the block model parameters in the plot file data record. If printed output is requested, subroutine PRT is called.

If the Kalman filter is requested, the system sensor output array is loaded in subroutine BLDZAL. The system phi matrix is constructed in subroutine BLDPHI. The system theta matrix is constructed in subroutine BLDTHT. The system sensor transform is constructed in subroutine BUILDH. Subroutine KALMAN is called to perform the Kalman filter calculations. If plot file output is requested, the Kalman filter parameters are loaded in the plot file data record through calls to subroutine LDVALU.

The results of the Kalman filter calculations may be used in the system feedback loop if requested.

Following completion of the time loop, the plot file header record is written, if required, and all open files are closed.

Figure A3-3 is the VCLR for the JNTMOD routine.

Figure A3-3

```
CALL INPUT to Obtain User Input Data
Set Logical Unit Numbers
Prompt for Kalman Filter Flag, KFFLAG
IF KFFLAG.EQ.1
  T: Prompt for Use Filter Results in Feed-
     back Loop Flag, KFFDBK
  F: Null
IF Printed Output Requested
  T: Open Print File
  F: Null
IF Plotted Output Requested
  T: Open Plot File
  F: Null
CALL INIT to Initialize All Matrices and
State, Observable, and Sensor Output Arrays
IF KFFLAG.EQ.1
  T: CALL KFINIT to Initialize All Matrices
     and State, Observable, and Sensor Output
     Arrays for Kalman Filter Computations
  F: Null
TIME = Start Time
    TIME = TIME + Step Size
    CALL CONTRL to Load the Control Array
    IF Plotted Output Requested
      T: CALL LDVALU to Load Plot File Array
      F: Null
    CALL UVEC to Load the Amplifier Control Array
    CALL AMP (Amplifier Model)
    IF Plotted Output Requested
      T: CALL LDVALU to Load Plot File Array
      F: Null
    IF Printed Output Requested
      T: CALL PRT to Print Amplifier Model
         Output
      F: Null
    CALL UVEC to Load the Motor Control Array
    CALL MOTOR (Motor Model)
    IF Plotted Output Requested
      T: CALL LDVALU to Load Plot File Array
      F: Null
    IF Printed Output Requested
      T: CALL PRT to Print Motor Model Output
      F: Null
    CALL UVEC to Load the Power Train Control Array
    CALL PWRTRN (Power Train Model)
    IF Plotted Output Requested
      T: CALL LDVALU to Load Plot File Array
      F: Null
    IF Printed Output Requested
      T: CALL PRT to Print Power Train Model
         Output
      F: Null
    CALL UVEC to Load the Load Control Array
    CALL LOAD (Load Model)
    IF Plotted Output Requested
      T: CALL LDVALU to Load Plot File Array
      F: Null
    IF Printed Output Requested
      T: CALL PRT to Print Load Model Output
      F: Null
    IF KFFLAG.EQ.1
      T: CALL BLDZAL to Build System Sensor
         Output Array and System Control Array
         CALL BLDPHI to Build System PHI Matrix
         CALL BLDTHT to Build System THETA Matrix
         CALL BUILDH to Build System H Matrix
         CALL KALMAN (Kalman Filter Model)
         IF Plotted Output Requested
           T: CALL LDVALU to Load Plot File Array
           F: Null
         IF KFFDBK.EQ.1
           T: Replace System Sensor Output
              with Kalman Filter Output
           F: Null
      F: Null
    IF Plotted Output Requested
      T: Output Record to Plot File
      F: Null
DOUNTIL [(Stop Time - TIME) .LE. Step
Size/2]
IF Plotted Output Requested
  T: CALL WRTHDR to Write Plot File Header
     Record
     Close Plot File
  F: Null
IF Printed Output Requested
  T: Close Print File
  F: Null
```

Figure A3-3 JNTMOD VCLR

3.1 GENERAL JOINT MODEL ROUTINES

This section contains descriptions of routines used for input, initialization, and printing. Also described are routines used in each of the model blocks for loading the control array and computing noise, and for sensor computations.

3.1.1 Program Input (INPUT)

Subroutine INPUT is called from the program main routine JNTMOD to handle the bulk of program inputs. Input may be totally through program prompts or a previously created disk file may be read to provide most of the data describing the system to be modeled.

If manual input of the joint model data is requested, the user is first prompted for controller data. Dimensions are required for the controller control array, state-variable array, and observable array. The constants or coefficients required for the controller in use are then input. The user then selects open- or closed-loop control. Finally, the user must specify the standard deviations to be used in noise calculations for each of the controller state variables.

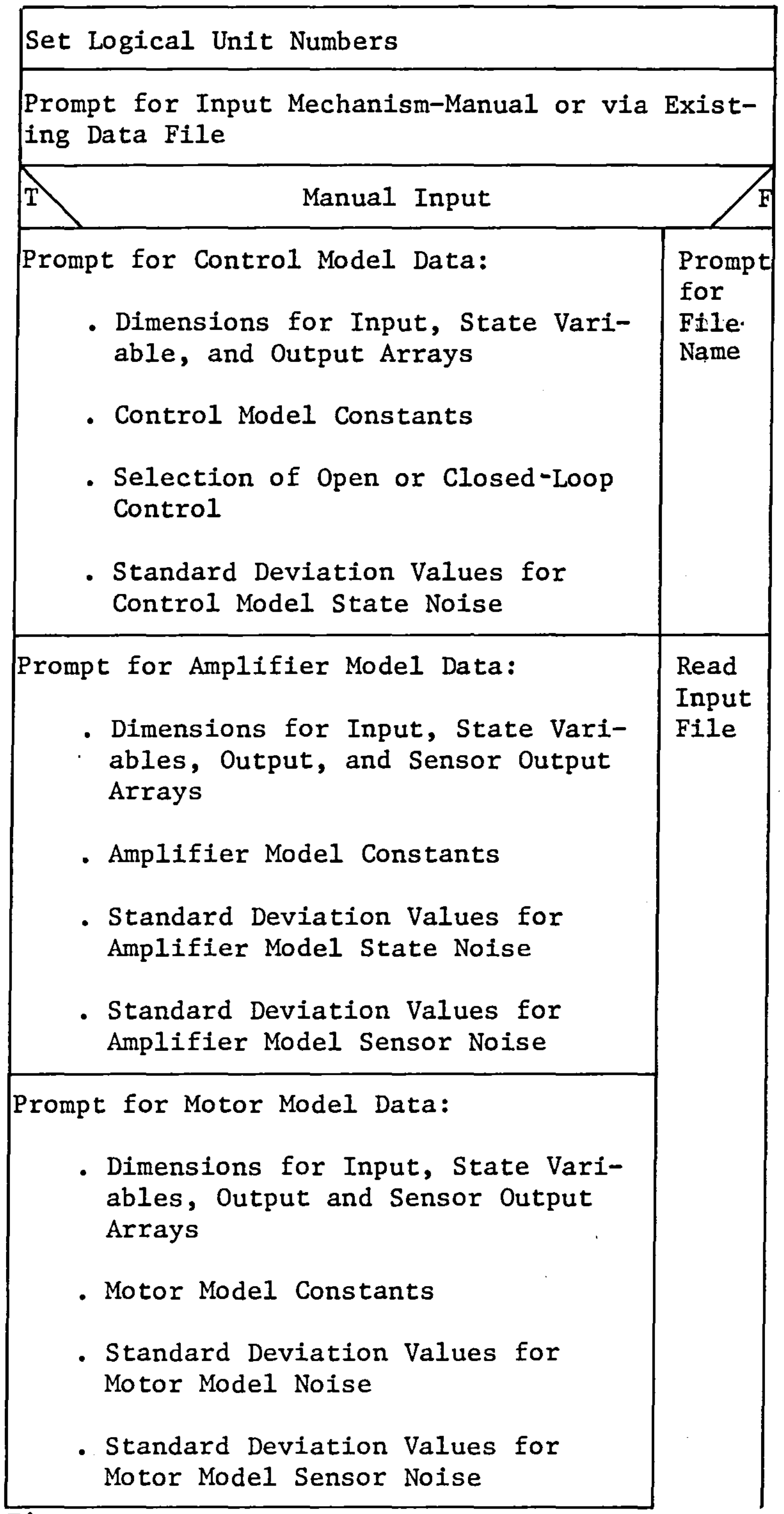
Following input of the controller data, the user must input data for each of the joint component models (amplifier, motor, power train, and load). The same data are required for each of the model blocks. First are the dimensions of the control, state-variable, observable, and sensor arrays. The constants or coefficients required for the model in use are then input. Finally, the standard deviation for each state variable and each sensor output variable are input for use in noise calculations.

The user may elect to write to disk file the data input defining the current joint model. This disk file can then be used as input for future executions.

Regardless of whether the previous data were introduced manually or read from disk file, the user is provided the opportunity to modify selected data parameters. The user may modify any of the constants, coefficients, or standard deviations for the controller, amplifier, motor, power train, or load models.

The user is then prompted for a seed value for random number generation; the simulation start time, stop time, and time step; and print and plot output flags.

