PS 390 DOCUMENT SET

GRAPHICS TUTORIALS 1–7

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GRAPHICS TUTORIALS

The *Graphics Tutorials GT1–7* and *GT8–16* consist primarily of a series of tutorials which teach PS 390 programming. Both volumes are designed to instruct programmers of various levels of expertise. Those with little computer graphics experience will want to read carefully through each section and do each exercise. Those with some computer graphics experience may find it sufficient to read these and supplement them with the *Reference Materials* volume. Though sophisticated users may want to rely primarily on the reference material, they are encouraged to read the *Graphics Tutorials* as well to become familiar with the approach to graphics programming taken in the *PS 390 Document Set.*

Each tutorial section covers a PS 390 programming concept or group of related concepts that provide you with experience in creating and manipulating an object on the screen using PS 390 commands. Because each section builds on information contained in the previous section, it is highly recommended that you read the sections in the established order. The following provides a capsule description of sections *GT1–GT7*:

GT1 Hands-on Experience

This brief section steps you through a first encounter with the PS 390. Even with no prior graphics experience, you can quickly learn to take advantage of the PS 390's capabilities.

GT2 Graphics Principles

This is the foundation of *Graphics Tutorials*. It presents the concepts of interactive graphics—how to construct models in a coordinate system—and illustrates how PS 390 programming puts these concepts into effect.

GT3 Tutorial Demonstrations

The tutorial demonstration package consists of programs which illustrate many of the graphics principles detailed in the tutorial sections. This set of software is distributed on magnetic tape. In addition to these programs, the tape contains a group of primitives which are required for many of the exercises in the tutorial sections. Before reading the tutorials, be sure to load the demonstration package.

GT4 Modeling

This section presents the first stage of graphics modeling, analyzing the model. This consists of breaking the model into interactive parts, organizing those parts into a hierarchy, and representing the hierarchy as a PS 390 display tree.

GT5 Command Language

This section details how to express the hierarchical display tree model in terms of the PS 390 command language.

GT6 Function Networks I

Function Networks I explains how to connect input devices to the model so you can interact with it.

GT7 Function Networks II

Function Networks II describes more advanced ways to use function networks. This includes multiple uses of dials (via function keys), labeling dial LEDs, limiting the motion of a model, and storing and retrieving variables.

GT1. HANDS-ON EXPERIENCE

GT1. HANDS-ON EXPERIENCE

INTRODUCTION TO PS 390 GRAPHICS

CONTENTS

ILLUSTRATIONS

Section GT1
Hands-On Experience
Introduction to PS 390 Graphics

In this section you will begin programming the PS 390 to display a few simple objects. Unlike the demonstration programs you have already worked with, where a preprogrammed object was displayed and you were able to manipulate it, here you will actually create the object before you interact with it. Everything you will be doing in this section will be done locally on the PS 390, without any help from your host computer.

1. Strategy

First you will build and display a square on the PS 390 screen. Next, you will make a rotated version of that same square to display as a diamond shape. Then, you will link these two shapes together for display as one object, an eight-pointed star. Last, you will make two slightly modified versions of the star and manipulate them. First, boot the PS 390. This is described in detail in Section *IS3 Operation and Communication*. Briefly, here is what you need to do.

Put the PS 390 graphics firmware diskette in the disk drive. Boot the system by turning on the power.

1.1 For Systems With a Non-IBM Host

Once the system is booted, hold down the CTRL key and press the LINE LOCAL key. Then press the RETURN key. You will see this prompt

@@

which indicates the PS 390 is now in command mode. It will accept any instructions you give it and execute them locally. (Command mode and other modes of operation are described in Section *IS3 Operation and Communication*.)

1.2 For Systems With an IBM Host

Once the system is booted, hold down the ALT key and press the LOCAL key. This prompt will appear:

```
@@
```

This indicates the PS 390 is in command mode and will accept any command you give it. When your host is an IBM, remember to enter a carriage return (<RETURN>) on the PS 390 keyboard (instead of the ENTER key) when you are working in command mode. The ENTER key does not work in command mode. (Command mode and other modes of operation are described in Section *IS3 Operation and Communication.*)

2. Displaying a Square

Before the PS 390 can display anything, it needs the coordinate points of the object you want to build—the square. Any wire-frame object you define must be specified as a collection of vectors, coordinate points and lines. The VECTOR_LIST command does this. Enter

```
Square := VECTOR_LIST .5,.5  .5,-.5  -.5,-.5  -.5,.5  .5,.5;
```

Enter this command exactly as you see it here and end it by entering <RETURN>. Pay special attention to all punctuation, but do not worry about capitalization (the PS 390 accepts either uppercase or lowercase letters). The "@@" prompt is shown here only because it appears on the screen when you enter commands. It is not something you have to enter.

If the command is accepted, another @@ prompt will appear on the next line, so this is what you should see on your screen.

```
@@Square := VECTOR_LIST .5,.5  .5,-.5  -.5,-.5  -.5,.5  .5,.5;
@@
```

If you get an error message instead, be sure you entered the line exactly as shown above. The "@@" prompt will not appear after an error message until you enter another carriage return. After an error message, enter the command again, exactly as shown above. Try this two or three times. If the command still is not accepted, the problem lies elsewhere.

After the PS 390 accepts this command, it knows about an object called Square that it will draw by going to the first point in the vector list (.5, .5) and then drawing to the next four points in the sequence listed (you need to end up back at .5, .5 to close the Square). The PS 390 will not display Square until you tell it to using the DISPLAY command. Enter

```
DISPLAY Square;
```

Square will appear centered on the screen. That is because Square is centered on the world coordinate system's origin, which currently corresponds to the center of the screen. By default, the part of the coordinate system viewed is from –1 to +1 in X and Y.

2.1 The Display List

As you have just seen, an object can be defined in the PS 390 and not be visible on the screen. When you use the DISPLAY command to display an object, the object's name is placed on a display list. The PS 390 continually checks this list to see if any names have been added or removed and then displays or "undisplays" the corresponding objects.

2.2 Coordinate Values

Right now, the screen shows a view of only part of the coordinate system, from plus 1 to minus 1 on both the X and Y axes. Anything to be drawn outside those coordinates will not show up on the screen. To see an object, you have to choose coordinates for it that are within these bounds. So, the coordinates for Square's corners are one-half unit in X and one-half unit in Y, and they appear about halfway from the center to the edge of the screen (Figure 1-1). Everything in this section will be two dimensional and take place in the plane defined by the X and Y axes, with Z equal to zero. The Z axis accounts for the third dimension of "depth."

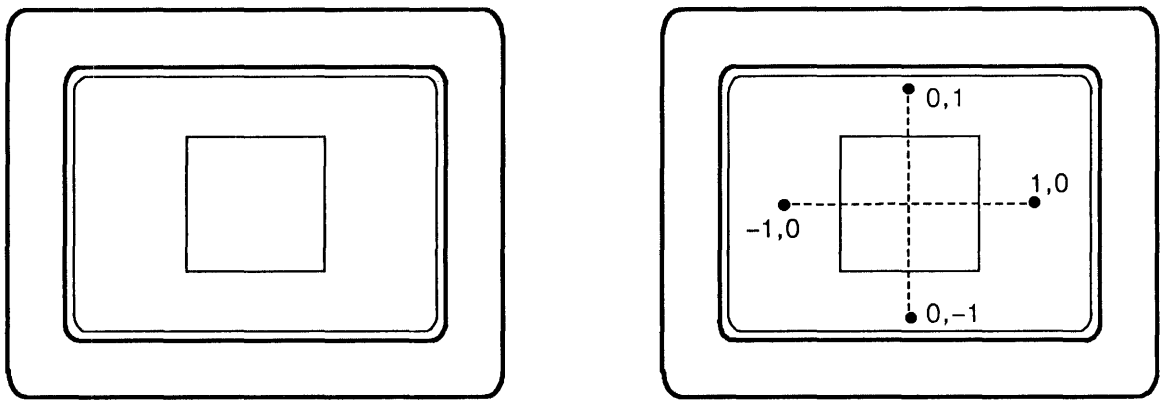

Figure 1-1. The Part of the Coordinate System that Appears on the Screen

2.3 Blanking the Screen

Two very useful keys, TERM and GRAPH, are located to the left of the typewriter section of the keyboard.

- Press the TERM key when you want to clear the screen of text. Labels or titles that are part of the displayed object are unaffected. This key toggles so you can press it again to redisplay, or "unblank," the text.
- Press the GRAPH key to blank any graphics being displayed on the screen. This will allow you an uncluttered view of the text. Press GRAPH again to redisplay the graphics.

3. Displaying a Diamond

After displaying a square, the next thing to do is to superimpose a diamond on it to make a star shape. Create the diamond as a rotated version of Square. Enter

```
Diamond := ROTATE IN Z 45 APPLIED TO Square;
```

which means essentially "create a new object by applying a 45-degree rotation to the object Square." To get a star figure to display on the screen, enter

```
DISPLAY Diamond;
```

Diamond is displayed superimposed on Square, resulting in a star-shaped object. At this point, you have done what you set out to do, which was to display a star shape on the screen. But if you want to do anything to the star now on the screen, you must issue two commands, one for each of the two objects that make it up. There is no single object named Star that you can manipulate. You can create such an object using an INSTANCE command. This command defines some new single object as a collection of other objects. You can define Star to be an instance of the two objects you already created. Enter

```
Star := INSTANCE OF Square, Diamond;
```

Now any operation you apply to Star will apply simultaneously to its two components, Square and Diamond.

4. Displaying Star

Before you display Star, remove the Square and Diamond from the screen. Enter

```
REMOVE Square;
```

and then

```
REMOVE Diamond;
```

The screen should now have nothing on it but text. There is a difference between removing objects from the screen this way and toggling the GRAPH key. When you press the GRAPH key, every object on the display list is blanked out from the screen (or unblanked so it will show up), but the contents of the display list stay the same. When you REMOVE something, it is removed from the display list and will not display no matter how many times you press the GRAPH key.

Now enter

```
DISPLAY Star;
```

Star will appear. It looks like the two objects you just removed, but now it is defined in the PS 390 as only one object.

5. Two More Versions of Star

With the SCALE command, you can scale an object on the screen to shrink it or enlarge it. For example, to make a new star one-fourth the size of Star, enter

```
Smallstar := SCALE BY .25 APPLIED TO Star;
```

and

```
DISPLAY Smallstar;
```

Smallstar will appear inside Star, centered on the screen origin. You can use the TRANSLATE command to define an object that is a "moved" version of some other object. Enter

```
Movestar := TRANSLATE BY .75,0 APPLIED TO Smallstar;
```

Movestar is a new version of Smallstar moved three-fourths of a unit to the right. The two values, .75 and 0, indicate how to move the object in X and Y. When the Y value is 0, the object translates horizontally only. Enter

```
DISPLAY Movestar;
```

and the new object will appear on the screen.

Even though the two newer stars, Smallstar and Movestar, are based on Star, they are separate objects with names of their own. You can do anything you want to Movestar or Smallstar and not affect Star. If you rotate or scale Smallstar, nothing will happen to Star. It will still be displayed at the center of the screen until you remove it. The reverse is not true. If you redefine Star in some way, that will affect Smallstar and Movestar because they are defined in terms of Star. Redefine Star as a triangle and watch what happens to Smallstar and Movestar. Enter

```
Star := VECTOR_LIST 0,.43  .5,-.43  -.5,-.43  0,.43;
```

These coordinates define an approximately equilateral triangle. As soon as you enter this command, what happens? Not only Star, but everything defined in terms of Star, changes. As a further illustration of how Smallstar and Movestar depend on Star, redefine Star once more, as the word "STAR". You need a couple of commands to accomplish this. You could do the same thing with one BEGIN_STRUCTURE... END_STRUCTURE. BEGIN_STRUCTURE...END_STRUCTURE is a convenient way to group related commands together. Enter

```
Star := BEGIN_STRUCTURE
CHARACTER SCALE .1;
CHARACTER -.2, 0 'STAR';
END_STRUCTURE;
```

All three objects will change from triangles to the word "STAR." Smallstar is still a quarter-size version of Star.And Movestar appears to the right of both of them. Briefly, here is what the two commands in the BEGIN_STRUCTURE... END_STRUCTURE did:

CHARACTER: The CHARACTER instruction specifies the word you want to display and the location of the lower left corner of the first character in the word. In this case, the S of STAR will be placed one-fifth unit (.2) out on the negative X axis. The characters in single quotation marks comprise the character string to be displayed.

CHARACTER_SCALE: Without scaling, each character would appear on the screen one unit in size. The first letter would cover the entire upper right quarter of the screen, and any letters following it would be out of view to the right. So this instruction scales the characters to one-tenth their normal size so they can all appear on the screen. The intricacies of BEGIN_STRUCTURE...END_STRUCTURE and the two CHARACTER commands (CHARACTER and CHARACTER SCALE) are explained in detail in other sections. You can redefine Star to be the eight-pointed figure it was before. Square and Diamond still exist in memory, so all you need to do is re-enter the command that defines Star as an instance of those two objects. For an exercise, do that now.

6. Updating Values, Connecting an Input Device

If you wanted to reposition Movestar, you could do so by redefining it with new translation values like this:

```
Movestar := TRANSLATE BY -.5,0 APPLIED TO Smallstar;
```

This would redefine Movestar at a new position to the left of the origin. There is a way to reposition Movestar without redefining it, and that is to SEND a new value to it. To do that, enter

```
SEND V3D(.75,.75,0) to <1>MOVESTAR;
```

Remember that Movestar is a translation applied to another object, Smallstar. Whenever you update a translation, you must send it a three-dimensional value; "V3D" stands for a three-valued vector. To supply Movestar with the right kind of data, you had to deal with all three dimensions, even though you are not making use of Z here. This SEND command immediately updates the translation values in Movestar (they were .75,0 with an assumed Z value of 0). Movestar shifts to the upper right corner of the screen. None of the definitions for any objects changed—the values changed. This is what input devices and function networks do. Without changing the basic definitions of objects, they alter and update values; how big to scale the objects, how much to rotate or translate them, and so on. To illustrate this, hook a simple function network from a control dial to an object to make it rotate. First, create the object. The PS 390 already knows about Smallstar, the scaled-down version of Star. Define Spinstar to be a version of Smallstar that can rotate. Enter

```
Spinstar := ROTATE IN Z 0 APPLIED TO Smallstar;
```

You must put 0 as the initial rotation value. Later, values coming from a dial will update Spinstar and make it rotate.

7. Another Way To Clear the Screen

You have defined Spinstar. The next step is to display it. But first, clear the screen of the other objects. When you did this before with Square and Diamond, you used REMOVE for each of them. It is much more convenient to use the INITIALIZE DISPLAY command. Enter

```
INITIALIZE DISPLAY;
```

This clears everything from the display list. Now display Spinstar by entering

```
DISPLAY Spinstar;
```

8. Connecting a Dial to Spinstar

Now build a simple function network to take values from the dial and turn them into values that can be used to update Spinstar. The PS 390 contains a "master" intrinsic function called F:DZROTATE that does that. To use it, make a copy of it and assign it a name, "Spinner" for example. Enter

```
Spinner := F:DZROTATE;
```

It is convenient to think of individual functions as "black boxes" with values coming in and other values going out. The functions are usually drawn as shown in Figure 1-2, as squares with input and output lines:

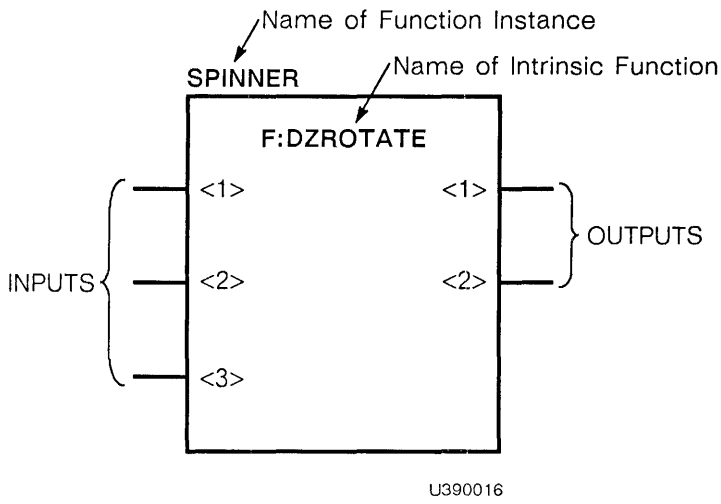

Figure 1-2. "Spinner" Function Diagram

Connect a dial to the first input of this function and the first output to Spinstar. Use the CONNECT command twice to do this.

```
CONNECT Dials<1>:<1>Spinner;
CONNECT Spinner <1>:<1>Spinstar;
```

These commands say to connect output <1> of the control dials (corresponding to the top left dial) to input <1> of the function Spinner. And connect output <1> of Spinner to input <1> of Spinstar. The numbers for the inputs of a function are to the left of the name, the output numbers are to the right. You are not quite finished setting up your function network, because Spinner needs to be "primed." It needs two initial values for its second and third inputs. You have already used the SEND command to update Movestar. You can use this command again to send 0 and 200 to Spinner's second and third inputs, respectively. Enter

```
SEND 0 TO <2>Spinner;
SEND 200 TO <3>Spinner;
```

The function network is now ready. If you turn dial 1, Spinstar will start turning. The values the dial generates update Spinstar so quickly that it appears to move in real time. When you turn the dial, Movestar responds instantaneously.

9. Conclusion

If any of what you have done is not completely clear to you, do not worry about it right now. The purpose of this section was to give you an opportunity to create and manipulate a few simple objects. In the remaining sections, you will discover in more detail how you can use these commands to create display structures and more complex function networks for models. You will also learn how to save the commands in a host file so they are more convenient to use.

GT2. GRAPHICS PRINCIPLES

GT2. GRAPHICS PRINCIPLES

HIGH-PERFORMANCE PS 390 DISTRIBUTED GRAPHICS

CONTENTS

ILLUSTRATIONS

Section GT2

Graphics Principles

High-Performance PS 390 Distributed Graphics

This guide introduces the concepts and terminology which you must understand to program the PS 390. It begins by explaining concepts which are common to most interactive graphics systems, but it soon becomes specific to the PS 390. The concepts introduced here are explained in much greater detail in the tutorial sections. In most cases, cross references are given to appropriate sections.

Examples of the PS 390 command language and of some PS 390 functions and function networks are given to show how specific computer graphics operations are performed by the PS 390. Little attempt is made to explain the syntax of commands or to explore all of the options of a particular command or function. Consult Sections *RM1 Command Summary*, *RM2 Intrinsic Functions*, and *RM3 Initial Function Instances*, for complete information on the commands and functions and their options.

Programmers with little or no experience of computer graphics systems should read this guide before embarking on the other tutorial sections. Experienced programmers who do not plan to use the tutorials sections can read this guide as an introduction to the documentation in the *Reference Materials* volume.

1. Creating Primitive Objects

A graphics programmer using the PS 390 for designing, viewing, and manipulating objects begins by creating a data base of the mathematical information that defines the objects. Objects are defined as two-dimensional or three-dimensional shapes consisting of points and lines or planes. Objects defined as points and the lines that connect them are wireframe models. Objects defined as planes are polygonal models, and differ from wireframe models because they contain surface or solid information.

The data space in which the programmer models objects is known as the world coordinate system. This system provides a way of expressing the location of all the points which define the object.

The simplest object in a graphical data base is a primitive. This consists entirely of points and lines or planes. The points specify the geometry of the object; the lines or planes specify the topology.

1.1 Coordinate Systems

The PS 390 displays convincing three-dimensional images of mathematically defined objects. All mathematical information that the designer enters to create an object (the data base) must be given in terms of a three-dimensional coordinate system. A coordinate system is a way of specifying a three-dimensional space in which objects can be modeled.

1.1.1 Right-Hand Coordinate System

One conventional method for representing three-dimensional space uses three lines (axes) originating at a common point in space (the origin) and drawn at right angles to each other in the dimensions of height, width, and depth. These axes are labeled X (width), Y (height), and Z (depth). Figure 2-1 represents a commonly used coordinate system known as the right-hand coordinate system.

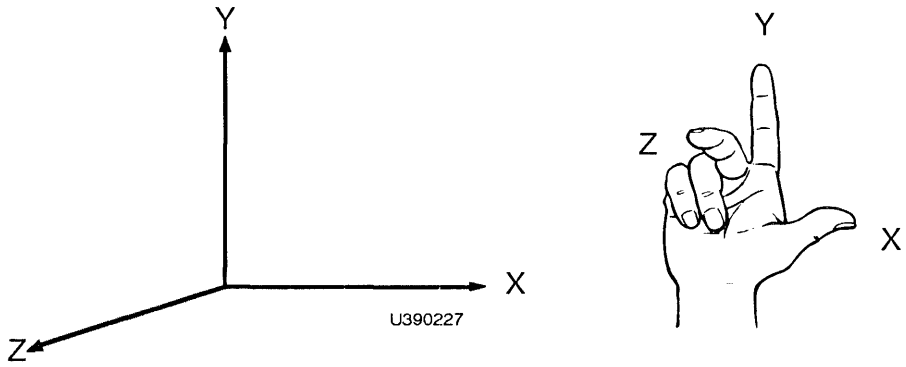

Figure 2-1. Right-Hand Coordinate System

As Figure 2-1 shows, the thumb and first two fingers of the right hand can be used as a mnemonic for the names and positive directions of the axes in this system. There is a disadvantage to this coordinate system for modeling with a computer graphics system. If you consider the computer screen to be parallel to the XY plane of this three-dimensional space, then positive values in the Z axis (depth) increase towards the eye of the viewer. The depth of an object displayed on the screen should be perceived as a dimension

into the screen. So a coordinate system is needed with a Z axis that has positive values which increase into the screen away from the viewer.

1.1.2 Left-Hand Coordinate System

A left-hand coordinate system, employed by many computer graphics systems including the PS 390, has a Z axis in which positive values increase away from the viewer. Figure 2-2 shows a representation of the left-hand coordinate system.

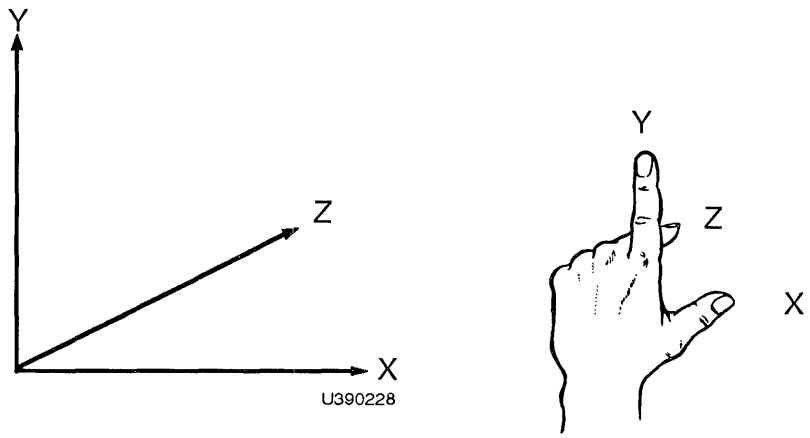

Figure 2-2. Left-Hand Coordinate System

Note that the thumb and first two fingers of the left hand indicate the positive direction of the axes in this coordinate system.

1.1.3 The World Coordinate System

The left-hand coordinate system with which the PS 390 graphics programmer works is known as the world coordinate system. The world coordinate system provides a way of expressing the mathematical data which the computer needs to create, display, and manipulate models in three dimensions. Figure 2-3 is a representation of the world coordinate system used in programming the PS 390.

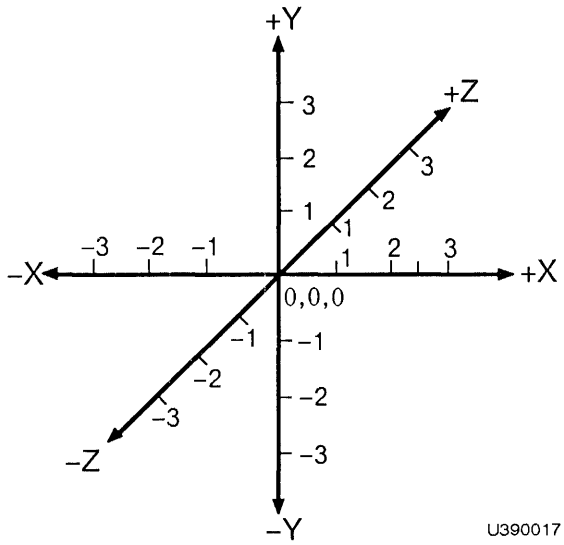

Figure 2-3. The World Coordinate System

All axes have a positive direction and a negative direction, and values are assigned for every point along an axis. The point at which the three axes meet is the origin.

1.2 Data Base For an Object

A data base for an object consists of points and lines (if the object is a wireframe model) or planes (if the object is a polygonal model) expressed in world coordinate values. The points, lines, and planes define the geometry and topology of the object.

1.2.1 Geometry

The geometry of an object is the location in the world coordinate system of the points which define it. If, for example, you want to create a square centered at the origin of the world coordinate system with sides five units long, then the coordinates of the four points A, B, C, and D that define the square are as shown in Figure 2-4.

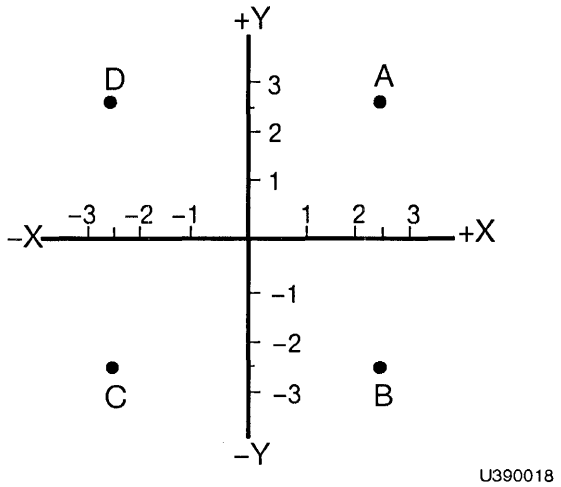

Figure 2-4. Coordinates of a Square

When these coordinates are connected with lines, the result is the square shown in Figure 2-5.

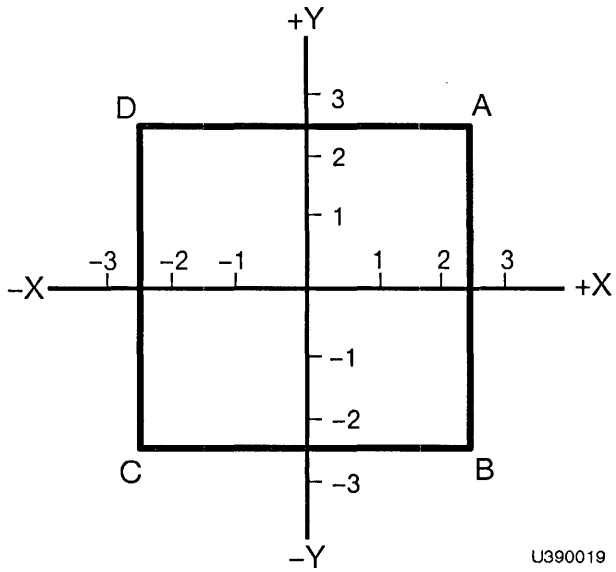

Figure 2-5. Location of the Square in the World Coordinate System

1.2.2 Coordinate Notation

The convention for defining coordinates in three-dimensional space is to give the X component first, then the Y component, and finally the Z component. For example, point A is 2.5 units in the positive X axis, 2.5 units in the positive Y axis, and zero units in the Z axis, since the square is a two-dimensional figure. The notation for this coordinate is (2.5,2.5,0) or just (2.5,2.5) with the value for Z defaulting to zero. Point B is also 2.5 units in the positive X axis, but 2.5 units in the negative Y axis, and zero units in the Z axis. The notation for this coordinate is (2.5,–2.5,0) or just (2.5,–2.5). The coordinates of the four corners of the square are as follows:

- Point A: (2.5,2.5,0) or (2.5,2.5)
- Point B: (2.5,–2.5,0) or (2.5,–2.5)
- Point C: (–2.5,–2.5,0) or (–2.5,–2.5)
- Point D: (–2.5,2.5,0) or (–2.5,2.5)

1.2.3 Topology

The coordinates of the points specify the geometry of the square. For the computer to draw the square, the manner in which the points are connected must be indicated. This is called the topology of the object. In the case of the square, A is connected to B, B to C, C to D, and D is connected back to A. Geometry and topology form a minimum data base for displaying an object. This combination forms a vector list or a polygon list, depending on whether the object is defined as a set of lines or bounded planes (surfaces).

1.2.4 Vector List

A vector list specifies an object that is composed of lines. A vector is a set of coordinate pairs (X,Y) or triples (X,Y,Z) and a direction. A vector list specifies points within the world coordinate system at which lines start and end, and the order of the direction in which lines are drawn.

The following PS 390 command creates a vector list named Square.

```
Square := VECTOR_LIST N = 5  2.5,2.5  2.5,-2.5  -2.5,-2.5
                            -2.5,2.5  2.5,2.5;
```

Notice that five items were needed in the vector list to specify the topology of this object. The computer must be told to draw from point D to point A

to complete the square. The "N = 5" clause is an estimate of the number of vectors so that sufficient memory can be allocated for the object.

The topology is implicit in the order in which coordinates are given. The first coordinate indicates a starting position. Each coordinate after that is a point to which a line is drawn. An alternative form of the VECTOR_LIST command uses the clause ITEMIZED and includes P (position) and L (line) identifiers to distinguish between move-to and draw-to coordinates. The same vector list as specified above can be written as follows.

```
Square := VECTOR_LIST ITEMIZED N = 5 P 2.5,2.5 L 2.5,-2.5 L -2.5,-2.5
                                     L -2.5,2.5 L 2.5,2.5;
```

Position and line indicators are essential in vector lists for shapes that are not closed figures. For example, to draw just the left and right sides of the square, a vector list such as the following is needed.

```
Sides := VECTOR_LIST ITEMIZED N = 4 P -2.5,2.5  L -2.5,-2.5
                                    P  2.5,2.5  L 2.5,-2.5;
```

1.2.5 Polygon List

A polygon is a set of points that enclose and define a plane or surface. Just like a vector list, a polygon list contains the coordinates of the endpoints of the lines that make up the polygon. Unlike a vector list, a polygon list does not have to repeat the first point to close the figure, since by definition a polygon is a closed figure. The following command creates a square as a polygon list.

```
Square := POLYGON  2.5,2.5  2.5,-2.5 -2.5,-2.5 -2.5,2.5;
```

Only four items are needed in the polygon list to specify the topology of the square when it is defined as a polygon.

Polygonal models differ from wireframe models created from vector lists in that they contain surface or solid information. This information is necessary for rendering operations applied to objects defined by the POLYGON command. Rendering operations include such things as cross-sectioning, hidden-line removal, and shading of the model. The specific parameters for the POLYGON command and a complete discussion of rendering operations can be found in Section *GT13 Polygonal Rendering*.

1.3 Graphical Primitives

Vector lists and polygon lists contain all the information needed to specify the geometry and topology of an object. Objects specified as vector lists or polygon lists are known as graphical primitives. The VECTOR_LIST and POLYGON commands are the two most commonly used to create primitives locally in the PS 390. Complex primitives are often created by a host application program and transferred to the PS 390 to be manipulated and viewed.

1.3.1 Same Geometry but Different Topologies

Primitive objects can have the same geometry, but different topologies. That is, the same set of world coordinates can be connected by lines to create open figures or polygons of different sorts, as shown in Figure 2-6.

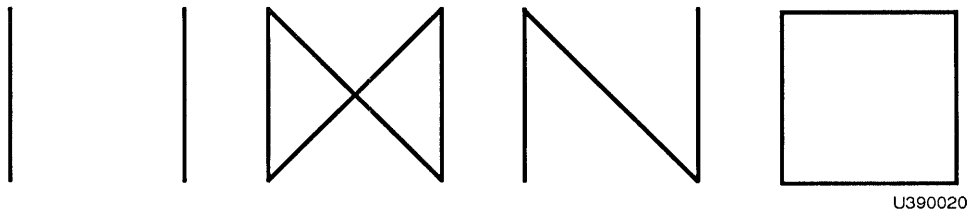

Figure 2-6. Primitives With the Same Geometry and Different Topologies

For example, the capital letter "N" can be created by the following vector list.

```
Capital_N := VECTOR_LIST N = 4  -2.5,-2.5 -2.5,2.5
                                 2.5,-2.5  2.5,2.5;
```

The bow tie shape can be created by the following vector list.

```
Bow_Tie := VECTOR_LIST N = 5  -2.5,-2.5  -2.5,2.5  2.5,-2.5
                               2.5,2.5  -2.5,-2.5;
```

For open figures, such as the two parallel lines, position and line identifiers must be included in the vector list. The following command creates the two parallel horizontal lines as a single primitive.

```
Lines := VECTOR_LIST ITEMIZED N = 5 P -2.5,2.5  L 2.5,2.5
                                    P -2.5,-2.5  L 2.5,-2.5;
```

Although the geometry is the same for all of these objects, their topologies are different, and so their vector lists are different. Each object must be defined as a separate primitive with its own vector list.

1.3.2 Same Topology but Different Geometries

Primitives can also share the same topology and have different geometries. All of the four-sided shapes in Figure 2-7, for instance, consist of four points connected in the same manner.

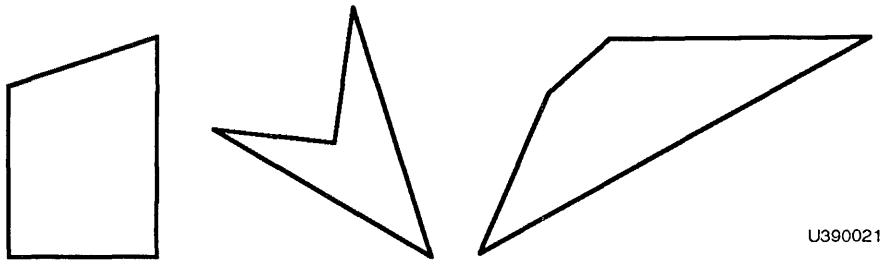

Figure 2-7. Primitives With the Same Topology and Different Geometries

Each of these objects must be defined as a separate primitive. However, as the next section, *Transforming Primitives* shows, there are ways of changing the geometry of a primitive to create a new object without creating a new primitive.