Figure A3-4 is the VCLR for subroutine INPUT.



```
Set Logical Unit Numbers
Prompt for Input Mechanism-Manual or via Existing Data File
IF Manual Input
  T:
    Prompt for Control Model Data:
      . Dimensions for Input, State Variable, and Output Arrays
      . Control Model Constants
      . Selection of Open or Closed-Loop Control
      . Standard Deviation Values for Control Model State Noise
    Prompt for Amplifier Model Data:
      . Dimensions for Input, State Variables, Output, and Sensor Output Arrays
      . Amplifier Model Constants
      . Standard Deviation Values for Amplifier Model State Noise
      . Standard Deviation Values for Amplifier Model Sensor Noise
    Prompt for Motor Model Data:
      . Dimensions for Input, State Variables, Output and Sensor Output Arrays
      . Motor Model Constants
      . Standard Deviation Values for Motor Model Noise
      . Standard Deviation Values for Motor Model Sensor Noise
  F:
    Prompt for File Name
    Read Input File
```

Figure A3-4 INPUT VCLR

```
Prompt for Power Train Model Data:                         | Read
                                                           | Input
    . Dimensions for Input, State Vari-                    | File
      able, Output, and Sensor Output                      |
      Arrays                                               |
                                                           |
    . Power Train Model Constants                          |
                                                           |
    . Standard Deviation Values for                        |
      Power Train Model State Noise                        |
                                                           |
    . Standard Deviation Values for                        |
      Power Train Model Sensor Noise                       |
                                                           |
Prompt for Load Model Data:                                |
                                                           |
    . Dimensions for Input, State Vari-                    |
      able, Output, and Sensor Output                      |
      Arrays                                               |
                                                           |
    . Load Model Constants                                 |
                                                           |
    . Standard Deviation Values for Load                   |
      Model State Noise                                    |
                                                           |
    . Standard Deviation Values for Load                   |
      Model Sensor Noise                                   |
                                                           |
Prompt for Input Save Option                               |
                                                           |
T   Save Input to Disk File Option                    F    |
      Selected                                             |
    Prompt for File name                         | Null    |
    Write Input Data to File                     |         |

Prompt for Modifications to Control Model Data

    . Control Constants

    . Standard Deviations for Control Model
      State Noise

Prompt for Modifcations to Amplifier Model Data:

    . Standard Deviations for Amplifier Model
      State Noise

    . Standard Deviations for Amplifier Model
      Sensor Noise
```

Figure A3-4 (Continued)

Prompt for Modifications to Motor Model Data:

- Standard Deviations for Motor Model State Noise
- Standard Deviations for Motor Model Sensor Noise

Prompt for Modifications to Power Train Model Data:

- Standard Deviations for Power Train Model State Noise
- Standard Deviations for Power Train Model Sensor Noise

Prompt for Modifications to Load Model Data:

- Standard Deviations for Load Model State Noise
- Standard Deviations for Load Model Sensor Noise

Prompt for Random Number Generator Seed Value

Prompt for Start Time, Stop Time, and Time Stop

Prompt for Print Output Frequency

Prompt for Plot Output Frequency

Figure A3-4 (Concluded)

3.1.2 Joint Model Initialization (INIT)

Subroutine INIT is called from the main routine JNTMOD to handle initialization of the joint model arrays and matrices. The state-variable, observable, and sensor arrays for each of the joint model blocks are set to initial values. All joint model block phi, theta, C, and M matrices are computed for the simulation start time. The D matrices used to develop the control arrays, and the feedback matrix, M, are set. The reference signal array, R, is loaded with start time values. Finally, if printed output is requested, subroutine PTINIT is called to write the system initial conditions.

Figure A3-5 is the VCLR for subroutine INIT.

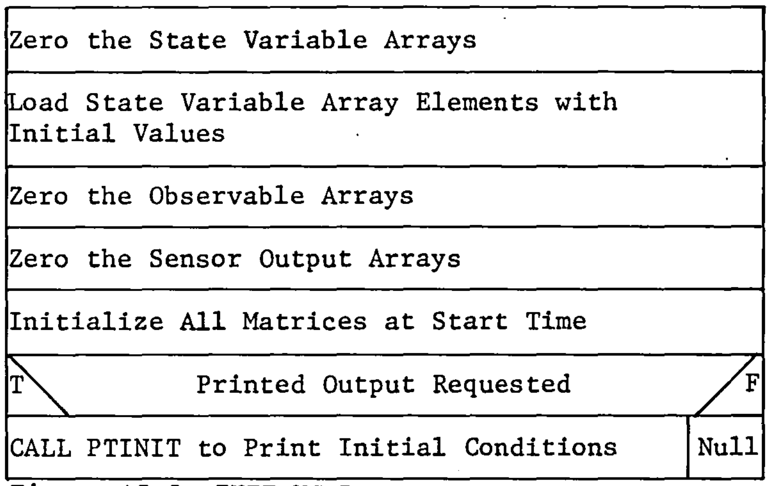

Zero the State Variable Arrays
Load State Variable Array Elements with Initial Values
Zero the Observable Arrays
Zero the Sensor Output Arrays
Initialize All Matrices at Start Time
T
Printed Output Requested
F
CALL PTINIT to Print Initial Conditions
Null

Figure A3-5 INIT VCLR

Print Initial Conditions (PTINIT) - Subroutine PTINIT is called from subroutine INIT to print the joint model initial conditions. First, the requested simulation start time, stop time, and time step are printed. Then the initial state-variable, observable, and sensor arrays for the amplifier, motor, power train, and load are printed.

Figure A3-6 is the VCLR for subroutine PTINIT.

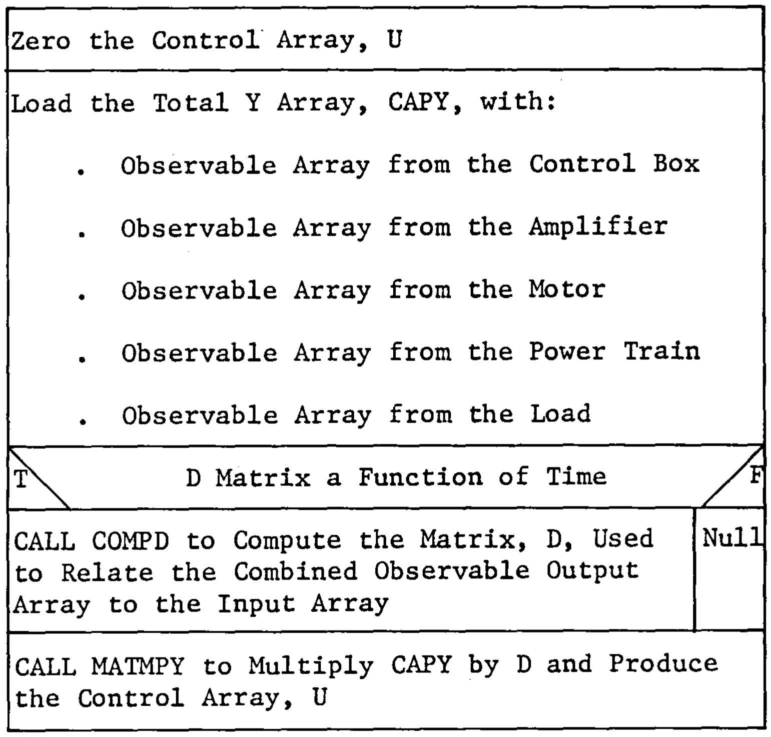
Start New Page and Print Page Header
Print Start Time, Stop Time, and Time Step
Print Amplifier Initial Conditions: . State Array . Observable Array . Sensor Array
Print Motor Initial Conditions: . State Array . Observable Array . Sensor Array
Print Power Train Initial Conditions: . State Array . Observable Array . Sensor Array
Print Load Initial Conditions: . State Array . Observable Array . Sensor Array

Figure A3-6 PTINIT VCLR

3.1.3 Load Control Array (UVEC)

Subroutine UVEC is called from the main routine JNTMOD prior to calls to each of the joint model component routines (AMP, MOTOR, PWRTRN, and LOAD). Subroutine UVEC loads the control array, U, required for each model block. The control array is composed of observable parameters from any of the joint model blocks (controller, amplifier, motor, power train, or load). The system observable array, CAPY, is loaded with the elements of the individual joint model block observable arrays. Subroutine COMPD is called to compute the D matrix for the requested model block. The D matrix provides the relationship between the system observable array and the control array for the requested model block. Subroutine MATMPY is called to multiply the D matrix and the CAPY array to produce the required control array, U.

Figure A3-7 is the VCLR for subroutine UVEC.



```
Zero the Control Array, U
Load the Total Y Array, CAPY, with:
    . Observable Array from the Control Box
    . Observable Array from the Amplifier
    . Observable Array from the Motor
    . Observable Array from the Power Train
    . Observable Array from the Load
D Matrix a Function of Time
    T: CALL COMPD to Compute the Matrix, D, Used
       to Relate the Combined Observable Output
       Array to the Input Array
    F: Null
CALL MATMPY to Multiply CAPY by D and Produce
the Control Array, U
```

Figure A3-7 UVEC VCLR

Compute D Matrix (COMPD) - Subroutine COMPD is called from subroutine UVEC to compute the D matrix for the requested joint model block (amplifier, motor, power train, or load). The control array required as input to each of the model blocks is composed of elements of the observable arrays from throughout the system. The D matrix relates the system observables to the control array for the requested model block.

Figure A3-8 is the VCLR for subroutine COMPD.