1.3.3 Curve Primitives

The examples used so far have been for primitives consisting of straight lines only. Other commands, such as the BSPLINE and POLYNOMIAL commands create curve primitives locally in the PS 390. For more information on these commands refer to Section *RM1 Command Summary.*

1.3.4 Text Primitives

Text is also treated as a graphical primitive in the PS 390. A standard 128-character ASCII set is provided with the system. The characters which compose this standard font are created as vector lists, so you do not have to create your own. However, if you want to create different fonts that can be used as a supplement to the standard font, there is a command which allows you to do this. The BEGIN_FONT ... END_FONT command lets you create 128 separate vector lists defining the characters which compose the font and assign them a single name. This font can be substituted for the standard font using the CHARACTER FONT command. For more details, refer to Sections *GT10 Text Modeling and String Handling* and *RM1 Command Summary.*

1.4 Summary

New Information Presented

1. To express the mathematical data which defines an object for graphical display, a programmer uses a coordinate system.
2. The coordinate system most useful for computer graphics purposes is a left-hand coordinate system. This coordinate system has a Z axis that has positive values which increase away from the eye of the viewer.
3. The coordinate system used in creating a data base for graphical objects is called the world coordinate system.
4. To create a model of an object with a graphics computer, you need to specify two things:
   - The positions of the endpoints of each line, expressed as three-dimensional (X,Y,Z) coordinates. This is known as the geometry of the object.
   - The way in which those points are connected by lines. This is known as the topology of the object.
5. The geometry and topology together form a vector list or polygon list for a graphical primitive. A primitive defined by a vector list is composed of lines. A primitive defined by a polygon list is composed of planes or surfaces.
6. Other primitives composed of points and lines are curves and text. Primitives of all sorts can be created locally using PS 390 commands. They can also be generated by a host application program and sent to the PS 390.

What Next?

At this point, you can create a graphical data base for a primitive. Vector lists define wireframe objects made of lines, and polygon lists define objects made of planes. In the next section you will see how to apply mathematical transformations to primitives to create new objects. These new objects will have the same topology as the primitives, but their geometries will be different.

2. Transforming Primitives

Mathematical operations called transformations can be applied to a primitive to change its geometry by moving some or all of its points to a new location in the world coordinate system. Transformations create a new object, based on the definition of the old one, which has the same topology as the primitive, but a different geometry.

Using transformations, you can, in effect, move primitives around in the coordinate system or add numerous different objects to the data base using a small number of primitive shapes.

2.1 Creating New Objects From Primitives

The data base of shapes so far consists of a square with sides five units long. If you want to add to the data base a two-dimensional diamond shape with sides that are five units long centered at the origin of the world coordinate system, you could create it as a primitive by entering a vector list like this.

```
Diamond := VECTOR_LIST N = 5  0,3.54 * 3.54,0  0,-3.54  -3.54,0
                              0,3.54;
```

The diamond will be located in the world coordinate system as shown in Figure 2-8.

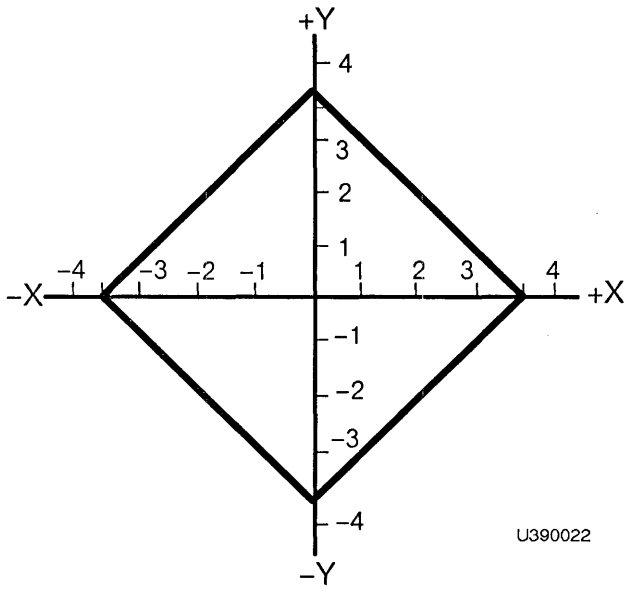

Figure 2-8. Location of the Diamond

Notice that the Diamond and the Square primitive that already exists share several features. They are both two-dimensional figures, they are the same size (5 units per side), and they have the same topology. In fact, the only difference between the two figures is their geometry. The points that define the four corners of the Square and the Diamond are in different locations within the world coordinate system. The diamond shape could be described as the square shape rotated 45 degrees around the Z axis.

Since the two objects share these relationships, there would be no need to create a separate primitive if there were some way to change the geometry of the square while maintaining its topology. PS 390 commands exist which do exactly that.

2.1.1 Applying Transformations

With the PS 390, you can apply mathematical operations to primitives that already exist to move them around in the coordinate system or create new shapes from them. The resulting objects are not defined as primitives themselves. Instead, they are structures which consist of matrix transformations applied to the coordinates which define a primitive.

Transformations are operations of matrix algebra which change the geometry of a graphical object, but do not affect the topology. When you create either a vector list or polygon list for an object, you have to calculate the coordinates of the points yourself. When you apply transformations to existing primitives, the PS 390 calculates the new coordinates for you. It is easier, for example, to create the diamond by rotating the square than to calculate yourself the coordinates of the diamond primitive. The following PS 390 command creates a diamond by rotating the square.

```
Diamond := ROTATE IN Z 45 APPLIED TO Square;
```

The structure of the diamond can be diagrammed as shown in Figure 2-9.

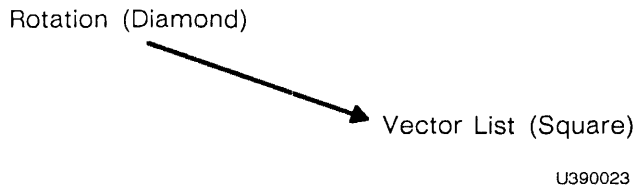

Figure 2-9. The Structure of the Diamond

The diamond is shown as a rotation transformation applied to the vector list defining the square.

2.2 Modeling Transformations

Transformations which are used to create new objects by changing the geometry of already defined primitives are often referred to as modeling transformations. There are three modeling transformations: rotation, translation, and scaling. Section *GT4 Modeling* gives examples of the use of modeling transformations to create and position the parts of a complex object.

2.2.1 Rotation

A new object can be created by rotating a primitive through any number of degrees in any of the three dimensions. To perform a rotation on a primitive, the computer uses the sine and cosine of the angle specified in the rotate command to create a rotation matrix, which is applied to the points in the vector list.

When an object is rotated in the world coordinate system, it rotates around one of the X, Y and Z axes in the directions shown in Figure 2-10.

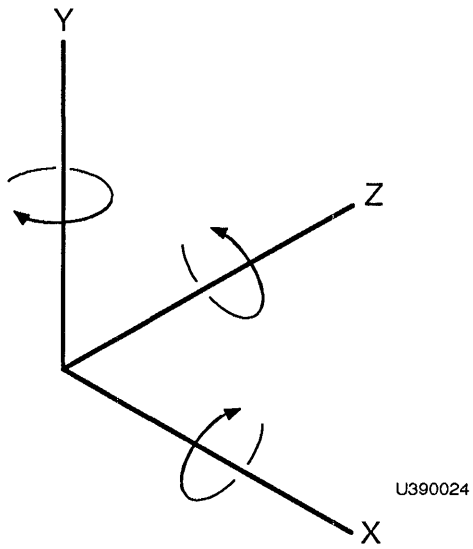

Figure 2-10. Rotation in the World Coordinate System

2.2.2 Rotations Around an Axis

Note the terms used to express rotations. A rotation "in X" means rotation around the X axis. To determine the direction of rotation around an axis, use the left-hand coordinate mnemonic. Point the thumb of your left hand in the positive direction of any axis, and your fingers will curl in the direction of positive rotation.

Rotations always occur around one of the world coordinate axes. Consider a new object called Rot_Arrow created by rotating an existing 2D arrow which is centered at the origin through 120 degrees in Z.

```
Rot_Arrow := ROTATE IN Z 120 APPLIED TO Arrow;
```

The orientation of the rotated arrow will be as shown in Figure 2-11.

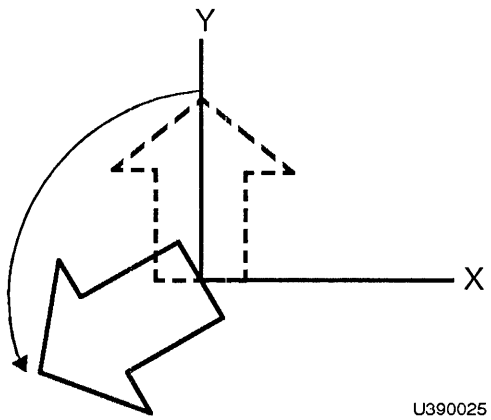

Figure 2-11. Orientation of the Rotated Arrow

The primitive arrow is drawn with dashed lines; the rotated arrow is drawn with solid lines. Since the primitive arrow was created with its base at the origin, the rotated arrow is based at the origin also. If an object is not centered at the origin, however, and a rotation is applied, the rotation about the world axis will have the effect of "swinging" the object around the axis, as illustrated in Figure 2-12.

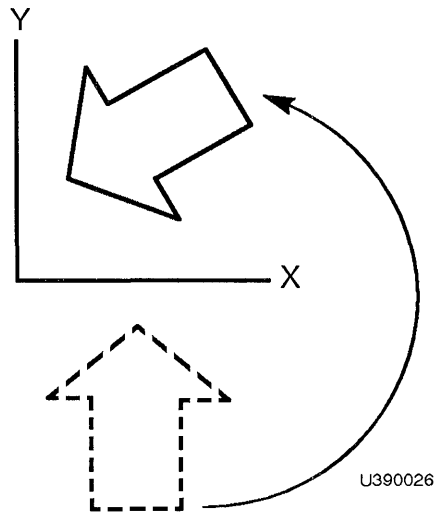

Figure 2-12. Rotation of an Object Not Centered at the Origin

Rotating an object while it is centered at the origin, then, effectively rotates it about its own center. Rotating an object which is not at the origin swings that object around one of the world axes to a new location in the world coordinate system.

2.2.3 Translation

Translating an object means moving it to a new location in the world coordinate system. An object which is translated in X is moved in the X direction. An object translated in X and Y is moved some distance in the X direction and some distance in the Y direction.

The PS 390 performs translations on a primitive by adding the X, Y, and Z values specified in the translation command to the coordinates of each vector.

Consider a new square created by translating the Square defined earlier by 2 units in the positive X axis.

```
Trans_Square := TRANSLATE 2,0 APPLIED TO Square;
```

The location of Trans_Square will be as shown in Figure 2-13.

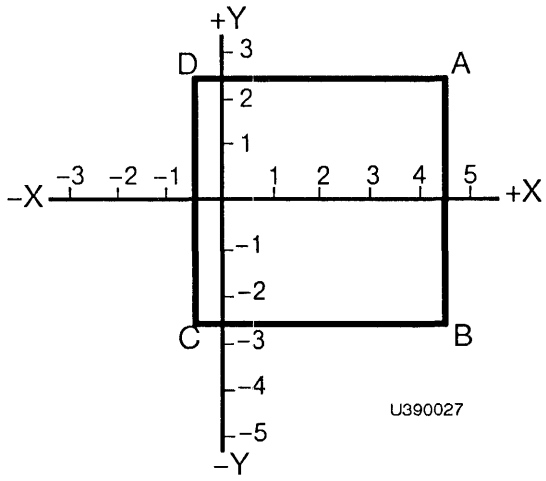

Figure 2-13. Location of the Translated Square

Notice that in a translation in X, the X component of each coordinate is changed (in this case, increased by 2) but the Y and Z components are not.

2.2.4 Translations in All Three Axes

The PS 390 performs translations in any direction (X, Y, or Z) and in any combination of directions. For example, a translation of 2 units in positive X and 2 units in negative Y can be applied to Square.

```
New_Trans_Square := TRANSLATE 2,-2 APPLIED TO Square;
```

The new translated square will be located as shown in Figure 2-14.

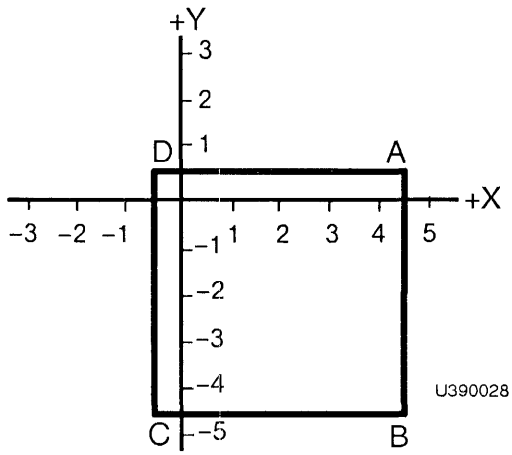

Figure 2-14. Square Translated in X and Negative Y

Naturally, translations may be specified in three dimensions. The notation used for representing translations is to give the X component, the Y component, then the Z component, separated by commas. So, for example, a translation of 3,–2,4 is 3 units in X, 2 units in negative Y, and 4 units in Z.

2.2.5 Scaling

Scaling an object makes it smaller or larger, depending on the scale factor that is specified. The PS 390 creates a scaling matrix which multiplies the points in the vector list by the scale factor in the scaling command to determine the new coordinates of the scaled object.

For example, a small square can be created by scaling the square defined at the origin of the world coordinate system by 0.5.

```
Small_Square := SCALE BY .5 APPLIED TO Square;
```

The small square will have the coordinates shown in Figure 2-15.

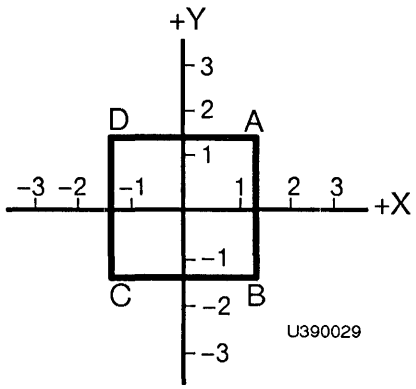

Figure 2-15. Scaling the Square

This type of scaling is called uniform scaling. The new object is created by scaling the primitive by the same amount in all dimensions. Another type of scaling, nonuniform scaling, consists of scaling an object by different amounts in different dimensions. For example, a rectangle can be created by scaling the Small_Square by 2 units in X only.

```
Rectangle := SCALE 2,1,1 APPLIED TO Small_Square;
```

The rectangle will have the following coordinates (Figure 2-16).

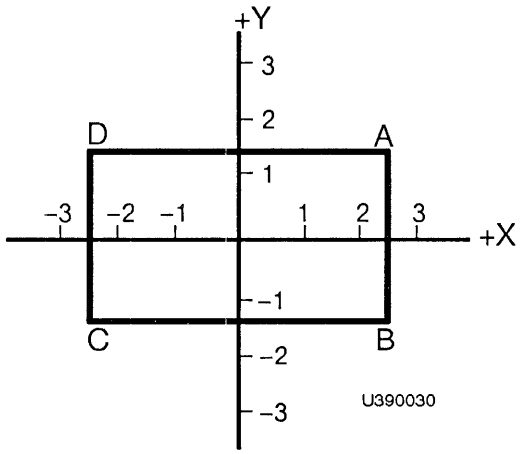

Figure 2-16. Nonuniform Scaling to Create a Rectangle

Nonuniform scaling is a commonly used modeling transformation; it distorts the shape of a primitive to produce a new object. For example, a nonuniform scale in Y and Z applied to a cube at the origin can create an object with the relative dimensions of a building brick. Circles can be scaled nonuniformly to create ellipses, and spheres to create ellipsoids, and so on.

2.3 The Ordering of Transformations

When a series of transformations is applied to a primitive, the order in which the transformations are applied always determines the final location and orientation of the object in the world coordinate system. For example, consider a 2D arrow which has been created within the world coordinate system as shown in Figure 2-17.

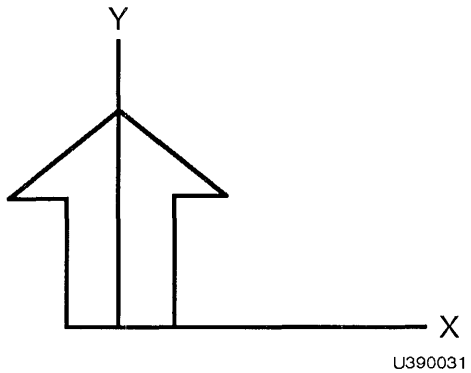

Figure 2-17. A Two-Dimensional Arrow

If the arrow is rotated 45 degrees in Z, rotation occurs around the Z axis. The rotated arrow (Arrow_1) is oriented as shown in Figure 2-18.

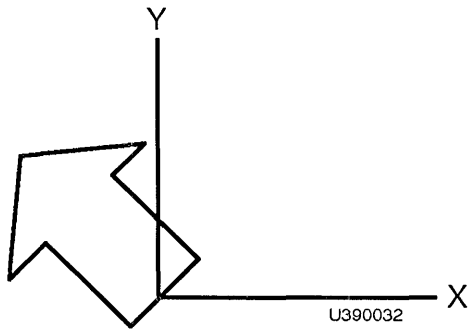

Figure 2-18. Rotated Arrow

A new object called Arrow_2 is now created by applying a translation in positive X and negative Y to the rotated arrow. The orientation of the translated arrow is still a rotation of 45 degrees in the plane of the Z axis, but its location would be something like this (Figure 2-19).