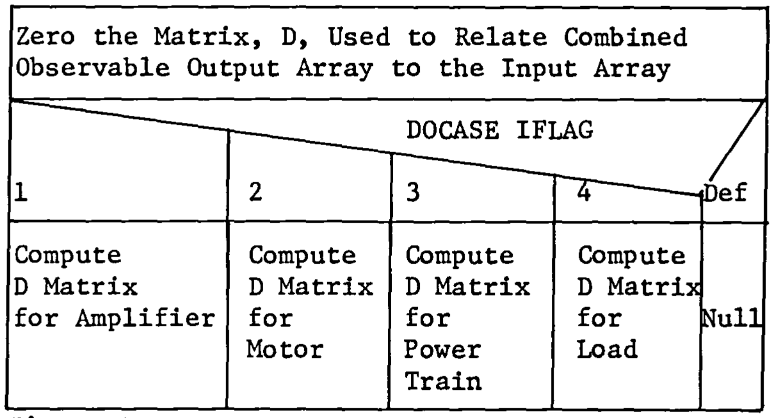

Zero the Matrix, D, Used to Relate Combined Observable Output Array to the Input Array
DOCASE IFLAG
1
2
3
4
Def
Compute D Matrix for Amplifier
Compute D Matrix for Motor
Compute D Matrix for Power Train
Compute D Matrix for Load
Null

Figure A3-8 COMPD VCLR

3.1.4 Process Noise (XNOISE)

Subroutine XNOISE is called from each of the model subroutines (AMP, MOTOR, PWRTRN, and LOAD) to compute the state-variable noise. The noise array, W, is first zeroed. Subroutine GGNML of the IMSL math package is called to compute a normal random value from a Gaussian distribution with zero mean and variance of one. The state noise, W, is then computed as the user-specified standard deviation for state noise times the value obtained from subroutine GGNML.

Figure A3-9 is the VCLR for subroutine XNOISE.

Zero the Noise Array
CALL GGNML to Obtain a Sample from a Gaussian Distribution with Zero Mean and Variance of One
Compute Noise Array for the State Variable Array (User-Specified Standard Deviation Times Sample Value)

Figure A3-9 XNOISE VCLR

3.1.5 Compute C Matrix (COMPC)

Subroutine COMPC is called from each model block routine (AMP, MOTOR, PWRTRN, or LOAD) to compute the C matrix for the requested model block. The C matrix transforms the state-variable array to the observable array in the state-variable formulation.

The C matrix is first zeroed. The nonzero matrix elements for the requested block are then set.

Figure A3-10 is the VCLR for subroutine COMPC.

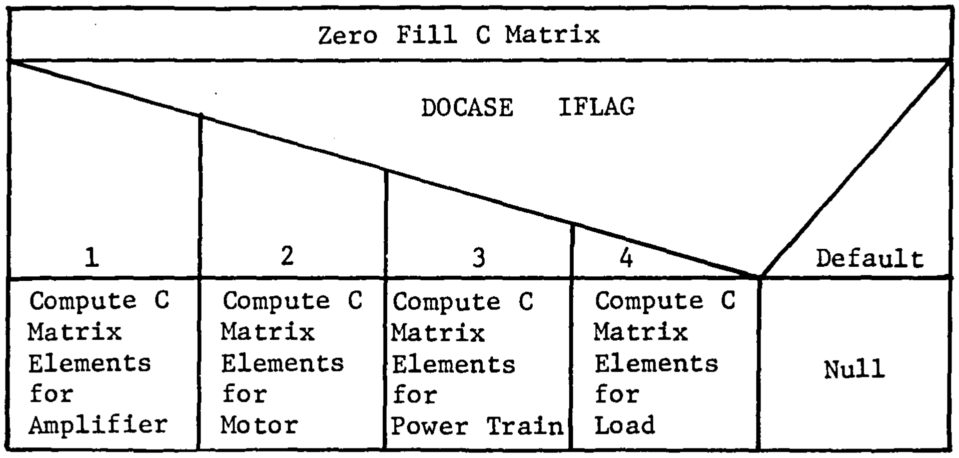

Zero Fill C Matrix
DOCASE IFLAG
1
2
3
4
Default
Compute C Matrix Elements for Amplifier
Compute C Matrix Elements for Motor
Compute C Matrix Elements for Power Train
Compute C Matrix Elements for Load
Null

Figure A3-10 COMPC VCLR

3.1.6 Sensor Model (SENSOR)

Subroutine SENSOR is called from each of the model subroutines (AMP, MOTOR, PWRTRN, or LOAD) to compute the sensor output. Subroutine SENSOR uses the state-variable formulation for sensor output computations. Subroutine HCOMP is called to provide the sensor transform matrix, H, for the specified model. Subroutine MATMPY is called to multiply the H matrix with the C matrix for the specified model to produce the CAPH matrix. The CAPH matrix transforms the state-variable array, X, to the sensor output array without noise, ZWON. Subroutine ZNOISE is called to compute the noise array, V, for the specified model sensor output. The final sensor output array, Z, is produced by adding the sensor noise array, V, to the sensor output without noise array, ZWON.

Figure A3-11 is the VCLR for subroutine SENSOR.

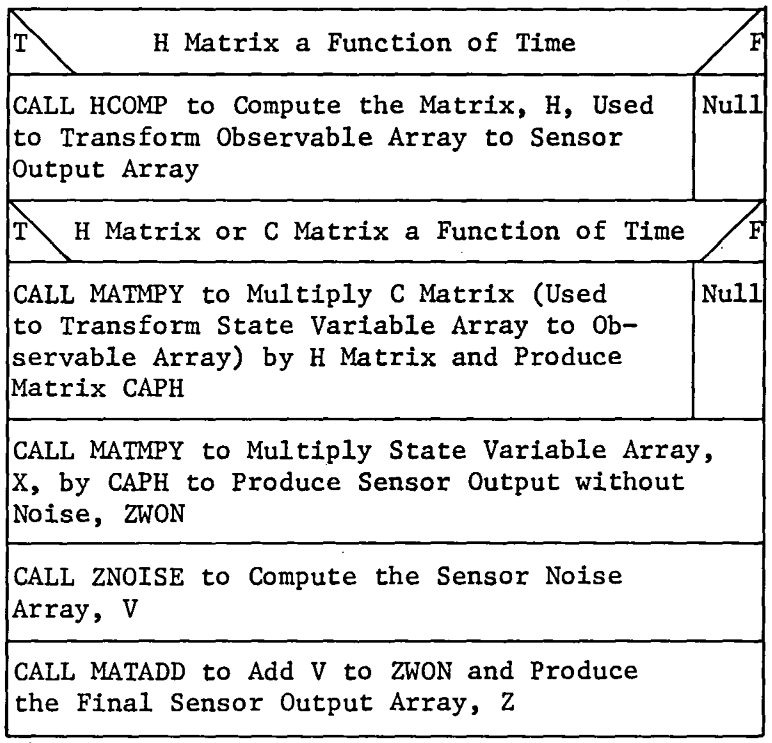

T
H Matrix a Function of Time
F
CALL HCOMP to Compute the Matrix, H, Used to Transform Observable Array to Sensor Output Array
Null
T
H Matrix or C Matrix a Function of Time
F
CALL MATMPY to Multiply C Matrix (Used to Transform State Variable Array to Observable Array) by H Matrix and Produce Matrix CAPH
Null
CALL MATMPY to Multiply State Variable Array, X, by CAPH to Produce Sensor Output without Noise, ZWON
CALL ZNOISE to Compute the Sensor Noise Array, V
CALL MATADD to Add V to ZWON and Produce the Final Sensor Output Array, Z

Figure A3-11 SENSOR VCLR

3.1.6.1 Compute H Matrix (HCOMP) - Subroutine HCOMP is called from subroutine SENSOR to compute the H matrix for the specified joint model component (amplifier, motor, power train, or load). The H matrix is used to transform the observable array into the sensor output array in the state-variable formulation. The H matrix is first zeroed. The nonzero elements for the specified model component are then set.

Figure A3-12 is the VCLR for subroutine HCOMP.

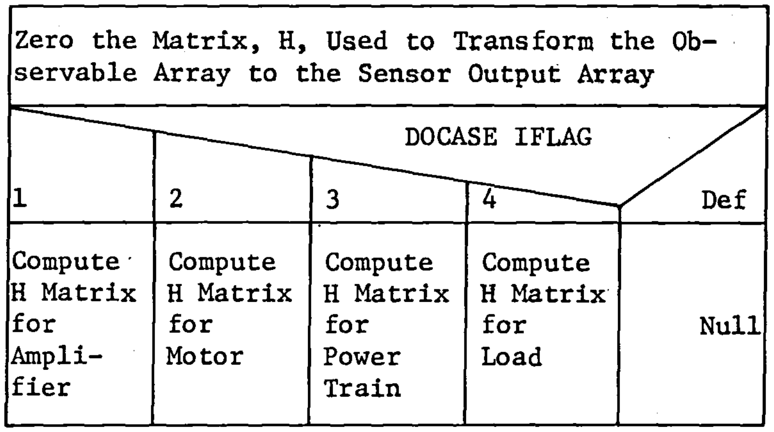

Zero the Matrix, H, Used to Transform the Observable Array to the Sensor Output Array
DOCASE IFLAG
1
2
3
4
Def
Compute H Matrix for Amplifier
Compute H Matrix for Motor
Compute H Matrix for Power Train
Compute H Matrix for Load
Null

Figure A3-12 HCOMP VCLR

3.1.6.2 <u>Sensor Noise (ZNOISE)</u> - Subroutine ZNOISE is called from subroutine SENSOR, which is called from each of the model subroutines (AMP, MOTOR, PWRTRN, and LOAD). Subroutine ZNOISE computes the sensor noise. The noise array, V, is first zeroed. Subroutine GGNML of the IMSL math package is called to compute a normal random value from a Gaussian distribution with zero mean and variance of one. The sensor noise, V, is then computed as the user-specified standard deviation for sensor noise times the value obtained from subroutine GGNML.