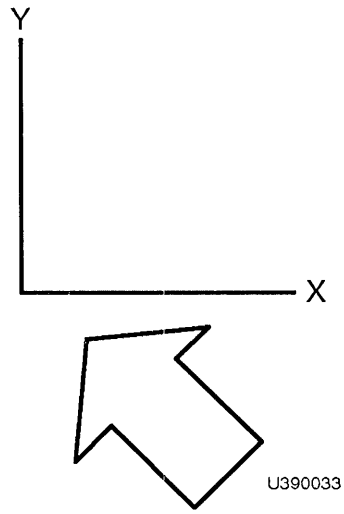

Figure 2-19. Arrow Rotated, Then Translated

The structure of Arrow_2 is a translation pointing to a rotation, pointing to a vector list. It can be diagrammed as shown in Figure 2-20.

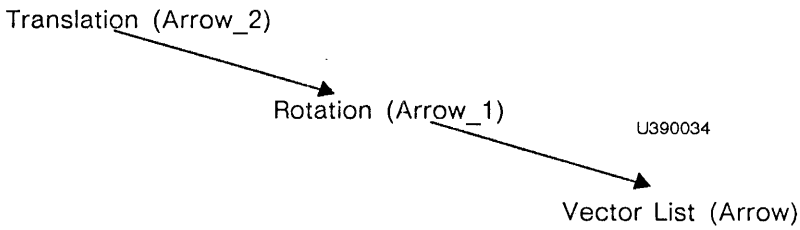

Figure 2-20. The Structure of Arrow

Now consider what happens if the original arrow is translated first, and then is rotated. Translating the arrow in positive X and negative Y creates an object (Arrow_3) located in the world coordinate system as shown in Figure 2-21.

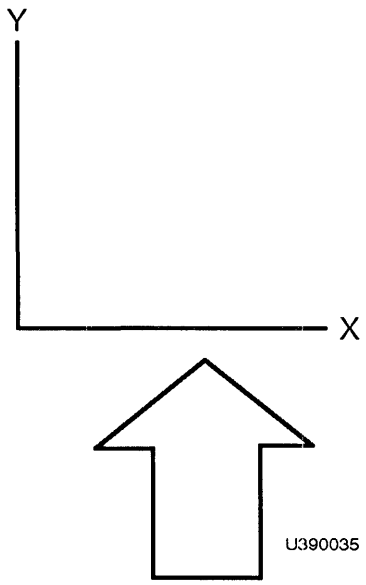

Figure 2-21. Translated Arrow

If a rotation of 45 degrees in Z is now applied to the translated arrow, the new object Arrow_4 will "swing" around the Z axis to a new location in the world coordinate system (Figure 2-22).

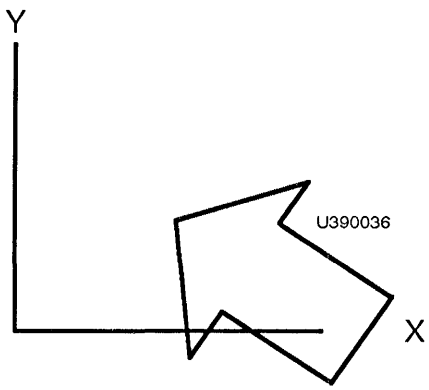

Figure 2-22. Arrow Translated, Then Rotated

The structure of Arrow_4 is a rotation pointing to a translation pointing to a vector list. It can be shown as follows (Figure 2-23).

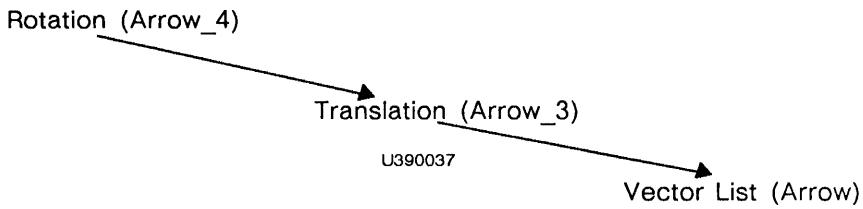

Figure 2-23. The Structure of Arrow_4

The order in which transformations are applied to objects determines the ultimate location and orientation of the new object in the world coordinate system. The same transformations applied to the same primitive in a different order produce different results. When you are applying a series of transformations to an object, you must take care to apply those transformations in the correct order to get the result you want.

2.3.1 Transformation Matrices

Translations, rotations, and scalings are the three basic transformations which are applied to data in a computer graphics system. We have called these three modeling transformations. As you will see in Section *2.5 Looking at Objects*, other transformations called viewing transformations can be applied to data to create different views of objects—for example, top views, side views, or perspective views. Although viewing transformations are more complex, they are still combinations of translations, rotations, and scales.

Later sections also describe how transformations can be applied interactively to data. Values from the keyboard, data tablet, dials, and buttons can be used to apply a series of transformations in rapid succession, giving the illusion of movement to displayed objects. All transformations applied to graphical data are performed by matrix algebra. The most commonly used matrices in computer graphics are 2x2 (two-dimensional rotations and scales for characters and text strings); 3x3 (three-dimensional rotations and scales for objects); and 4x3 and 4x4 (most of the viewing transformations described in Section *2.5*).

All matrices are governed by the laws of matrix algebra. Of particular interest to the graphics programmer is the law that matrix A times matrix B does not equal matrix B times matrix A. This property is known as the noncommutativity of matrices. The noncommutativity of matrices makes the careful ordering of transformations necessary in graphics programming.

When a transformation is applied to an object, the new coordinates of the vectors which compose the object are calculated by multiplying the old coordinates by the elements in the matrix.

When more than one transformation is applied to graphical data, the matrices are concatenated. This means that each matrix is premultiplied to a matrix called the current transformation matrix. The current transformation matrix contains the accumulation of all transformations that are to be applied to graphical data and preserves the order in which they are to be applied. A 4x4 current transformation matrix is large enough to handle all of the transformations needed for computer graphics operations.

Matrix concatenation works like this. Suppose you want to scale a primitive to twice its size, rotate it 180 degrees in Z, and then translate it in X and Y. Instead of applying three separate matrices to the points that define the object, the PS 390 premultiplies the matrices that represent these transformations into the current transformation matrix. This single matrix is then applied to the vector list that defines the object.

The current transformation matrix (CTM) starts out as an identity matrix, as shown in Figure 2-24.

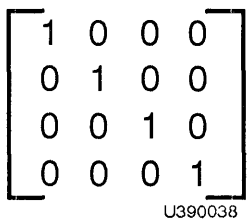

Figure 2-24. An Identity Matrix

An identity matrix is composed of ones and zeros, with the ones running in a diagonal. Multiplying by an identity matrix is the equivalent of multiplying by one: nothing changes. Each transformation matrix in turn—scale, rotate, and translate—is premultiplied to the identity matrix. The result is a CTM which consists of the cumulative transformations and the order in which they are to be applied to the data. The vector list defining the object is run through the CTM as the last stage in the process, as shown in Figure 2-25.

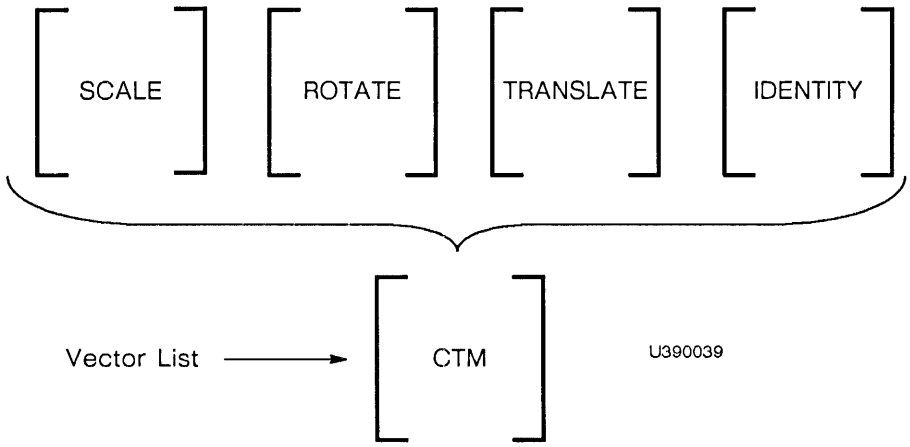

Figure 2-25. Concatenating Matrices

The transformed vectors which result form the points and lines of the newly oriented object. If the order of the transformations were changed, then the final CTM would be different. If this matrix were applied to the data defining the object, the ultimate location and orientation in the world coordinate system of the transformed object would change.

For more information about matrix algebra, consult Newman, W.M., and Sproull, R.F., *Principles of Interactive Computer Graphics, Second Edition*, McGraw-Hill, 1979. This text contains an appendix which introduces vectors and matrices.

2.4 Summary

New Information Presented

1. New objects can be created by applying transformations to primitives.
2. Transformations change the geometry of the primitives but leave their topology the same.
3. Three basic transformations are translations, rotations, and scales.
4. When more than one transformation is applied to an object, the order in which the transformations are applied affects the final location and orientation of the object in the world coordinate system.
5. All transformations are applied through matrix algebra. Transformations are concatenated into a single matrix known as the current transformation matrix.
6. Matrices are said to be noncommutative. That is, matrix A times matrix B does not equal matrix B times matrix A. The noncommutativity of matrix multiplication requires the careful ordering of transformations to be applied to graphical data.

What Next?

By applying matrix transformations to existing primitives you are now able to move objects around and create new objects of different sizes and shapes.

In the next section, you will see how to create compound objects. Commands exist to group collections of primitives and transformations created from the VECTOR_LIST command under one name. The resulting compound object can be transformed as a single entity.

3. Creating Compound Objects

Compound objects can be created with the PS 390 using primitives and transformations.

Primitive objects and transformed primitives can be grouped into one named object which can be transformed as a single entity.

3.1 Building with Primitives and Transformations

No matter how complicated an object is, you can create it as a primitive by figuring out the vector list or polygon list needed to specify the coordinates of all the line endpoints and the way in which those points are connected. An alternative, however, is to use primitives and transformations as building blocks to create new objects which are compound structures.

3.1.1 Creating a Star Primitive

If, for example, you want to create an eight-pointed star centered at the origin, making the object out of lines (not polygons) five units long, you could create it as a primitive by entering the following vector list:

```
Star := VECTOR_LIST  ITEMIZED N = 10 P  0,3.54  L 3.54,0  L 0,-3.54
                                     L -3.54,0  L 0,3.54  P 2.5,2.5
                                     L 2.5,-2.5  L -2.5,-2.5
                                     L -2.5,2.5  L 2.5,2.5;
```

Notice that this form of the vector list has the word ITEMIZED and has P and L identifiers preceding each coordinate. This is necessary because the star shape cannot be drawn as a set of continuous lines. The new primitive, Star, created by this command is located in the world coordinate system as shown in Figure 2-26.

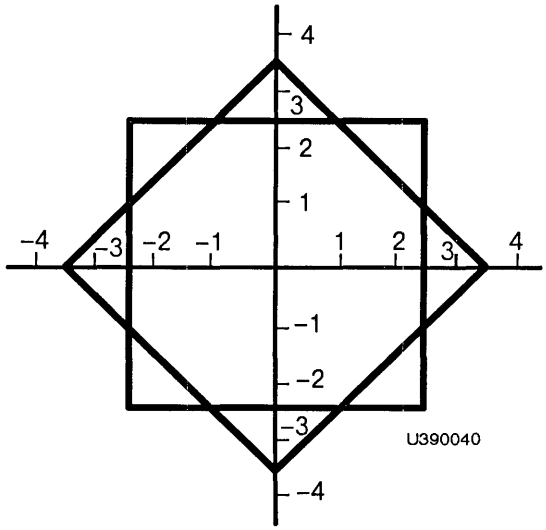

Figure 2-26. Location of the Star Primitive

When Star is displayed with the correct viewing transformations applied to it (these are discussed in Section2.5), it will be located on the screen as shown in Figure 2-27.

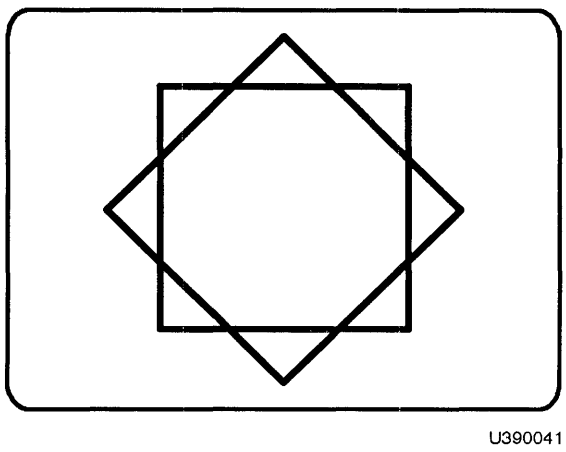

Figure 2-27. The Star Primitive Displayed on the Screen

The same shape can be displayed using existing primitives without adding a new primitive to the graphical data base. If you display at the same time the Square primitive and the Diamond primitive that already exist in the graphical data base, the picture on the screen will look the same as when you displayed the Star primitive.

The advantage of using the Square and the Diamond is that you do not have to calculate the coordinates for the Star primitive vector list. Your task as a programmer is simplified by using existing objects. If however, you want to do more than just display a picture of the star—if you want to apply transformations to the star to rotate or translate it, for example—the new primitive is easier to use than the Square and Diamond.

If you want to create a small star and move it to the upper-right corner of the screen, you can create the small star by scaling the primitive and then apply a translation in positive X and positive Y to the small star.

```
Scale_Star := SCALE BY .25 APPLIED TO Star;
Trans_Star := TRANSLATE .5,.5 APPLIED TO Scale_Star;
```

When displayed, Trans_Star will appear on the screen as shown in Figure 2-28.

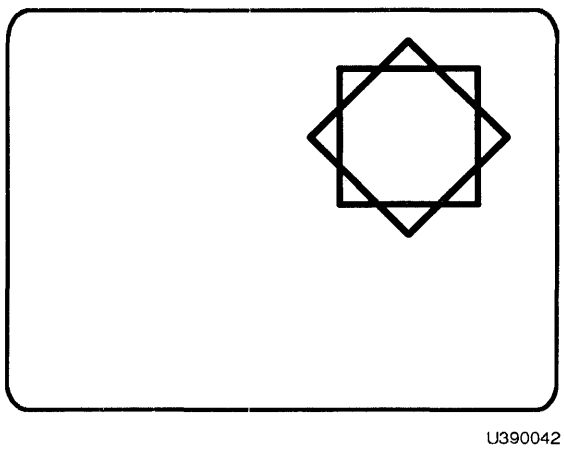

Figure 2-28. The Location of Trans_Star on the Screen

The structure of Trans_Star can be diagrammed as shown in Figure 2-29.

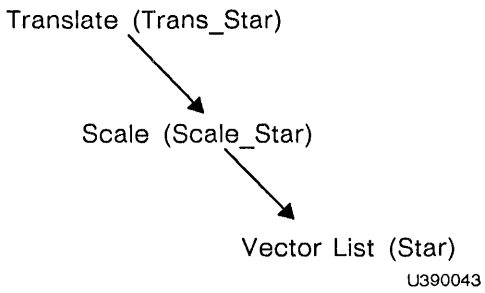

Figure 2-29. The Structure of Trans_Star

If you use the Square primitive and the Diamond structure (rotation applied to the Square) instead of the Star primitive, however, four new objects have to be created and displayed to get the same picture. You must create a scaled square, a scaled diamond, a translated small square, and a translated small diamond, and display them together.

```
Scale_Square := SCALE BY .25 APPLIED TO Square;
Scale_Diamond := SCALE BY .25 APPLIED TO Diamond;

Trans_Square := TRANSLATE .5,.5 APPLIED TO Scale_Square;
Trans_Diamond := TRANSLATE .5,.5 APPLIED TO Scale_Diamond;
```

The two structures look like this (Figure 2-30).

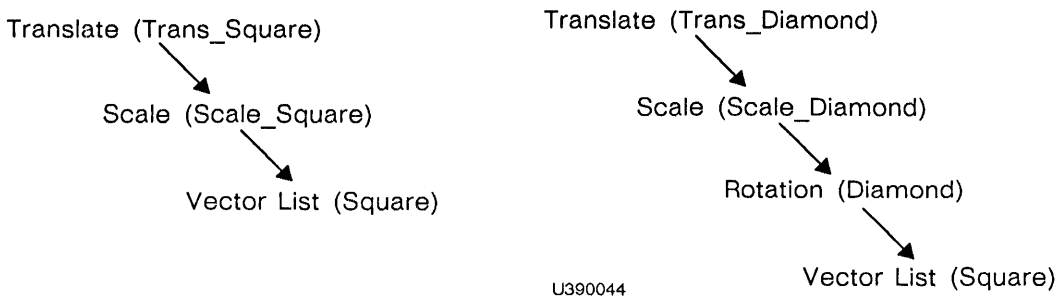

Figure 2-30. The Structures of Trans_Square and Trans_Diamond

When they are displayed together, Trans_Square and Trans_Diamond look just like Trans_Star. However, unless this shape can be manipulated as a single entity, some of the programming time and effort saved by not creating the star as a primitive will be lost.