Figure A3-13 is the VCLR for subroutine ZNOISE.

Zero the Noise Array
CALL GGNML to Obtain a Sample from a Gaussian Distribution with Zero Mean and Variance of One
Compute Noise Array for Sensor Output (User-Specified Standard Deviation Times Sample Value)

Figure A3-13 ZNOISE VCLR

3.1.7 Print Joint Model Parameters (PRT) - Subroutine PRT is called from the main routine JNTMOD following the call to each of the system model routines (AMP, MOTOR, PWRTRN, or LOAD). Subroutine PRT prints all of the parameters associated with that model. Each call to subroutine PRT results in a block of output that contains the following data:

1) Current time;

2) State-variable arrays--X, XHOM, XPAR, XWON, and W;

3) Observable array--Y;

4) Sensor arrays--Z, ZWON, and V.

Figure A3-14 is the VCLR for subroutine PRT.

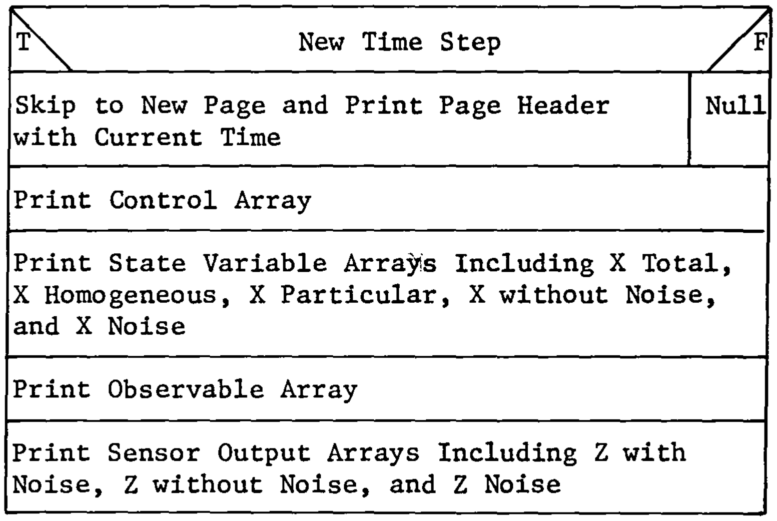

T
New Time Step
F
Skip to New Page and Print Page Header with Current Time
Null
Print Control Array
Print State Variable Arrays Including X Total, X Homogeneous, X Particular, X without Noise, and X Noise
Print Observable Array
Print Sensor Output Arrays Including Z with Noise, Z without Noise, and Z Noise

Figure A3-14 PRT VCLR

3.2 CONTROLLER MODEL (CONTRL)

Subroutine CONTRL models the controller using the state-variable formulation. Subroutine COMPM is called to compute the feedback matrix, M. The sensor output from all model blocks is combined into a system sensor array, CAPZ. If closed-loop control is requested, subroutine MATMPY is called to multiply the system sensor array with the feedback matrix to produce the feedback array. If open-loop control is requested, the feedback array is set to zero. Subroutine LOADR is then called to load the reference input array, R. The ALPHA array used as input to the Kalman filter routine is loaded with the elements of the R and CAPZ arrays. The joint model control array, U, is formed by adding the feedback array with the reference input array through a call to subroutine MATADD.

Subroutine PHIC is called to compute the state-variable formulation phi matrix for the controller. Subroutine THETAC is called to compute the state-variable formulation theta matrix for the controller. Subroutine MATMPY is called to multiply the phi matrix and the current controller state-variable array, X, to produce the homogeneous state array, XHOM. Subroutine MATMPY is then called to multiply the theta matrix with the control matrix, U, to produce the particular state array, XPAR. The state array without noise is the sum of XHOM and XPAR. Subroutine CNOISE is called to compute the controller process noise array, W. The process noise, W, plus XWON produces the updated controller state variable array, X.

Subroutine CONTC is called to compute the controller state-to-observable transform matrix, C. Subroutine MATMPY is called to multiply the C matrix and the state array, X, to produce the controller observable array, Y.

Figure A3-15 is the VCLR for subroutine CONTRL.

```
M Matrix a Function of Time
  T: CALL COMPM to Compute the Matrix, M, Used to Relate Sensor Output
     to Reference Input Array
  F: Null
Load the System Sensor Output Array, CAPZ, with Sensor Output Arrays
from the Amplifier, Motor, Power Train, and Load
.NOT. Open Loop
  T: CALL MATMPY to Multiply CAPZ by M and Obtain Feedback Array, U
  F: Zero the Feedback Array, U
R Matrix a Function of Time
  T: CALL LOADR to Load the Reference Input Array, R
  F: Null
Load R and CAPZ Arrays into ALPHA Array Used as Input to Kalman Filter
CALL MATADD to Add R to U and Produce the Total Control Array, U
Controller PHI Matrix a Function of Time
  T: CALL PHIC to Compute Controller PHI Matrix
  F: Null
Controller THETA Matrix a Function of Time
  T: CALL THETAC to Compute Controller THETA Matrix
  F: Null
CALL MATMPY to Multiply State Variable Array, X, by PHI to Produce X
Homogeneous, XHOM
CALL MATMPY to Multiply U by THETA and Produce X Particular, XPAR
CALL MATADD to Add XHOM to XPAR and Produce X without Noise, XWON
CALL CNOISE to Compute Control Noise Array, W
CALL MATADD to Add W to XWON and Produce the Final State Variable Array, X
C Matrix a Function of Time
  T: CALL CONTC to Compute Matrix, C, Used to Transform X to the Observable
     Array Y
  F: Null
CALL MATMPY to Multiply X by C and Produce the Observable Array Y
```

Figure A3-15 CONTRL VCLR

3.2.1 Compute Feedback Matrix (COMPM)

Subroutine COMPM is called from subroutine CONTRL to compute the feedback matrix, M. The M matrix relates the sensor output from all joint model blocks to the reference input for feedback purposes.

The M matrix is first zeroed. If open loop control is desired, program control is returned to subroutine CONTRL. Otherwise, the elements are set within the M matrix as required for the feedback needed in the control technique defined in subroutine CONTRL.

Figure A3-16 is the VCLR for subroutine COMPM.

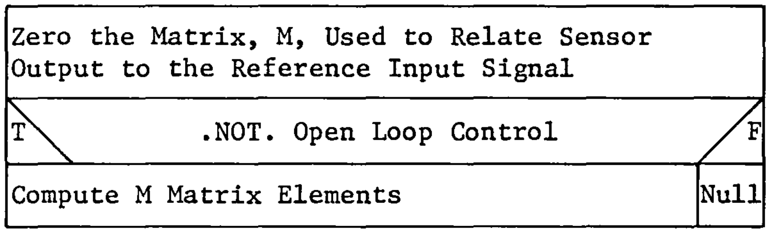

Zero the Matrix, M, Used to Relate Sensor Output to the Reference Input Signal
T
.NOT. Open Loop Control
F
Compute M Matrix Elements
Null

Figure A3-16 COMPM VCLR

3.2.2 Load Reference Signal (LOADR)

Subroutine LOADR is called from subroutine CONTRL to load the reference signal array, R. The reference array is first zeroed. The appropriate array elements are then set to the reference signal values valid for the current time.

Figure A3-17 is the VCLR for subroutine LOADR.

Zero the Reference Input Signal Array, R
Set R Array Elements

Figure A3-17 LOADR VCLR

3.2.3 Compute Controller Phi Matrix (PHIC)

Subroutine PHIC is called from subroutine CONTRL to compute the state-variable formulation phi matrix for the controller. The phi matrix is first zeroed. The required elements of the phi matrix are then computed based on the controller equations placed in state-variable formulation form.

Figure A3-18 is the VCLR for subroutine PHIC.

Zero Fill PHI Matrix
Compute PHI Matrix Elements for Controller

Figure A3-18 PHIC VCLR

3.2.4 Compute Controller Theta Matrix (THETAC)

Subroutine THETAC is called from subroutine CONTRL to compute the state-variable formulation theta matrix for the controller. The theta matrix is first zeroed. The required elements of the theta matrix are then computed based on the controller equations placed in state-variable formulation form.

Figure A3-19 is the VCLR for subroutine THETAC.

Zero Fill THETA Matrix
Compute THETA Matrix Elements for Controller

Figure A3-19 THETAC VCLR

3.2.5 <u>Compute Controller C Matrix (CONTC)</u>

Subroutine CONTC is called from subroutine CONTRL to compute the matrix, C, which transforms the controller state-variable array to the controller observable array. Under current implementation this matrix is always the identity matrix.

Figure A3-20 is the VCLR for subroutine CONTC.

Zero the Matrix, C, used to Transform the State Variable Array to the Observable Array
Compute C Matrix Elements

Figure A3-20 CONTC VCLR

3.2.6 Controller Process Noise (CNOISE)

Subroutine CNOISE is called from subroutine CONTRL to compute the state-variable noise for the controller. The noise array, W, is first zeroed. Subroutine GGNML of the IMSL math package is called to compute a normal random value from a Gaussian distribution with zero mean and variance of one. The controller state noise, W, is then computed as the user-specified standard deviation for controller state noise times the value obtained from subroutine GGNML.