3.1.2 Grouping Primitives and Transformations

The PS 390 allows you to construct a single named object from groupings of primitives and transformed primitives generated from the VECTOR_LIST command. The resulting compound structure represents an object which is composed of separate parts, but which can be treated as a single item, much like a primitive.

The INSTANCE command lets you create compound objects such as this:

```
Star1 := INSTANCE OF Diamond, Square;
```

The object called Star1 has the same dimensions and location in the coordinate system as Star, but it is not defined as a primitive vector list. It is a compound object which groups the two existing definitions Diamond and Square under a single name.

This compound object can be manipulated as easily as a primitive. A small star can be created by scaling Star1.

```
Scale_Star1 := SCALE BY .25 APPLIED TO Star1;
```

And the small star can be moved to the upper-right of the screen by translating Scale_Star1.

```
Trans_Star1 := TRANSLATE .5,.5 APPLIED TO Scale_Star1;
```

The structure for Trans_Star1 can be diagrammed as shown in Figure 2-31.

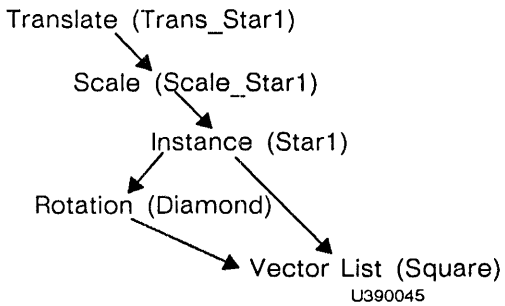

Figure 2-31. The Structure of Trans_Star1

The name Trans_Star1 identifies the translation which points to Scale_Star1. The scaling transformation points to the name Star1. Star1 groups the vector list defining the square with the rotation that defines the diamond. Both Diamond and Square share the same primitive definition.

A complete set of commands which would create Trans_Star1 is as follows.

```
Trans_Star1 := TRANSLATE .5,.5 APPLIED TO Scale_Star1;
Scale_Star1 := SCALE BY .25 APPLIED TO Star1;
Star1 := INSTANCE OF Diamond, Square;
Diamond := ROTATE IN Z 45 APPLIED TO Square;
Square := VECTOR_LIST  N = 5  2.5,2.5  2.5,-2.5  -2.5,-2.5
                             -2.5,2.5  2.5,2.5;
```

Unlike the separate parts it is composed of, the compound object named Star1 created by the INSTANCE command can now be treated as a single entity. The translation and scale transformations (Trans_Star1 and Scale_Star1) are applied directly to Star1. There is no longer any need to transform the Diamond and Square separately, now that they are grouped into a compound object.

There is also a structuring command BEGIN_STRUCTURE ... END_STRUCTURE which groups primitives and transformations into compound structures with a single name. Refer to Section *GT5 Command Language* for details on using this command.

3.2 Summary

New Information Presented

1. Compound objects can be created by grouping primitives and transformed primitives under a single name.
2. Groupings such as these can be treated as a single object. Transformations applied to the named compound object automatically apply to the parts it is composed of.

What Next?

The data base of graphical objects now consists of:

- Graphical primitives.
- Transformed primitives.
- Compound objects: structures consisting of primitives and transformed primitives grouped into one object.

In the next section, you will learn how compound objects are used to create complex models with parts that can be manipulated using the interactive devices of the PS 390.

4. Designing a Model for Interaction

The transformations discussed so far have been called modeling operations. They are equivalent in the real world to assembling the raw materials for a model and making the parts that the model is composed of. Complex 3D models consisting of separate parts are made by building each part as a compound object made of primitives and transformations. The parts are then grouped together to form the complete model.

Complex models are designed as a hierarchical structure called a display tree. The display tree shows the dependencies of parts within the structure of the model and contains all the primitives and transformations needed to create the model in the memory of the PS 390.

Models designed as hierarchical trees are a tremendously flexible design tool. Complicated models can be created in smaller parts and assembled as the designer requires. Changes can be made to any component of the model without affecting other parts. Interaction with the entire model or with any component is possible using the dials, buttons, function keys, and data tablet of the PS 390.

Section *GT4 Modeling* gives an extended example of designing a model as a display tree.

4.1 Designing a Complex Model

The PS 390 can be used to model objects of any complexity. Consider the articulated mechanical arm shown in Figure 2-32.

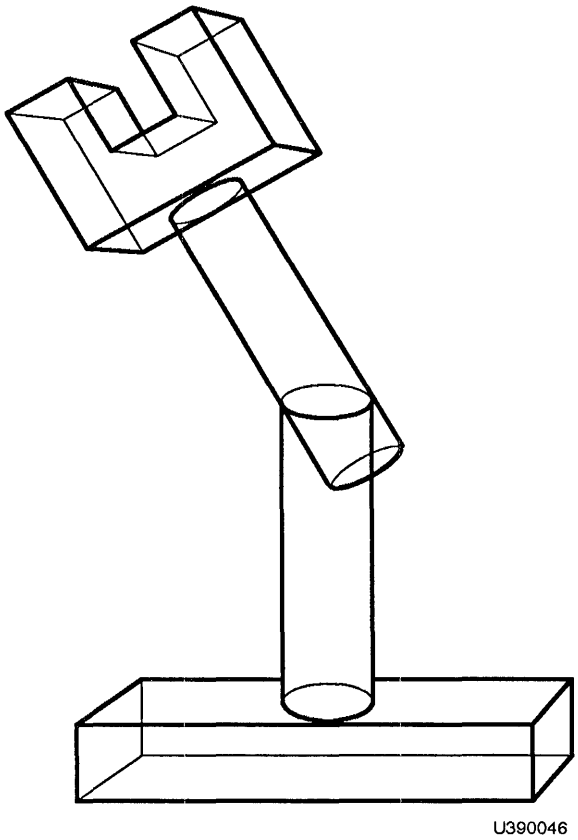

Figure 2-32. An Articulated Mechanical Arm

The arm consists of a base, two jointed sections, and a hand. The base is fixed and cannot move. The whole arm can rotate at the base. The two arm pieces and hand are affected by this movement. The movement at the "elbow" affects the upper arm and hand only. And movement at the "wrist" only affects the hand.

Clearly, a computer model which simulates this mechanical arm cannot be created as a primitive vector list or polygon list. Even if the object were created as a primitive by a host application program, it would not be a useful model of the mechanical arm. Transformations could be applied to translate, rotate, or scale the complete model, but there would be no way to interact with the individual parts. The arm could not be made to rotate at the base, the elbow joint would not bend, and the hand could not twist at the wrist.

4.1.1 Analyzing a Model as a Hierarchy

Complex models such as the mechanical arm which are to be designed on the PS 390 are analyzed to determine a hierarchy of the parts that compose the model, and to show their dependencies. A hierarchy is a principled organization of components. The organizing principle will vary depending on the relationship between components which the hierarchy is designed to show. The model for the mechanical arm, for example, can be represented by the hierarchy in Figure 2-33. This hierarchy shows the dependent and independent motion of the components.

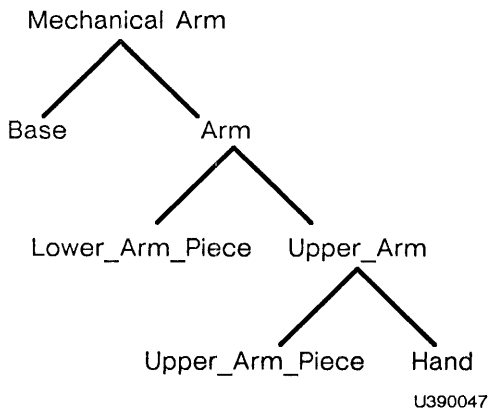

Figure 2-33. Hierarchy of Parts for the Mechanical Arm

This hierarchy shows that the model consists of a base and an arm. The arm consists of a lower arm and an upper arm. The upper arm is made up of the upper-arm piece and hand.

If the whole mechanical arm moves, then all the parts that compose it move too. If the arm moves, the lower-arm piece and upper arm move with it. If the upper arm moves, the upper-arm piece and hand move. The hand can also move on its own without affecting anything else.

4.2 Display Trees

For a complex model designed to be manipulated interactively with the PS 390, a hierarchy is drawn as a display tree. Much like a flowchart for a conventional computer program, a display tree represents the graphical primitives that must be created and the transformations that must be applied to create this model in the memory of the PS 390. It also indicates the interaction points in the structure of the model to which interactive devices will be connected to change the model dynamically.

4.2.1 Display Tree for the Mechanical Arm

The hierarchy that has been established for the mechanical arm can be used to create the display tree shown in Figure 2-34.

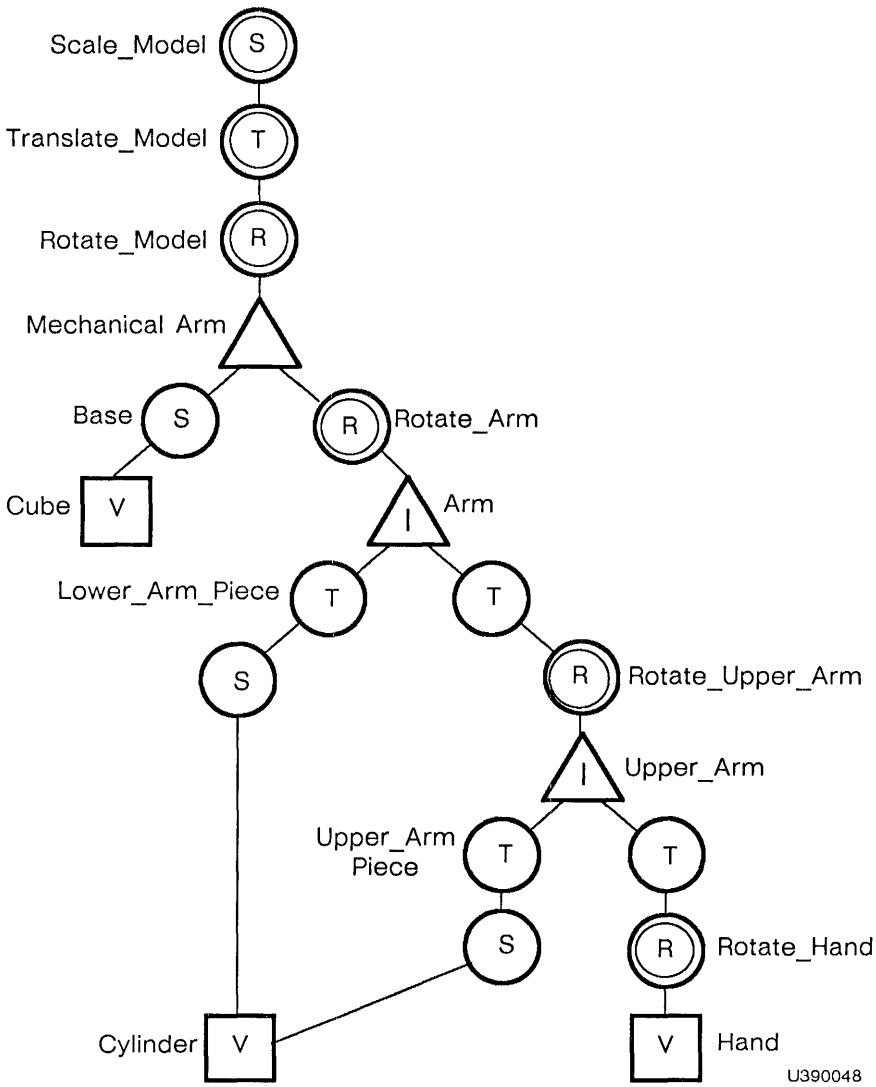

Figure 2-34. Display Tree for the Mechanical Arm

The display tree shows details of the structure of the model in the PS 390 which the hierarchy of parts in Figure 2-33 does not. In particular, it includes the primitives, the modeling transformations which create the parts of the model from the primitives, and the interaction points which will provide motion to the whole model and its parts.

4.2.2 Display Tree Terminology

Display trees consist of nodes and the branches that connect them. A node is an element in the hierarchy. The squares are data nodes. These are used to represent the primitives from which individual pieces of the model are built: the cube, the cylinder, and the hand. The triangles are instance nodes. These represent the grouping of primitives and modeling transformations into parts: the Upper arm, the Arm, and the complete Mechanical Arm. Circles represent transformations and are called operation nodes. Single circles represent the modeling transformations that are applied to primitives to create the pieces and move them into place. Double circles represent interaction points. These are the operation nodes in the model which will receive new values from interactive devices such as dials or the data tablet.

4.2.3 Nodes

Nodes are created by PS 390 commands. Commands such as VECTOR_LIST and POLYGON create data nodes. ROTATE, SCALE, and TRANSLATE commands are three of the many which create operation nodes. The INSTANCE command creates instance nodes.

4.2.4 Updating Nodes

Each data and operation node contains information. A rotation node contains a rotation matrix, a vector list node contains point and line information, and so on. An instance node does not contain data in the same way. It acts as a pointer to paths in the display tree and occurs at the head of a hierarchical branch. All operation nodes and most data nodes can have their contents changed in several ways. You can redefine the command that created the node and change its contents that way. You can send a new value to a node using the SEND command. Or you can program an interactive device to send a stream of constantly changing values to a node and so change the model dynamically.

Nodes have inputs to which data can be sent. The number of inputs depends on the type of node. An input will only accept data compatible with its contents. A rotation node, for instance, will only accept a 3x3 matrix; a translation node will only accept a 2D or 3D vector, and so on.

4.2.5 Data Nodes

Data nodes represent primitive objects. Vector lists, polygon lists, curves, and text are all defined as graphical primitives using commands which cre-

ate data nodes. These nodes always appear at the bottom of a branch. Data nodes have inputs so that their contents can be updated. Figure 2-35 shows the inputs to a vector list data node.

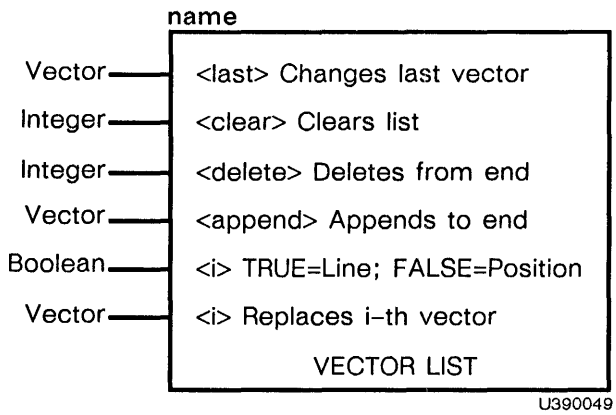

Figure 2-35. Inputs to a Vector List Node

Most of the inputs to a vector list node are named instead of being numbered. A new vector sent to input <last> is substituted for the last vector in the list. An integer sent to input <clear> removes the vector whose position in the list corresponds to the number sent; for example, sending 4 will remove the fourth vector. An integer sent to input <delete> will delete that many vectors from the end of the vector list. Any vector sent to input <append> is added to the end of the vector list. A Boolean TRUE or FALSE can be sent to a numbered input (shown as input <i>). This will change the identifier of that vector to an L for line or a P for position. A vector sent to any numbered input is substituted for the vector whose position in the list corresponds to the number of the input. By sending new values to this node, you can change the geometry and topology of an object.

4.2.6 Operation Nodes

Operation nodes represent transformations that are applied to objects: translations, rotations, and scales, viewing transformations (discussed in Section *2.5*), attribute operations (discussed in Section *2.6*), and rendering operations (discussed in Section *2.8*). Operation nodes have inputs which will accept data to update a node. Figure 2-36 shows the input to a rotation node.

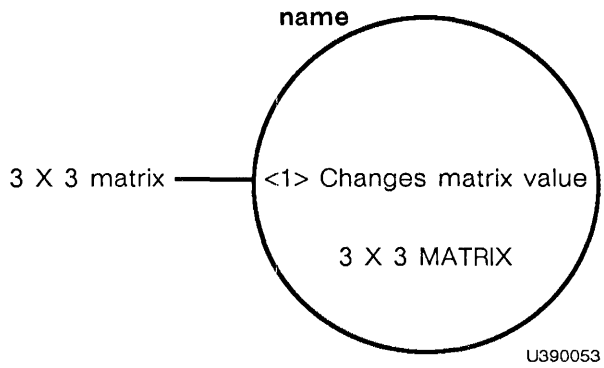

Figure 2-36. Inputs to a Rotation Node

The rotation node has a single input which accepts a 3x3 matrix which is substituted for the matrix currently contained in the node. Operation nodes may be created for modeling purposes or for interaction.

Modeling nodes represent transformations used to create the original static model by sizing the pieces and moving or rotating them into place. These nodes are shown as single circles in the display trees. The value contained in a modeling node is not usually updated.

Interaction nodes represent places in the model which will be connected to interactive devices. These are operation nodes whose contents will be updated with data from the devices to which they are connected. Interaction nodes are shown as double circles in a display tree. Naturally, any node that can be updated has the potential for being an interactive node. But certain nodes are specifically created as interaction points in the structure of a model.

In Figure 2-34, for example, the scale node called Base is used for modeling purposes: it scales the vector list Cube by a fixed amount in X, Y, and Z to create the shape which forms the base of the arm.

The scale node called Scale_Model, however, serves a different purpose. It is drawn as a double circle to show that it is an interaction point in the structure. This node will be created with a value of one (scaling by one has no effect on the model at all). Then a dial will be programmed to supply a 3x3 scaling matrix to this node. Each time the dial is turned, a different scaling matrix will be sent to update the node and the model will grow smaller or larger on the screen.

A rotation node designed for interaction is usually created with a value of zero. When the object is displayed, the zero rotation will have no effect on the object's orientation. As rotation matrices are supplied to the node from a dial, the object will rotate. Translation nodes set up for interaction are created with a value of zero in X, Y, and Z. As new vectors are sent to the translation node, the object will move in any of the three directions.

4.2.7 Instance Nodes

Instance nodes group operation nodes and data nodes into larger named entities and set up and maintain spheres of influence in the display tree.

4.2.8 Grouping

Instance nodes form what were called compound objects in Section *2.3*. They group transformations and primitives into a single named entity. In a display tree for a complex model, instance nodes are often at the "head" of branches which represent the individual parts of the model. Recall the notation used in Section *2.3* to show the structure of the object called Trans_Star1.

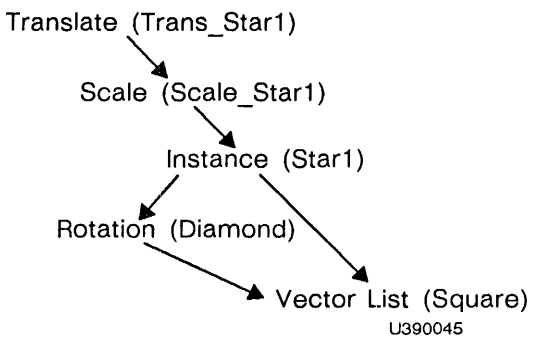

Figure 2-37. The Structure of Trans_Star1

The name Trans_Star1 is a translation which points to Scale_Star1. Scale_Star1 is a transformation that points to Star1. Star1 groups the untransformed vector list defining the Square with the rotated square that defines the Diamond. Both Diamond and Square share the same primitive definition.

If the structure Trans_Star1 is now drawn as a display tree, it appears as shown in Figure 2-38.

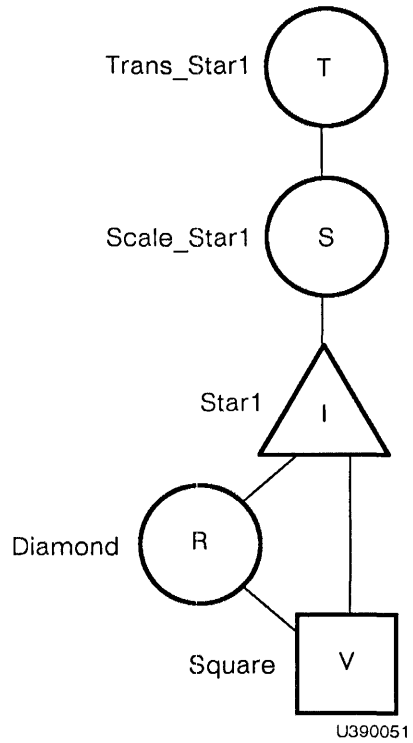

Figure 2-38. Display Tree for Trans_Star1

The single instance node, Star1, groups all of the transformations that are applied to the primitive Square under one name.

Because an instance node performs this grouping function, it has more than one branch out of it. An instance node is the only node in a display tree which may have more than one branch coming out of it, though a data node and an operation node may have more than one branch into it.

4.2.9 Sphere of Influence

In a display tree, nodes higher up in the structure affect nodes lower down. For example, the nodes Trans_Star1 and Scale_Star1 at the head of the display tree in Figure 2-38 affect everything below them. If a new scaling matrix is sent to Scale_Star1, the complete model will get bigger or smaller on the screen.

However, a node can only affect its descendants, that is, other nodes below it on the same hierarchical branch. Consider a simplified representation of the structure for the upper arm of the mechanical arm model (Figure 2-39).

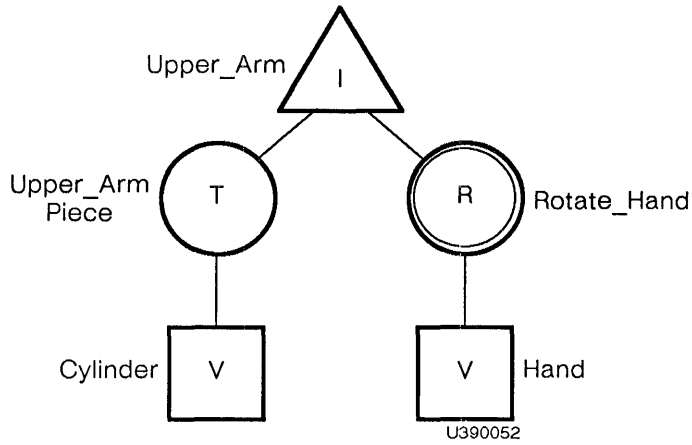

Figure 2-39. Structure of the Upper Arm

When a dial is connected to the interaction node Rotate_Hand, only the hand must move, not the upper-arm piece it is connected to. So the rotation node is placed on a different branch from the Upper_Arm_Piece data node to restrict the sphere of influence of the rotation. The rotation will only affect the data node Hand.

Instance nodes govern the spheres of influence in a hierarchy. Every branch out of an instance node is affected by operations above the instance node. Operations below the instance node in one branch affect only data in that branch. Instance nodes maintain the integrity of each branch they govern. Consider the following simple tree in Figure 2-40.

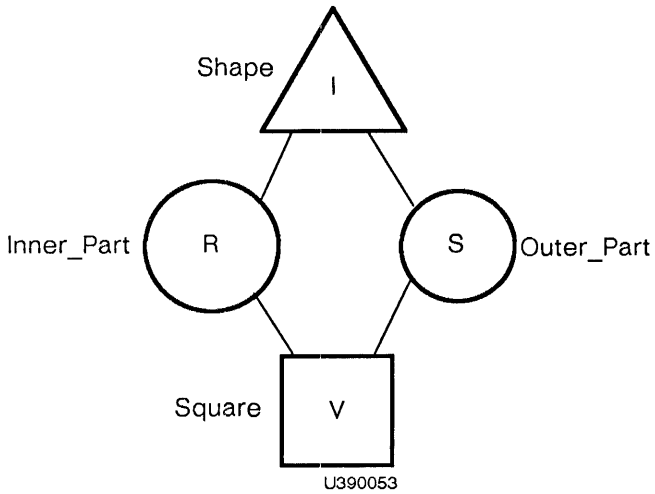

Figure 2-40. A Simple Display Tree

The tree in Figure 2-40 represents the structure of the shape in Figure 2-41.

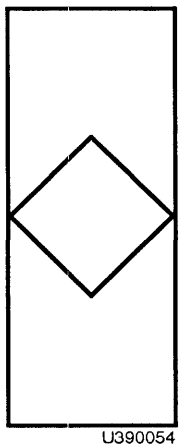

Figure 2-41. Shape Represented by Display Tree in Figure 2-40

The shape is created in two parts from a single square primitive. The inner part is the square rotated 45 degrees in Z. The outer part is made by scaling the square nonuniformly in X and Y. The instance node Shape groups the primitive and both transformations into a single compound object.

Both transformations are applied to the same primitive, but they apply independently. The instance node Shape ensures that this occurs. The rotation in the left-most hierarchical branch out of Shape does not affect the scale in

the right branch, and vice versa. Any transformations applied to Shape (that is, above Shape in the display tree) would then affect both branches grouped by the instance node.

4.3 Summary

New Information Presented

1. Complex models consisting of separately maneuverable parts are designed as a hierarchy of the components of the model.
2. A display tree is a hierarchy which shows the primitives, transformations, and groupings that are used to create the model in the PS 390. Display trees consist of data nodes, operation nodes, and instance nodes, and the branches that connect them.
3. Data nodes and operation nodes can have their contents modified. Certain operation nodes serve as interaction points in the model. They are designed to be updated by values from the interactive devices. In this way, a dial can be connected to a rotation node, for example, to allow the model to be dynamically rotated.

What Next?

The data base now contains all of the "building blocks" for complex models.

- Primitives
- Transformed primitives
- Compound objects
- Complex objects: hierarchical groupings of independent parts of a model, equipped with interaction points

In the next section, you will see how viewing nodes are added to the display tree to create different views of the model that has been created.

5. Looking at Objects

When you have created an object as a primitive, a compound object, or a complex model, you will want to get some view of that model on the screen. In the real world you can see a different view of an object by moving it. This is simulated in a graphics system by applying modeling transformations (translations and rotations) to the object. An alternative in the real world is for you to move. Leaving the object alone, you can walk around it and change your viewpoint.

The PS 390, in effect, lets you do the same thing. Using viewing operations, you can obtain a number of "natural" views of a model on the screen.

These operations mimic the way you look at objects in real life. You decide your eye point in the coordinate system and the direction you are looking in. You can determine how much of the world coordinate system (and the model) will appear in your view. You can enhance your perception of three dimensions using perspective (to make objects further away appear smaller) and depth cueing (to make them dimmer as they recede). In the real world, objects at a distance or outside your range of view disappear naturally. The PS 390 performs clipping to eliminate objects or parts of objects that lie outside the screen boundaries.

Once you have determined the particulars of the view (the viewpoint and "window" into the world coordinate system) you can determine where that view will appear on the screen. Areas of the PS 390 screen can be defined as viewports in which views of the models will appear.

There are two types of viewports: the dynamic viewport, and the static viewport. The dynamic viewport is designated for manipulation and display of wireframe models, while the static viewport is used for the display of hidden-line and shaded renderings. An unlimited number and combination of viewports can be specified.

Viewing operations are defined as part of the structure of a model. They are represented as operation nodes in the display tree, with the exception of the static viewport specification. Refer to Section *GT8 Viewing Operations* for a complete description.

5.1 Viewing Operations

The modeling transformations discussed earlier let you use primitives as building blocks for the components of a hierarchically structured model, changing their basic shape and moving them into position. Once the model is designed, you need to get a picture of it on the screen. The PS 390 offers a set of viewing operations that can be applied to a model to create various views of objects in the world coordinate system.

5.1.1 Displaying an Object

With the PS 390, you can get a picture of a model on the screen by entering a single command. Consider a square with sides one unit long. This shape can be created by entering the following vector list.

```
Square := VECTOR_LIST N = 5  .5,.5  .5,-.5  -.5,-.5,
                             -.5,.5,  .5,.5;
```

To display this shape on the screen, it is sufficient to enter

```
DISPLAY Square;
```

The Square shape will appear on the screen as shown in Figure 2-42.

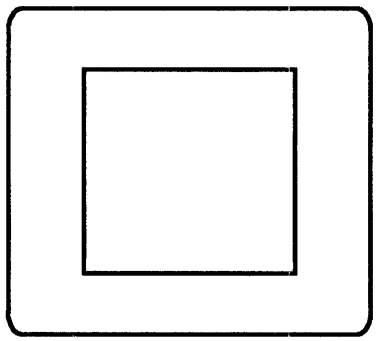

Figure 2-42. The Location of the Square on the Screen

The apparent operation of a single command is, in fact, more complicated. The PS 390 does not simply display Square; it displays a view of Square.

Before the PS 390 can display this view it needs information about

- *A line of sight*—your vantage point (as viewer) in the world coordinate system and the direction in which you are looking.

- *A viewing area*—what part of the world coordinate system to include in the view.
- *A viewport*—where on the PS 390 screen to display the view.

If you do not specify a line of sight, a viewing area, and a viewport, the PS 390 uses default values. It assumes you are looking from the origin along the positive Z axis. The viewing area extends from -1 to 1 in X and Y and from almost zero to 10 -15 in Z. And the viewport defaults to the full dynamic PS 390 screen. These three default values are in effect when you simply display the Square.

5.2 Establishing a Line of Sight

In the real world, you establish a line of sight by standing in some spot, looking towards something, and possibly tilting your head. This gives you a specific view of the object you are looking at. The PS 390 simulates this same ability with a LOOK command. Suppose, for example, the world coordinate system contains a cube with its faces labeled top, bottom, front, back, left and right. The cube is centered around the origin, as shown in Figure 2-43.

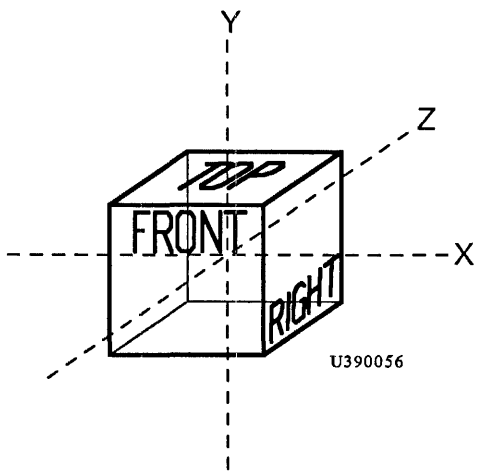

Figure 2-43. A Cube With Labeled Faces

For clarity in the following illustrations, only three labels are shown at a time. If you display the cube without changing the default line of sight, viewing area, or viewport, the screen will show the picture in Figure 2-44.

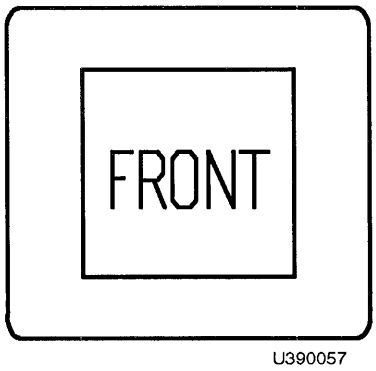

Figure 2-44. Displaying the Cube

If you want a picture of the top of the cube, you can think of this as moving your eye above the cube and looking down the Y axis at it, as shown in Figure 2-45.

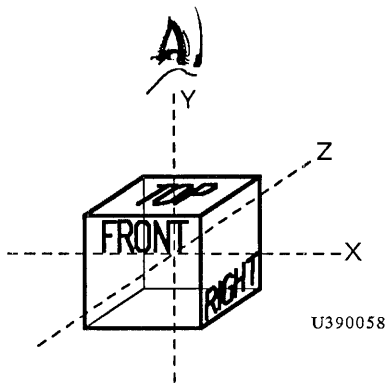

Figure 2-45. "Looking Down" the Y Axis at the Cube

The view of the cube which will be displayed is shown in Figure 2-46.

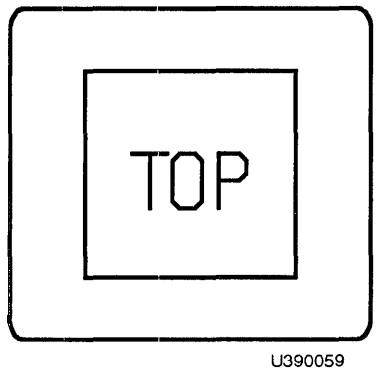

Figure 2-46. Looking Down at the Cube: the View on the Screen

A PS 390 command which will create this view of the object is as follows:

```
Top_View := LOOK AT 0,0,0 FROM 0,.5,0 APPLIED TO Cube;
```

An optional UP clause in the command lets you specify what direction is up. This is equivalent to tilting your head left or right.

The concept of "looking at an object" is a very natural way for humans to think. With a graphics system, of course, every visual effect is an illusion. When you look at an object from a location in the world coordinate system, the computer cannot actually move your eye to that location. Instead, it applies transformations to the points and lines that comprise the object and creates a picture of what you would see if you could move your eye.

To get this effect, the LOOK command actually performs the following transformations. First, it translates all points in the coordinate system so that the FROM point is at the origin. It then rotates all points so that you are looking along the positive Z axis towards the AT point. It also rotates points so that the "up" vector is in the positive YZ plane. The ultimate effect of all this is to place your "eye" at the origin and place the object you are looking at in front of your "face" in the positive Z axis.

After you create Top_View with the LOOK command, the world coordinate system and the points and lines defining the cube have been transformed as shown in Figure 2-47.

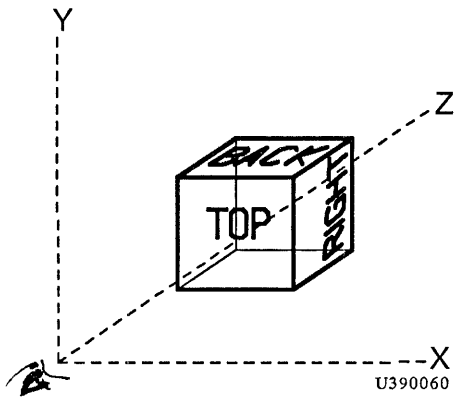

Figure 2-47. How the LOOK Command Rearranges the Coordinate System

This rearrangement of the world coordinate system is accomplished with a 4x3 transformation matrix, a compound matrix of rotations and translations. The PS 390 uses the information you supply in the LOOK command to create this matrix. It then multiplies all coordinates by this matrix to create the correct "view" of the object for the line of sight you specified.

Section *GT8 Viewing Operations* teaches how to use the LOOK command with all of its options. Mastering this command lets you locate your viewpoint anywhere in the world coordinate system, look in any direction, and specify any direction as "up" to create a specific view of an object.