Figure A3-21 is the VCLR for subroutine CNOISE.

Zero the Noise Array
CALL GGNML to Obtain a Sample from a Gaussian Distribution with Zero Mean and Variance of One
Compute Noise Array for the Control Array (User-Specified Standard Deviation Times Sample Value)

Figure A3-21 CNOISE VCLR

3.3 AMPLIFIER MODEL (AMP)

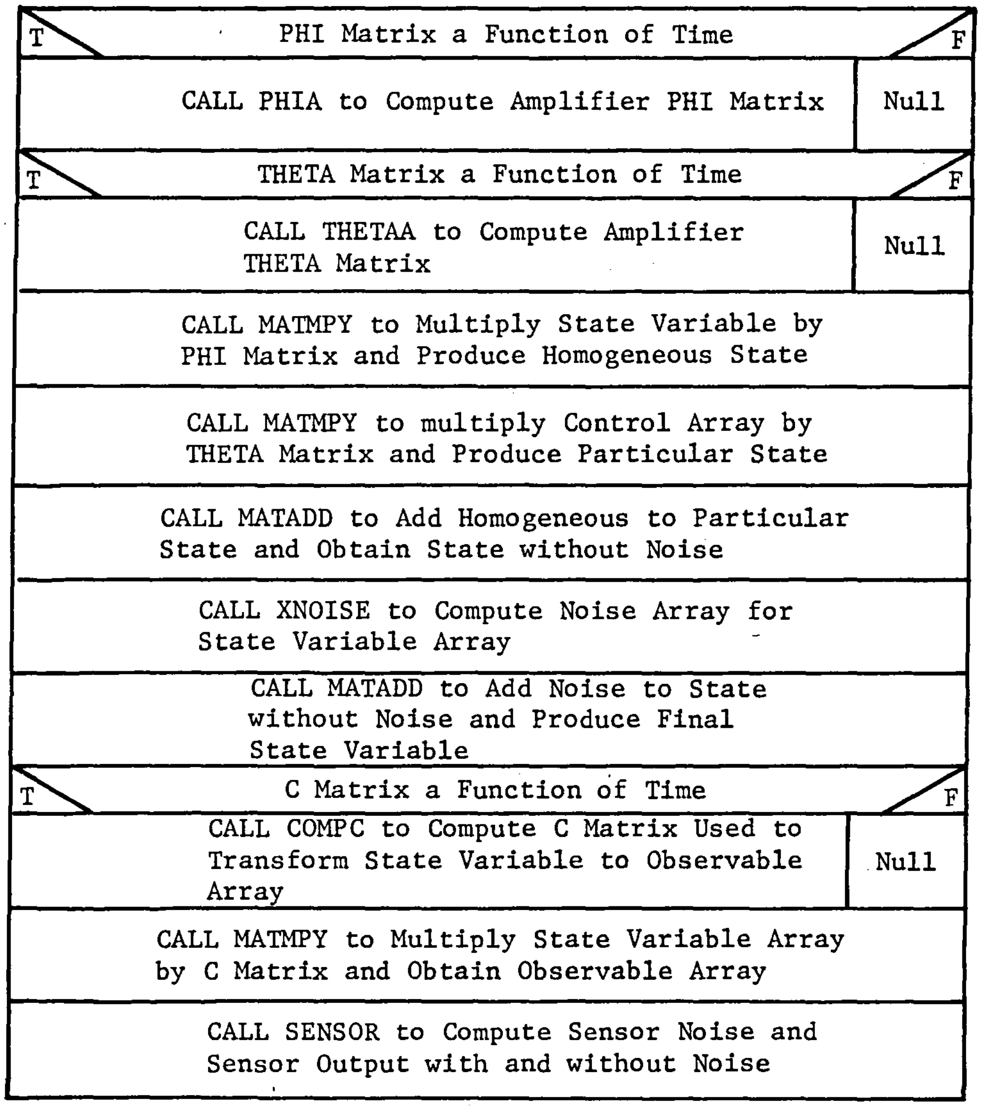
Subroutine AMP is called from the main routine JNTMOD to model the amplifier using the state-variable formulation.

Subroutine PHIA is called to compute the state-variable formulation phi matrix for the amplifier. Subroutine THETAA is called to compute the state-variable formulation theta matrix for the amplifier. Subroutine MATMPY is called to multiply the phi matrix and the current amplifier state-variable array, X, to produce the homogeneous state array, XHOM. Subroutine MATMPY is then called to multiply the theta matrix with the input control matrix, U, to produce the particular state array, XPAR. The state array without noise is the sum of XHOM and XPAR. Subroutine XNOISE is called to compute the amplifier process noise array, W. The process noise, W, plus XWON, produces the updated amplifier state variable array, X.

Subroutine COMPC is called to compute the amplifier state-to-observable transform matrix, C. Subroutine MATMPY is called to multiply the C matrix and the state array, X, to produce the observable array, Y, for the amplifier model.

Subroutine SENSOR is called to compute the sensor output without noise, ZWON; the sensor noise, V; and the sensor output including noise, Z.

Figure A3-22 is the VCLR for subroutine AMP.



```
IF PHI Matrix a Function of Time
  T: CALL PHIA to Compute Amplifier PHI Matrix
  F: Null
IF THETA Matrix a Function of Time
  T: CALL THETAA to Compute Amplifier THETA Matrix
  F: Null
CALL MATMPY to Multiply State Variable by PHI Matrix and Produce Homogeneous State
CALL MATMPY to multiply Control Array by THETA Matrix and Produce Particular State
CALL MATADD to Add Homogeneous to Particular State and Obtain State without Noise
CALL XNOISE to Compute Noise Array for State Variable Array
CALL MATADD to Add Noise to State without Noise and Produce Final State Variable
IF C Matrix a Function of Time
  T: CALL COMPC to Compute C Matrix Used to Transform State Variable to Observable Array
  F: Null
CALL MATMPY to Multiply State Variable Array by C Matrix and Obtain Observable Array
CALL SENSOR to Compute Sensor Noise and Sensor Output with and without Noise
```

Figure A3-22 AMP VCLR

3.3.1 Compute Amplifier Phi Matrix (PHIA)

Subroutine PHIA is called from subroutine AMP to compute the state-variable formulation phi matrix for the amplifier. The phi matrix is first zeroed. The required elements of the phi matrix are then computed based on the amplifier equations placed in state-variable formulation form. Several types of amplifiers may be modeled. Input argument ITYPE is used to select the desired amplifier model.

Figure A3-23 is the VCLR for subroutine PHIA.

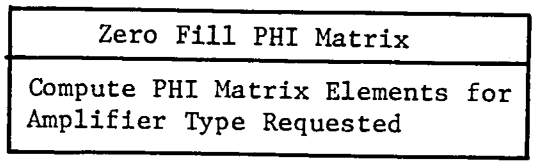


Figure A3-23 PHIA VCLR

3.3.2 Compute Amplifier Theta Matrix (THETAA)

Subroutine THETAA is called from subroutine AMP to compute the state-variable formulation theta matrix for the amplifier. The theta matrix is first zeroed. The required elements of the theta matrix are then computed based on the amplifier equations placed in state-variable formulation form. Several types of amplifiers may be modeled. Input argument ITYPE is used to select the desired amplifier model.

Figure A3-24 is the VCLR for subroutine THETAA.

Zero Fill THETA Matrix
Compute THETA Matrix Elements for Amplifier Type Requested

Figure A3-24 THETAA VCLR

3.4 MOTOR MODEL (MOTOR)

Subroutine MOTOR is called from the main routine JNTMOD to model the motor using the state-variable formulation.

Subroutine PHIM is called to compute the state-variable formulation phi matrix for the motor. Subroutine THETAM is called to compute the state-variable formulation theta matrix for the motor. Subroutine MATMPY is called to multiply the phi matrix and the current motor state variable array, X, to produce the homogeneous state array, XHOM. Subroutine MATMPY is then called to multiply the theta matrix with the input control matrix, U, to produce the particular state array, XPAR. The state array without noise is the sum of XHOM and XPAR. Subroutine XNOISE is called to compute the motor process noise array, W. The process noise, W, plus XWON, produces the updated motor state-variable array, X.

Subroutine COMPC is called to compute the motor state-to-observable transform matrix, C. Subroutine MATMPY is called to multiply the C matrix and the state array, X, to produce the observable array, Y, for the motor model.

Subroutine SENSOR is called to compute the sensor output without noise, ZWON; the sensor noise, V; and the sensor output including noise, Z.

Figure A3-25 is the VCLR for subroutine MOTOR.

```
T  PHI Matrix a Function of Time  F
    T: CALL PHIM to Compute the Motor PHI Matrix
    F: Null
T  THETA Matrix a Function of Time  F
    T: CALL THETAM to Compute the Motor THETA Matrix
    F: Null
CALL MATMPY to Multiply the State Variable Array, X by PHI and Produce X Homogeneous, XHOM
CALL MATMPY to Multiply the Control Array, U, by THETA and Produce X Particular, XPAR
CALL MATADD to Add XHOM to XPAR and Produce X without Noise, XWON
CALL XNOISE to Compute the Noise Array, W, for X
CALL MATADD to Add XWON to W and Produce the Final State Variable, X
T  C Matrix a Function of Time  F
    T: CALL COMPC to Compute the Matrix, C, Used to Transform X to the Observable Array, Y
    F: Null
CALL MATMPY to Multiply X by C and Produce the Observable Array, Y
CALL SENSOR to Compute the Sensor Output without Noise, ZWON; The Sensor Noise, V; and the Sensor Output Including Noise, Z
```

Figure A3-25 MOTOR VCLR

3.4.1 Compute Motor Phi Matrix (PHIM)

Subroutine PHIM is called from subroutine MOTOR to compute the state-variable formulation phi matrix for the motor. The phi matrix is first zeroed. The required elements of the phi matrix are then computed based on the motor equations placed in state-variable formulation form. Several types of motors may be modeled. Input argument ITYPE is used to select the desired motor model.

Figure A3-26 is the VCLR for subroutine PHIM.

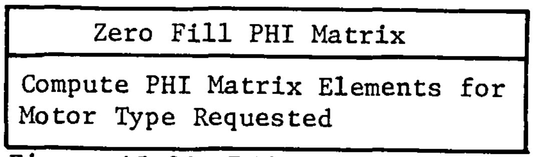


Figure A3-26 PHIM VCLR

3.4.2 Compute Motor Theta Matrix (THETAM)

Subroutine THETAM is called from subroutine MOTOR to compute the state-variable formulation theta matrix for the motor. The theta matrix is first zeroed. The required elements of the theta matrix are then computed based on the motor equations placed in state-variable formulation form. Several types of motors may be modeled. Input argument ITYPE is used to select the desired motor model.

Figure A3-27 is the VCLR for subroutine THETAM.

Zero Fill THETA Matrix
Compute THETA Matrix Elements for Motor Type Requested

Figure A3-27 THETAM VCLR

3.5 POWER TRAIN MODEL (PWRTRN)

Subroutine PWRTRN is called from the main routine JNTMOD to model the power train using the state-variable formulation.

Subroutine PHIP is called to compute the state-variable formulation phi matrix for the power train. Subroutine THETAP is called to compute the state-variable formulation theta matrix for the power train. Subroutine MATMPY is called to multiply the phi matrix and the current power train state-variable array, X, to produce the homogeneous state array, XHOM. Subroutine MATMPY is then called to multiply the theta matrix with the input control matrix, U, to produce the particular state array, XPAR. The state array without noise is the sum of XHOM and XPAR. Subroutine XNOISE is called to compute the power train process noise array, W. The process noise, W, plus XWON, produces the updated power train state-variable array, X.

Subroutine COMPC is called to compute the power train state-to-observable transform matrix, C. Subroutine MATMPY is called to multiply the C matrix and the state array, X, to produce the observable array, Y, for the power train model.

Subroutine SENSOR is called to compute the sensor output without noise, ZWON; the sensor noise, V; and the sensor output including noise, Z.

Figure A3-28 is the VCLR for subroutine PWRTRN.

```
IF PHI Matrix a Function of Time
    T: CALL PHIP to Compute the Power Train PHI Matrix
    F: Null
IF THETA Matrix a Function of Time
    T: CALL THETAP to Compute the Power Train THETA Matrix
    F: Null
CALL MATMPY to Multiply the State Variable Array, X by PHI and Produce X Homogeneous, XHOM
CALL MATMPY to Multiply the Control Array, U, by THETA and Produce X Particular, XPAR
CALL MATADD to Add XHOM to XPAR and Produce X without Noise, XWON
CALL XNOISE to Compute the Noise Array, W, for X
CALL MATADD to Add XWON to W and Produce the Final State Variable Array, X
IF C Matrix a Function of Time
    T: CALL COMPC to Compute the Matrix, C, Used to Transform X to the Observable Array, Y
    F: Null
CALL MATMPY to Multiply X by C and Produce the Observable Array, Y
CALL SENSOR to Compute the Sensor Output without Noise, ZWON; the Sensor Noise, V; and the Sensor Output Including Noise, Z
```

Figure A3-28 PWRTRN VCLR

3.5.1 Compute Power Train Phi Matrix (PHIP)

Subroutine PHIP is called from subroutine PWRTRN to compute the state-variable formulation phi matrix for the power train. The phi matrix is first zeroed. The required elements of the phi matrix are then computed based on the power train equations placed in state-variable formulation form. Several types of power trains may be modeled. Input argument ITYPE is used to select the desired power train model.

Figure A3-29 is the VCLR for subroutine PHIP.

Zero Fill PHI Matrix
Compute PHI Matrix Elements for Power Train Type Requested

Figure A3-29 PHIP VCLR

3.5.2 Compute Power Train Theta Matrix (THETAP)

Subroutine THETAP is called from subroutine PWRTRN to compute the state-variable formulation theta matrix for the power train. The theta matrix is first zeroed. The required elements of the theta matrix are then computed based on the power train equations placed in state variable formulation form. Several types of power trains may be modeled. Input argument ITYPE is used to select the desired power train model.

Figure A3-30 is the VCLR for subroutine THETAP.

Zero Fill THETA Matrix
Compute THETA Matrix Elements for Power Train Type Requested

Figure A3-30 THETAP VCLR

3.6 LOAD MODEL (LOAD)

Subroutine LOAD is called from the main routine JNTMOD to model the load using the state-variable formulation.

Subroutine PHIL is called to compute the state-variable formulation phi matrix for the load. Subroutine THETAP is called to compute the state-variable formulation theta matrix for the load. Subroutine MATMPY is called to multiply the phi matrix and the current load state variable array, X, to produce the homogeneous state array, XHOM. Subroutine MATMPY is then called to multiply the theta matrix with the input control matrix, U, to produce the particular state array, XPAR. The state array without noise is the sum of XHOM and XPAR. Subroutine XNOISE is called to compute the load process noise array, W. The process noise, W, plus XWON, produces the updated load state-variable array, X.

Subroutine COMPC is called to compute the load state-to-observable transform matrix, C. Subroutine MATMPY is called to multiply the C matrix and the state array, X, to produce the observable array, Y, for the load model.

Subroutine SENSOR is called to compute the sensor output without noise, ZWON, the sensor noise, V, and the sensor output including noise, Z.

Figure A3-31 is the VCLR for subroutine LOAD.

```
IF PHI Matrix a Function of Time
  T: CALL PHIL to Compute the Load PHI Matrix
  F: Null
IF THETA Matrix a Function of Time
  T: CALL THETAL to Compute the Load THETA Matrix
  F: Null
CALL MATMPY to Multiply the State Variable, Array, X, by PHI and Produce X Homogeneous, XHOM
CALL MATMPY to Multiply the Control Array, U, by THETA and Produce X Particular, XPAR
CALL MATADD to Add XHOM to XPAR and Produce X without Noise, XWON
CALL XNOISE to Compute the Noise Array, W, for X
CALL MATADD to Add XWON to W and Produce the Final State Variable Array, X
IF C Matrix a Function of Time
  T: CALL COMPC to Compute the Matrix, C, Used to Transform X to the Observable Array, Y
  F: Null
CALL MATMPY to Multiply X by C and Produce the Observable Array, Y
CALL SENSOR to Compute the Sensor Output without Noise, ZWON; the Sensor Noise, V; and the Sensor Output Including Noise, Z
```

Figure A3-31 LOAD VCLR

3.6.1 Compute Load Phi Matrix (PHIL)

Subroutine PHIL is called from subroutine LOAD to compute the state-variable formulation phi matrix for the load. The phi matrix is first zeroed. The required elements of the phi matrix are then computed based on the load equations placed in state-variable formulation form. Several types of loads may be modeled. Input argument ITYPE is used to select the desired load model.

Figure A3-32 is the VCLR for subroutine PHIL.

Zero Fill PHI Matrix
Compute PHI Matrix Elements for Load Type Requested

Figure A3-32 PHIL VCLR

3.6.2 Compute Load Theta Matrix (THETAL)

Subroutine THETAL is called from subroutine LOAD to compute the state-variable formulation theta matrix for the load. The theta matrix is first zeroed. The required elements of the theta matrix are then computed based on the load equations placed in state-variable formulation form. Several types of loads may be modeled. Input argument ITYPE is used to select the desired load model.

Figure A3-33 is the VCLR for subroutine THETAL.

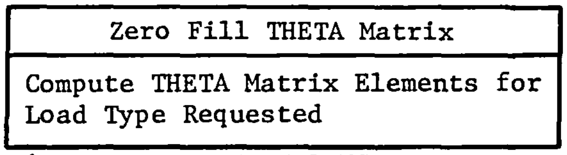


Figure A3-33 THETAL VCLR

3.7 KALMAN FILTER

This section describes all routines related to the Kalman filter implemented within the JNTMOD program.

3.7.1 Kalman Filter Initialization (KFINIT)

Subroutine KFINIT is called from the main routine JNTMOD to perform initialization of the matrices and arrays used in the Kalman filter.

Subroutine BLDPHI is called to compute the system phi matrix element for the simulation start time. Subroutine MATTRN is called to compute the transpose of the system phi matrix. Subroutine BUILDH is called to compute the system sensor transform matrix at the simulation start time. Subroutine MATTRN is called to compute the transpose of the system sensor matrix. Subroutine BLDTHT is called to compute the elements of the system theta matrix at the simulation start time.