5.3 Including Part of the World Coordinate System

In the real world, your view is limited by several factors. If you do not change your position, you cannot see things that are behind you or to either side beyond your field of view. Your view is further limited if you are looking out of a window, or through binoculars or the view finder of a camera. You can only see whatever part of the world is "framed" by the window or the lenses.

With a graphics system, looking at the world coordinate system is much like looking through a view finder. You must specify how much of the world will appear in the view which is displayed on the screen. An area of the world specified for viewing is called a viewing area or a window. To "see" an object in the world coordinate system, that object must lie in the direction of your line of sight and must be contained within the viewing area you specify.

5.3.1 Viewing Areas in the World Coordinate System

The PS 390 lets you create two types of viewing areas. The WINDOW command creates a viewing area for orthographic or parallel projection views. The FIELD_OF_VIEW and EYE commands create a viewing area for displaying objects as perspective projection views.

5.3.2 Orthographic Views

A viewing area for orthographic views can be thought of as a box which can be positioned anywhere in world coordinate space but oriented with its sides parallel to the three major coordinate system planes (XY, XZ, and YZ), as shown in Figure 2-48.

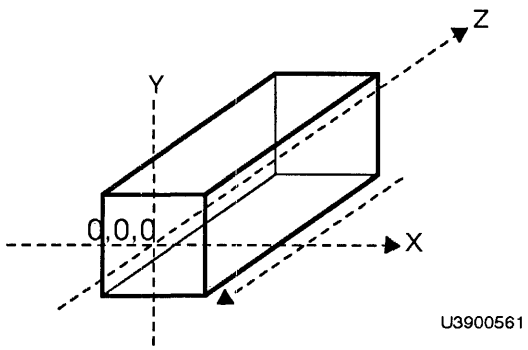

Figure 2-48. An Orthographic Viewing Area

The viewing area defined by the box has limited X (width), Y (height), and Z (depth) dimensions. In general, if an object lies within the area, it is visible; if it is outside the space, it is not visible. The X and Y boundaries of the viewing space are always in effect. Any object outside those boundaries is never visible. The XY planes at the front and back of the box, however can be enabled or disabled at will. If these planes are disabled, as long as an object lies within the X and Y boundaries, it will be visible no matter where it is located along the positive or negative Z axis. This is shown in Figure 2-49.

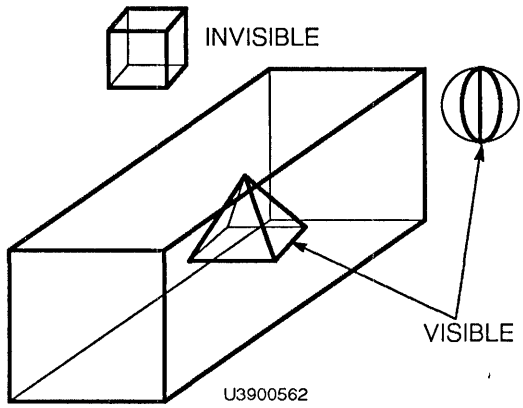

Figure 2-49. "Visible" and "Invisible" Objects

If an object is only partially within the XY bounds of the viewing area, only parts of it are visible. In this case, the computer calculates which lines are visible and clips those that are not visible from the view (Figure 2-50).

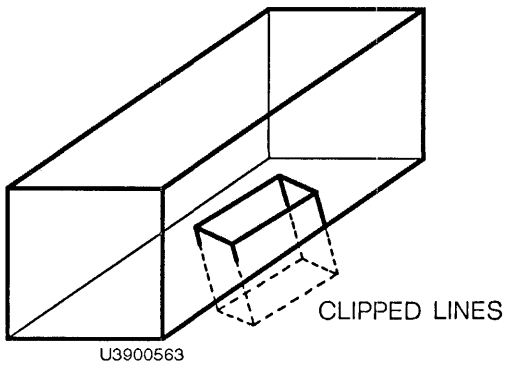

Figure 2-50. Clipping Parts of an Object

Clipping can also be specified in the Z dimension by enabling the front and back faces of the viewing space which are called clipping planes. The front boundary is sometimes called the hither plane; the back is called the yon plane. Objects or parts of objects that lie outside the front and back boundaries may be clipped from view. This is known as depth clipping, and is illustrated in Figure 2-51.

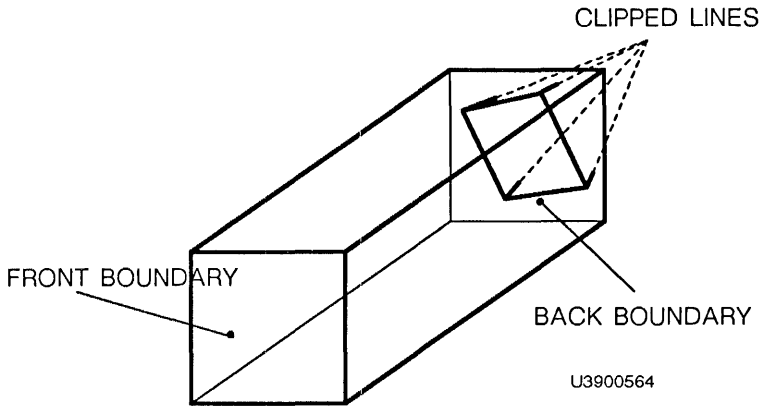

Figure 2-51. Depth Clipping of Objects

Objects within an orthographic viewing area are displayed in orthographic or parallel projection. This produces a view in which lines that are parallel in the object remain parallel in the view. A rotated cube viewed in orthographic projection, for example, appears as shown in Figure 2-52.

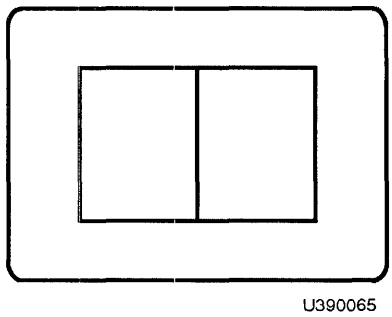

Figure 2-52. Orthographic View of a Rotated Cube

An object must be enclosed in a viewing space before it can be displayed. If you simply display an object (as with Square at the beginning of this section) without explicitly defining a viewing space, the PS 390 defines one for you. The default viewing space imposed by the system is shown in Figure 2-53.

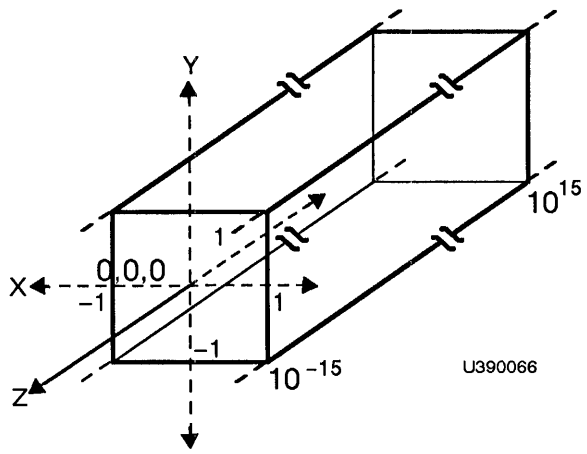

Figure 2-53. The Default Viewing Space

This is a viewing space for orthographic views only. It extends from -1 to 1 in the X and Y dimensions, and from 10^{-15} (almost Zero) to 10^{+15} in Z.

With the PS 390, a viewing space for orthographic views is created explicitly with the WINDOW command. For example, the command

```
New_View := WINDOW X = -2:2, Y = -2:2 APPLIED TO Cube;
```

creates a viewing space twice as high and twice as wide as the default space, but with the same depth. Optional parameters of the command allow you to change Z values by specifying the location of front and back clipping planes. The section, *Defining An Orthographic Window* in *GT8 Viewing Operations* explains the WINDOW command and its options.

5.3.3 Perspective Views

One way in which the PS 390 creates the illusion of depth on a flat screen is to display objects in perspective.

In perspective views, parallel lines that go back from your eye point appear to be converging. A rotated cube viewed in perspective might appear as shown in Figure 2-54.

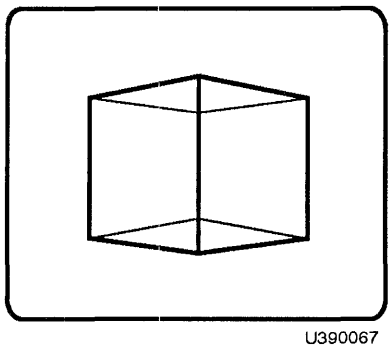

Figure 2-54. Perspective View of a Rotated Cube

A perspective viewing space is a volume shaped like a frustum, a section of a pyramid bounded by the front and back clipping planes. If you extend the sides of the pyramid back, the apex of the pyramid is the eye point as defined in the LOOK command (Figure 2-55).

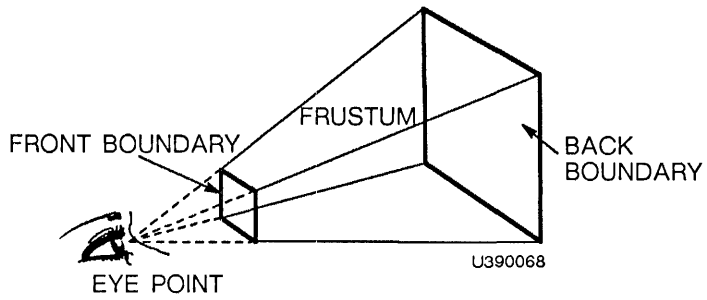

Figure 2-55. A Viewing Area for Perspective Views

Two PS 390 commands create perspective views: the FIELD_OF_VIEW command and the EYE command. Both commands are used in conjunction with the LOOK command.

The FIELD_OF_VIEW command lets you specify an angle of view from the eye point, which is the FROM point specified in the LOOK command. Optional clauses let you specify the location of front and back boundaries. These determine the depth of the viewing area created with this command. A perspective view is fully defined in conjunction with a LOOK transformation. If no LOOK is specified, the default values are assumed.

The following commands set up a line of sight and a perspective view of an object called Cube using a viewing angle of 30 degrees.

```
Look_Cube := LOOK AT 0,0,0 FROM 0,0,-5 APPLIED TO Cube;
View_Cube := FIELD_OF_VIEW 30 FRONT = 4.5 BACK = 5.5
             APPLIED TO Look_Cube;
```

The LOOK transformation will place the center of the Cube at 5 in the positive Z axis, so assuming the cube is one unit square, front and back boundaries of 4.5 and 5.5 should enclose it. When View_Cube is displayed, the screen will show a cube seen in true perspective.

Note that the angle you enter in the FIELD_OF_VIEW command does not alter the severity of the perspective imposed on the object. That is determined by the distance between your eye and the object and depth of the object itself. Instead, the angle lets you see more or less of the world coordinate system. The larger the angle, the larger the portion of the world that will be included in the view.

In a perspective view created using the FIELD_OF_VIEW command, the line of sight established by the LOOK command is always perpendicular to the front and back boundaries of the frustum and passes through their centers. The viewing "pyramid" is always right-angled. This is shown in Figure 2-56.

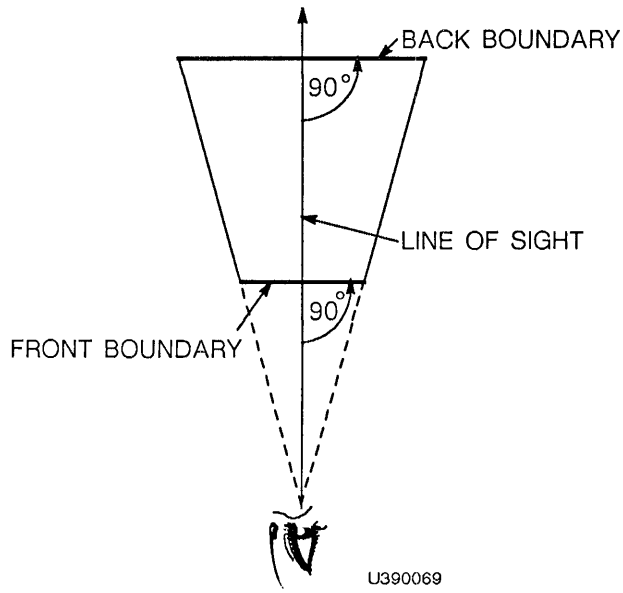

Figure 2-56. The FIELD_OF_VIEW Viewing Pyramid

The EYE command is used to create a view of an object as it would appear displayed on a screen which is positioned at an angle to your line of sight, not perpendicular to it. This perspective view simulates the "natural" distortion of screen displays that your own eye would see if it were some distance back, up or down, and left or right of the PS 390 screen.

Like the FIELD_OF_VIEW command, the EYE command creates a perspective view of an object. The eye point and the front and back clipping planes specify a pyramid-shaped viewing area. However, if the eye point is offset left, right, up, or down, the pyramid is skewed, unlike the right rectangular pyramid created by the FIELD_OF_VIEW command (Figure 2-57).

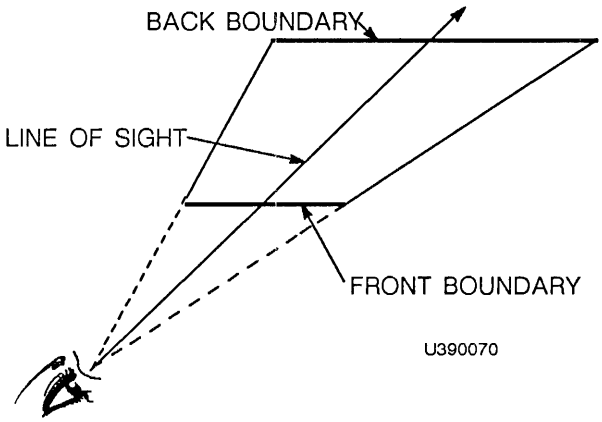

Figure 2-57. The Viewing Pyramid Created by the EYE Command

The LOOK command must be used first to establish a line of sight on the object to be displayed. Then, clauses in the EYE command let you specify the front and back boundaries of the viewing area in world coordinates and your eye location relative to the center of the screen in relative room coordinates. Note the difference between room coordinates and world coordinates. World coordinates are locations in the world coordinate system where models are built and viewed. Room coordinates are locations within the real world (the computer room where the PS 390 lives) and are used to simulate the actual location of your eyes relative to the PS 390 screen. This is a rare instance of when it is permissible to mix the computer's coordinate system and real-world coordinates, since the room coordinate values in the command are used for ratio and proportion operations only.

The following is an example of setting up a viewing area with the EYE command.

```
Look_Cube := LOOK AT 0,0,0 FROM 0,0,-5 APPLIED TO Cube;
Oblique_View := EYE BACK 20 LEFT 5 UP 12 FROM SCREEN
                AREA 20 WIDE
                FRONT = 4.5 BACK = 5.5 APPLIED TO Cube;
```

In this command, the front and back boundaries are chosen to enclose the cube after the LOOK transformation has taken place. When Oblique_View is displayed, the cube will appear in the correct perspective to simulate an eye position that is back from the screen, over to the left and somewhat high.

The section called *Defining Perspective Windows* in *GT8 Viewing Operations* fully explains the FIELD_OF_VIEW and EYE commands with all of their options.

5.4 Displaying an Image in Some Area of the Screen

Whenever you instruct the PS 390 to display an object by simply using the DISPLAY command, as long as the object fits within the default window (that is, from 1 to -1 in X and Y and from 10^{-15} (almost Zero) to 10^{+15} in Z) it will occupy the full screen. For example, a cube defined around the origin with sides 2 units long fits exactly in the default window. When the cube is displayed, an orthographic view will appear which fills the entire display area of the screen, as shown in Figure 2-58.

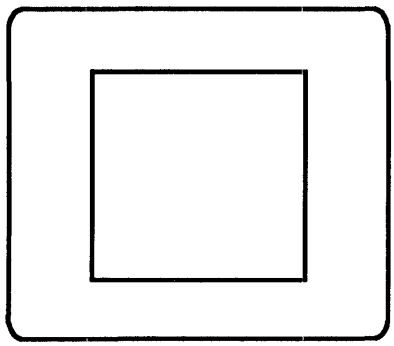

Figure 2-58. Displaying an Object With the Default Window

5.4.1 Specifying a Viewport

When an image is displayed on the screen, the view of the object contained in the viewing area is mapped to a viewport. A viewport is an area of the screen with horizontal (X) and vertical (Y) boundaries. A viewport may be specified as either dynamic or static, depending upon what kind of operations are to be performed in the viewport. Real-time manipulation and display of wireframe models is done in a dynamic viewport, while the display of hidden-line or shaded renderings is done in a static viewport.

The dynamic viewport has an optional intensity range. The intensity range specifies the dimmest and the brightest that lines will be drawn on the screen. Lines at the front clipping plane of the viewing area will be brightest. By default, lines at the back clipping plane will be dimmest. The variation of intensity levels within a viewport creates an effect known as depth cueing.

Perspective views created with the FIELD_OF_VIEW or the EYE command naturally give the illusion of depth to any object displayed on the screen. This illusion is further enhanced by depth cueing. When intensity levels have been set for a dynamic viewport, the PS 390 varies the intensity of lines in the view that represent the Z dimension (depth) of the object. A line that recedes in the Z axis from the eye point gets dimmer as positive Z values increase. This gives the impression that objects are being displayed in a place that is brightly lit close to you and more dimly lit farther away. Depth cueing can be turned on or off. The default is on.