The P, Q, and R inverse matrices are zeroed. The diagonal elements of the P matrix are set to 100.0. The diagonal elements of the Q matrix are set to the process noise variance values. The diagonal elements of the R inverse matrix are set to the reciprocal of the sensor variance values.

The XHAT array elements are initialized to zero. The H transpose-R inverse-H matrix is computed as is the H transpose-R inverse matrix.

Figure A3-34 is the VCLR for subroutine KFINIT.

CALL BLDPHI to Compute Initial System PHI Matrix, Φ
CALL MATTRN to Compute Transpose of Initial System PHI Matrix, Φ^T
CALL BUILDH to Compute Initial System Sensor Matrix, H
CALL MATTRN to Compute Transpose of Initial System Sensor Matrix, H^T
CALL BLDTHT to Compute Initial System THETA Matrix, θ
Initialize P Matrix with 100.0 along Diagonal
Set Diagonal Elements of Q Matrix to System Noise Variance Values
Set Diagonal Elements of R^{-1} Matrix to the Inverse of the System Sensor Noise Variance Values
Initialize $\hat{x}$ Values to Zero
Compute Initial Value of $H^T R^{-1} H$
Compute Initial Value of $H^T R^{-1}$

Figure A3-34 KFINIT VCLR

3.7.2 Build System Sensor Array (BLDZAL)

Subroutine BLDZAL loads the system sensor output array ZALL. The elements of the sensor output arrays from the amplifier, motor, power train, and load models are combined to form the ZALL array.

Figure A3-35 is the VCLR for subroutine BLDZAL.

Zero System Sensor Array
Build System Sensor Array Using Sensor Output Arrays from Amp, Motor, Power Train, and Load

Figure A3-35 BLDZAL VCLR

3.7.3 Build System Phi Matrix (BLDPHI)

Subroutine BLDPHI loads the system phi matrix needed for the Kalman filter used in conjunction with the state-variable formulation. The system phi matrix is constructed using matrices from each of the joint model blocks as follows:

$$
\Phi = \left[\begin{array}{c|cccc} \phi_C & 0 & 0 & 0 & 0 \\ \hline 0 & \phi_A & & & 0 \\ 0 & & \phi_M & & \\ 0 & & & \phi_P & \\ 0 & 0 & & & \phi_L \end{array}\right] + \left[\begin{array}{cccc} 0 & 0 & 0 & 0 \\ \hline \theta_A & & & 0 \\ & \theta_M & & \\ & & \theta_P & \\ 0 & & & \theta_L \end{array}\right] \left[\begin{array}{c} D_A \\ \hline D_M \\ \hline D_P \\ \hline D_L \end{array}\right] \left[\begin{array}{c|cccc} C_C & 0 & 0 & 0 & 0 \\ \hline 0 & C_A & & & 0 \\ 0 & & C_M & & \\ 0 & & & C_P & \\ 0 & 0 & & & C_L \end{array}\right]
$$

where the subscripts are defined as

C = Controller;
A = Amplifier;
M = Motor;
P = Power train;
L = Load.

Figure A3-36 is the VCLR for subroutine BLDPHI.

Zero All Output Matrices
Build Script Phi Matrix Using Phi Matrices from Controller, Amp, Motor, Power Train, and Load as Block Diagonals
Build Script Theta Matrix Using Theta Matrices from Controller, Amp, Motor, Power Train, and Load as Block Diagonals
Build System D Matrix
Build System C Matrix
CALL MATMPY to Compute Product of System D Matrix and System C Matrix
CALL MATMPY to Multiply Result by Script Theta Matrix
CALL MATADD to Add Result to Script Phi Matrix, Producing System Phi Matrix

Figure A3-36 BLDPHI VCLR

3.7.4 Build System Theta Matrix (BLDTHT)

Subroutine BLDTHT loads the system theta matrix needed for the Kalman filter used in conjunction with the state-variable formulation. The system theta matrix is constructed using matrices from the joint model controller block as follows:

$$\Theta = \left[\begin{array}{c|c} \theta_C & \theta_C M \\ \hline 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{array}\right]$$

where the subscripts are defined as

C = Controller.

Figure A3-37 is the VCLR for subroutine BLDTHT.

Zero Output Matrix
CALL MATMPY to Multiply Controller Theta Matrix and M Matrix
Load Elements of Result and Controller Theta Matrix into System Theta Matrix

Figure A3-37 BLDTHT VCLR

3.7.5 Build System Sensor Transform Matrix (BUILDH)

Subroutine BUILDH loads the system sensor transform matrix needed for the Kalman filter used in conjunction with the state-variable formulation. The system sensor transform matrix is constructed using matrices from each of the joint model blocks as follows:

$$H = \left[\begin{array}{c|cccc} 0 & H_A & & & 0 \\ 0 & & H_M & & \\ 0 & & & H_P & \\ 0 & 0 & & & H_L \end{array}\right]$$

where the subscripts are defined as

A = Amplifier;

M = Motor;

P = Power train;

L = Load.

Figure A3-38 is the VCLR for subroutine BUILDH.

Zero Script H Matrix (System Sensor Matrix)
Build Script H Matrix Using H Matrices from Amp, Motor, Power Train, and Load as Block Diagonals

Figure A3-38 BUILDH VCLR

3.7.6 Kalman Filter Computations (KALMAN)

Subroutine KALMAN is called from the main routine JNTMOD to perform the Kalman filter calculations. Subroutine BUILDG is called to compute the G matrix. All other matrices and arrays are available for use. The matrix equations used in subroutine KALMAN are as follows:

$$\hat{z}(k+1) = H(k+1)\ \phi(k+1,k)\hat{x}(k/k)$$

$$\hat{x}(k+1/k+1) = \phi(k+1,k)\hat{x}(k/k) + \theta(k+1,k)\alpha(k) + G(k+1)\{z(k+1)-\hat{z}(k+1)\}$$

where

$\hat{z}(k+1)$ is the best estimate of the system sensor output

$\hat{x}(k+1/k+1)$ is the best estimate of the system state

Subroutine PRTKF is called if printed output of the Kalman filter results is desired.

Figure A3-39 is the VCLR for subroutine KALMAN.

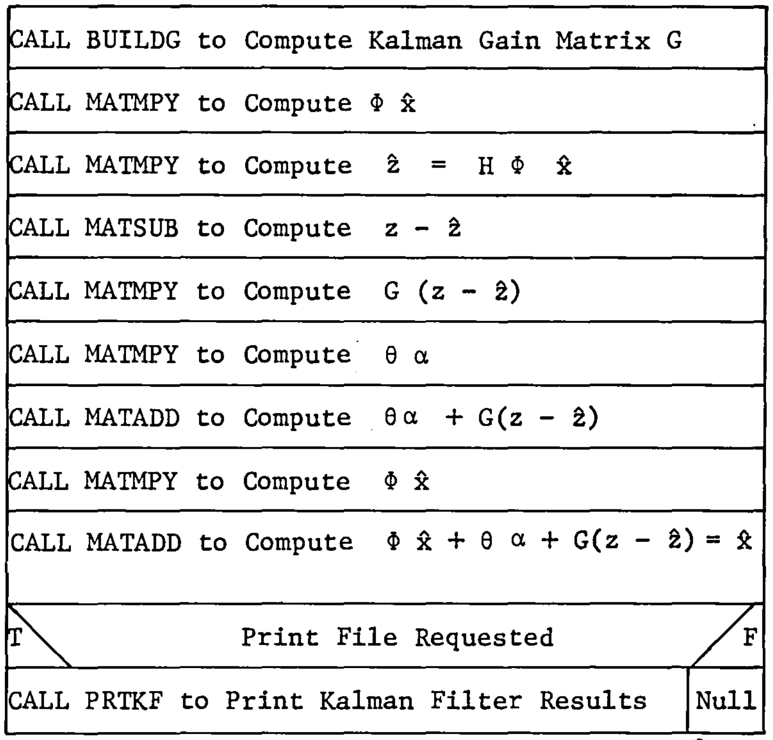

CALL BUILDG to Compute Kalman Gain Matrix G
CALL MATMPY to Compute $\Phi\ \hat{x}$
CALL MATMPY to Compute $\hat{z} = H\ \Phi\ \hat{x}$
CALL MATSUB to Compute $z - \hat{z}$
CALL MATMPY to Compute $G\ (z - \hat{z})$
CALL MATMPY to Compute $\theta\ \alpha$
CALL MATADD to Compute $\theta\alpha + G(z - \hat{z})$
CALL MATMPY to Compute $\Phi\ \hat{x}$
CALL MATADD to Compute $\Phi\ \hat{x} + \theta\ \alpha + G(z - \hat{z}) = \hat{x}$
T
Print File Requested
F
CALL PRTKF to Print Kalman Filter Results
Null

Figure A3-39 KALMAN VCLR

3.7.6.1 <u>Build G Matrix (BUILDG)</u> - Subroutine BUILDG is called from subroutine KALMAN to build the G matrix needed in the Kalman filter used in conjunction with the state-variable formulation. The following equations define the G matrix.

$$P(k+1/k) = \Phi(k+1,k)P(k/k)\Phi^T(k+1,k) + Q(k)$$

$$P(k+1/k+1) = \{P(k+1/k)^{-1} + H^T R^{-1} H\}^{-1}$$

$$G(k+1) = P(k+1/k+1)H^T(k+1)R^{-1}(k+1)$$

Figure A3-40 is the VCLR for subroutine BUILDG.

CALL MATTRN to Compute Φ^T
CALL MATTRN to Compute H^T
CALL MATMPY to Compute $P\ \Phi^T$
CALL MATMPY to Compute $\Phi\ P\ \Phi^T$
CALL MATADD to Compute $P = \Phi\ P\ \Phi^T + Q$
CALL LGINF to Compute P^{-1}
CALL MATMPY to Compute $P^{-1}\ H$
CALL MATMPY to Compute $H^T\ P^{-1}\ H$
CALL MATADD to Compute $P^{-1} + H^T\ P^{-1}\ H$
CALL LGINF to Compute $(P^{-1} + H^T\ R^{-1}\ H)^{-1} = P$
CALL MATMPY to Compute $H^T\ P^{-1}$
CALL MATMPY to Compute $P\ H^T\ R^{-1} = G$

Figure A3-40 BUILDG VCLR

3.7.6.2 <u>Print Kalman Filter Results (PRTKF)</u> - Subroutine PRTKF is called from subroutine KALMAN to print the Kalman filter results. At each call to subroutine PRTKF, the following parameters are printed:

1) Sensor output arrays--Z, ZHAT, and Z-ZHAT;

2) State-variable arrays--XHAT and SIGMAX.

Figure A3-41 is the VCLR for subroutine PRTKF.

Start New Page and Print Page Header with Current Time
Print Sensor Output
Print State Variable Output of Kalman Filter

Figure A3-41 PRTKF VCLR

3.8 PLOT FILE ROUTINES

This subsection describes the routines required to produce the plot file. The plot file contains all of the data generated in the joint model and Kalman filter routines. The contents of the plot file can be displayed as parameter versus parameter plots using the general plotting routine GENPLT.

3.8.1 Generate Symbol Record (PLTSET)

Subroutine PLTSET is called from the main routine JNTMOD to generate the symbol record for the plot file. The symbol record contains character symbols in the same location within the symbol record that is occupied by the corresponding data in the data records. The symbols in the symbol record allow the corresponding data to be easily located by routines that read the plot file.

Symbols for all possible plot parameters are stored in DATA statements within subroutine PLTSET. The symbol record array elements are loaded from the data in these DATA statements using the system dimension parameters for the joint system being modeled. After the symbol record is filled, the plot file is opened as an unformatted direct access file. A dummy header record is written followed by the symbol record.

Figure A3-42 is the VCLR for subroutine PLTSET.

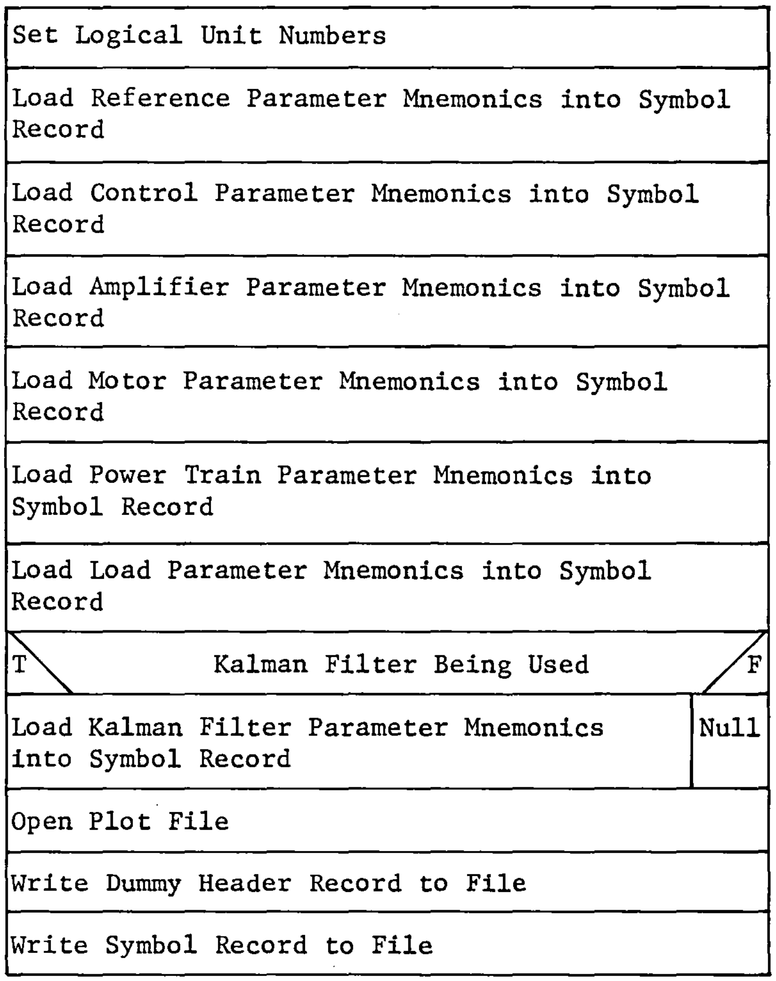

Set Logical Unit Numbers
Load Reference Parameter Mnemonics into Symbol Record
Load Control Parameter Mnemonics into Symbol Record
Load Amplifier Parameter Mnemonics into Symbol Record
Load Motor Parameter Mnemonics into Symbol Record
Load Power Train Parameter Mnemonics into Symbol Record
Load Load Parameter Mnemonics into Symbol Record
T
Kalman Filter Being Used
F
Load Kalman Filter Parameter Mnemonics into Symbol Record
Null
Open Plot File
Write Dummy Header Record to File
Write Symbol Record to File

Figure A3-42 PLTSET VCLR

3.8.2 Load Plot File Record (LDVALU)

Subroutine LDVALU is called from the main routine JNTMOD to load values into the plot file record. Subroutine LDVALU loads the values in input array A into the next available locations within the plot record. The values of array A are checked against the current maximum and minimum values corresponding to the array parameters. The maximum and minimum values are updated if necessary.

Figure A3-43 is the VCLR for subroutine LDVALU.

Load Plot Output Array with Values of Current Time
Update Max/Min of Values Stored for each Parameter

Figure A3-43 LDVALU VCLR

3.8.3 Write Header Record (WRTHDR)

Subroutine WRTHDR is called from the main routine JNTMOD after the simulation time loop is finished. Subroutine WRTHDR writes the header record to the plot file. The header record contains the maximum and minimum values for each parameter in the plot file data records.

Figure A3-44 is the VCLR for subroutine WRTHDR.

Load Header Record Buffer with: . Number of Records Written to Plot File . Max/Min Values in Plot File for Each Parameter in Plot File
Write Header Record Out to Plot File

Figure A3-44 WRTHDR VCLR

3.9 MATRIX MATH ROUTINES

This subsection contains the descriptions of the matrix math routines used throughout the JNTMOD program. The routines documented in this section are:

1) MATADD - Matrix addition;

2) MATMPY - Matrix multiplication;

3) MATTRN - Matrix transpose;

4) MATSUB - Matrix subtraction.

All matrix routines use variably dimensioned arrays that allow matrix, vector, and scalar operations.

3.9.1 Matrix Addition (MATADD)

Subroutine MATADD adds input matrix A to input matrix B to produce output matrix C. All arrays are variably dimensioned, which allows matrix, vector, or scalar operation.

Figure A3-45 is the VCLR for subroutine MATADD.

Add the Two Input Matrices (or Vectors)

Figure A3-45 MATADD VCLR

3.9.2 Matrix Multiplication (MATMPY)

Subroutine MATMPY multiplies input matrix A and input matrix B to produce output matrix C. All arrays are variably dimensioned, which allows matrix, vector, or scalar operation.

Figure A3-46 is the VCLR for subroutine MATMPY.

Zero the Output Array
Multiply the Two Input Matrices (or Vectors)

Figure A3-46 MATMPY VCLR

3.9.3 Matrix Transpose (MATTRN)

Subroutine MATTRN loads the output matrix B with the transpose of input matrix A.

Figure A3-47 is the VCLR for subroutine MATTRN.

Compute the Transpose of the Input Matrix

Figure A3-47 MATTRN VCLR

3.9.4 Matrix Subtraction (MATSUB)

Subroutine MATSUB subtracts input matrix B from input matrix A to produce output matrix C. All arrays are variably dimensioned, which allows matrix, vector, or scalar operation.

Figure A3-48 is the VCLR for subroutine MATSUB.

Subtract the Second Input Matrix (or Vector) from the First Input Matrix (or Vector)

Figure A3-48 MATSUB VCLR

3.10 IMSL MATH PACKAGE ROUTINES

This subsection briefly describes the two math routines used from the IMSL math package.

1) CALL GGNML - Compute normal random value from a Gaussian distribution with zero mean and variance of one;

2) CALL LGINF - Compute matrix inverse or pseudo-inverse.

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16. Abstract

This report contains Appendix A to NASA Contractor Report NASA CR-165975. Appendix A contains documentation of the preliminary software developed as a framework for a generalized integrated robotic system simulation. The program structure is composed of three major functions controlled by a program executive. The three major functions are: system definition, analysis tools, and post processing. The system definition function handles user input of system parameters and definition of the manipulator configuration. The analysis tools function handles the computational requirements of the program. The post processing function allows for more detailed study of the results of analysis tool function executions. Also documented is the manipulator joint model software to be used as the basis of the manipulator simulation which will be part of the analysis tools capability.

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