The default viewport to which the PS 390 maps views of objects in the viewing area is the full dynamic screen, and the full intensity range (from 0 to 1) is in effect. There are two commands that let you change the size of the dynamic viewport, relocate it anywhere on the screen, and vary the intensity. These are the VIEWPORT and the LOAD_VIEWPORT commands. The VIEWPORT command specifies a viewport relative to the current viewport, implying that a new viewport specification may be no larger than the current viewport. The LOAD_VIEWPORT command, however, does not have this restriction, and specifies viewports relative to the full PS 390 screen.

The following command, for example, creates a viewport in the upper-right quadrant of the screen, and sets an intensity range from .5 to 1.

```
New_Viewport := VIEWPORT HORIZONTAL=0:1 VERTICAL=0:1 INTENSITY=.5:1
                APPLIED TO Cube;
```

When New_Viewport is displayed, a cube will appear in the upper-right quadrant of the screen. There will be less contrast between the brightest and the dimmest lines than in the original view of Cube.

Specification of a static viewport is done by sending a value to an input of the SHADINGENVIRONMENT initial function instance. The SHADINGENVIRONMENT function also allows you to clear either the current viewport or the entire screen, and specify whether it is to be treated as a dynamic or static viewport.

To obtain an accurate view of an object, the viewport it is displayed in must have the same aspect ratio as the viewing area that encloses the object. The aspect ratio is the ratio of height to width. Objects defined in viewing areas with square front and back boundaries and displayed in nonsquare viewports will appear distorted.

An arrow enclosed in a square viewing area and displayed in nonsquare viewports, for instance, may look like this (Figure 2-59).

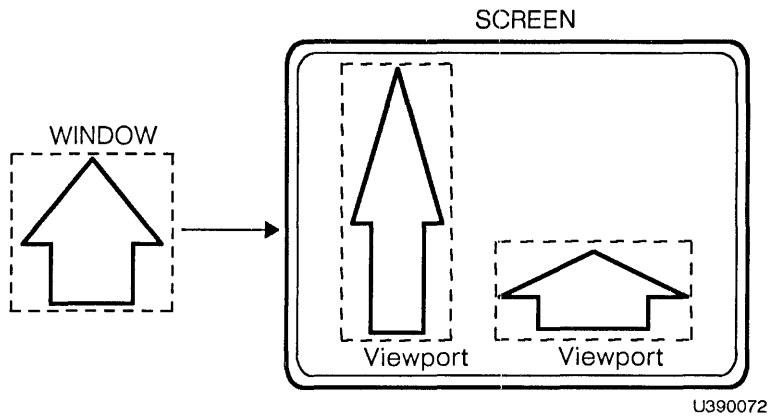

Figure 2-59. Distorted Views of the Arrow

Distortion also occurs when nonsquare viewing areas are displayed in square viewports. The FIELD_OF_VIEW and EYE commands always create

viewing areas with an aspect ratio of 1:1, a square. The WINDOW command can be used to create a viewing area with an aspect ratio that is not 1:1, a nonsquare viewing area.

Any size and any number of viewports may be displayed at the same time. In this way the screen can be used to show multiple views of the same object or different views of different objects.

Note that viewport operations are the only viewing operations which are not matrix transformations of graphical data. When the contents of a viewing area are mapped to a viewport, this is a ratio and proportion operation, not a transformation of coordinates in the world coordinate system.

5.5 Viewing Transformations and Display Trees

When views of objects are created, viewing operation nodes are added to the display tree.

Consider, for example, the group of objects shown in Figure 2-60.

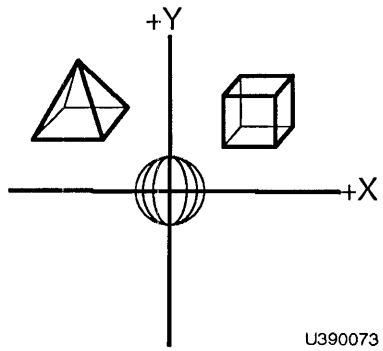

Figure 2-60. A Group of Objects in the Coordinate System

The group consists of three primitives: a sphere centered around the origin, and a cube and pyramid translated off the origin. These primitives have been grouped as an instance called Shapes. The display tree for Shapes is shown in Figure 2-61.

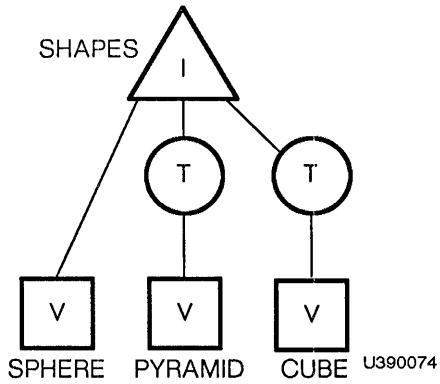

Figure 2-61. Display Tree for Shapes

If you use the DISPLAY command to view Shapes, the picture on the screen will be as shown in Figure 2-62.

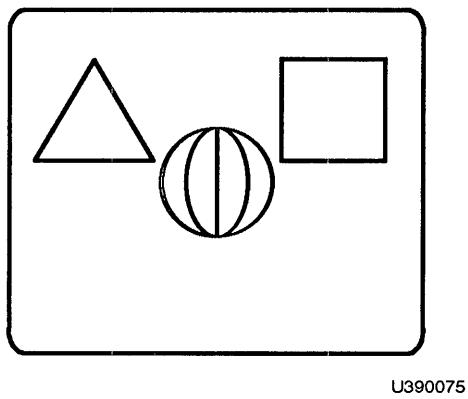

Figure 2-62. DISPLAYing Shapes

The default viewing space is a window for orthographic projection, the default LOOK is in effect, and the default viewport is the dynamic full screen. To get any other view of Shapes on the screen, you must explicitly use the viewing commands.

To establish a different line of sight, for instance, use the LOOK command as follows. Look towards the origin from a position that is left (negative X), up (positive Y), and back (negative Z) from the origin.

```
View_Shapes := LOOK AT 0,0,0 FROM -1,1,-5 APPLIED TO Shapes;
```

The LOOK command adds the following node to the display tree (Figure 2-63).

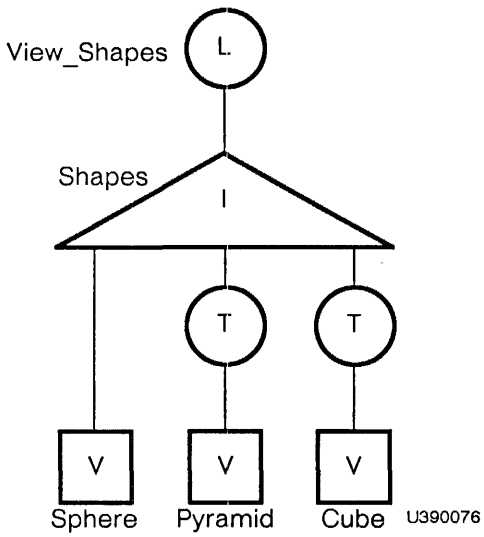

Figure 2-63. Adding the LOOK Node

Now build a viewing area around Shapes so that the objects can be seen in perspective projection. First calculate where the LOOK command has actually placed the objects in the coordinate system. Remember that all coordinates are translated and rotated so that the FROM point is at the origin and the AT point is in the positive Z axis. The new location of an object in Z is found by taking the square root of the following equation.

$$(Xa - Xf)^2 + (Ya - Yf)^2 + (Za - Zf)^2$$

In this equation, "a" is the AT point in X, Y, and Z and "f" is the FROM point.

In a LOOK command with a FROM point of 0,0,0 and an AT of -1,1,-5, the new location in Z of the sphere (the one object exactly at the origin) is the square root of 27, or 5.1962. This is shown in Figure 2-64.

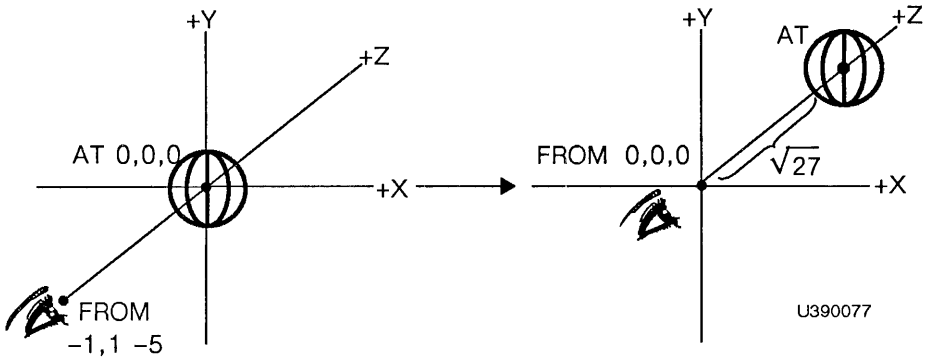

Figure 2-64. The LOOK Transformation

For maximum depth-cueing of the objects, the front and back boundaries of the perspective viewing area should be close to the objects. The sphere is a primitive with a radius of .15, so the front boundary should be placed at 5.1962 – 0.15, which is 5.0462. The back boundary can be placed further back at about 6. This is shown in Figure 2-65.

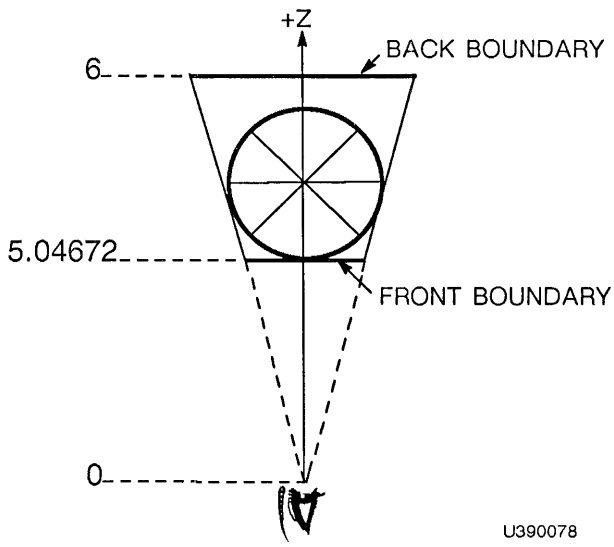

Figure 2-65. Calculating the Front and Back Boundaries

Finally a viewing angle must be chosen. An angle of about 28 degrees should suffice. The command to create the perspective view, then, is as follows.

```
Perspective_View := FIELD OF VIEW 28 FRONT = 5.0462 BACK = 6
                    APPLIED TO View_Shapes;
```

This adds a viewing matrix node to the display. The new structure is shown below (Figure 2-66).

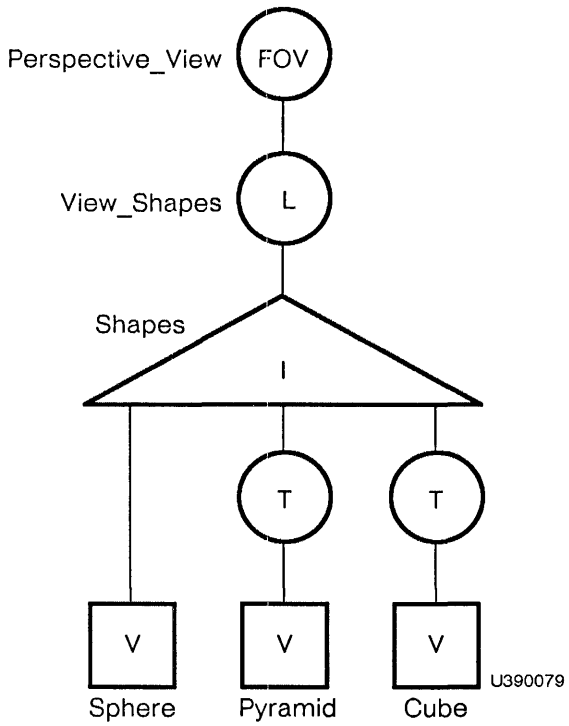

Figure 2-66. Adding the FIELD_OF_VIEW Node

Now, create a viewport in the upper-right corner of the screen. This is where the view of Shapes will be displayed. Do not use the optional intensity clause, so that Shapes will be displayed with the full intensity in effect for maximum depth-cueing.

```
Final_View := VIEWPORT HORIZONTAL=0:1 VERTICAL=0:1
              APPLIED TO Perspective_View;
```

The display tree for the final view is shown in Figure 2-67.

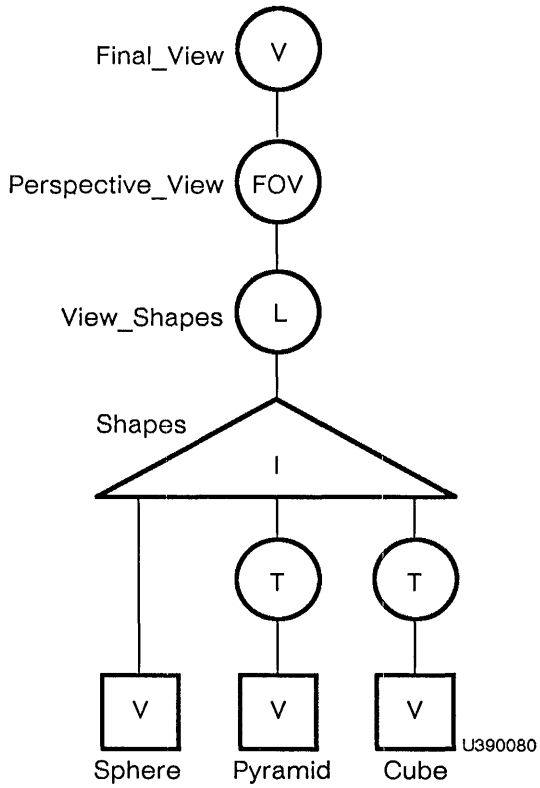

Figure 2-67. Adding the VIEWPORT Node

When Final_View is displayed, the PS 390 screen will appear as shown in Figure 2-68.

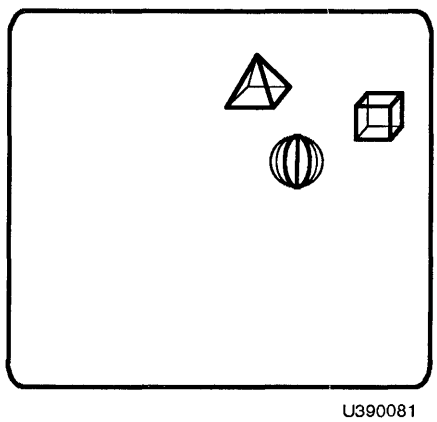

Figure 2-68. The Final Display

5.6 Summary

New Information Presented

1. Viewing operations are matrix and nonmatrix operations that let you create a variety of views of objects and display those views anywhere on the PS 390 screen.
2. A complete "view" is created by establishing a line of sight, defining a viewing area in the world coordinate system, and defining a viewport on the PS 390 screen. The PS 390 assumes default values for all three if they are not explicitly specified.
3. A line of sight is a matrix operation which specifies a point to look from and a direction to look at. You can also specify which direction is up. Whatever values you assign to these variables, the PS 390 translates coordinates so that the "look from" point is at the origin and the "look at" point is somewhere in the positive Z axis. It also rotates all coordinates so that "up" is in the YZ plane.
4. Viewing areas result from matrix transformations which produce orthographic or perspective views of objects. For an object to be visible, it must be enclosed in a viewing area. Objects or parts of objects that lie outside the viewing area are clipped, and do not appear in the view displayed on the screen.
5. A viewport is the area of the screen in which the contents of a viewing area are displayed. Viewports are not matrix operations. Two kinds of viewports can be specified, dynamic or static. Any number of viewports and any sized viewports can be displayed at the same time. A difference between the aspect ratio (width to height) of the viewing area and the aspect ratio of the viewport will result in a distorted view of the object.
6. Viewing transformations add operation nodes to the display tree for an object.

What Next?

The data base now contains display trees that represent many different views of the basic models that have been created. By displaying these views, any number of images can be displayed on any part of the PS 390 screen.

In the next section, you will see how attributes can be assigned to the objects you create.

6. Using Attributes

Modeling operations let you create objects of any complexity with the PS 390. Using viewing operations, you can create an infinite number of different views of the objects and display them anywhere on the screen. Another set of operations add a further range of possibilities to the images that are displayed. They let you assign attributes to an object to enhance its usefulness in modeling and analysis applications.

6.1 Attributes

All modeling and viewing operations (other than viewports) transform the coordinates of objects in the world coordinate system to create new objects. Each transformation adds an operation node which applies matrix operations to the object definitions.

The PS 390 lets you add other operation nodes to a display structure which do not transform graphical data and so do not create transformation matrices. These nodes assign attributes to an object.

Attributes offer a variety of possibilities for changing the characteristics of a displayed image. These include:

- Determining aspects of the image such as color, intensity, and the character font in which text appears.
- Referencing objects or parts of objects for display only when certain conditions are met.
- Marking parts of the displayed image as capable of being "picked" with a stylus, puck, or other pointing device.

Attribute settings are different from transformations because they are not matrix operations. Attribute nodes set and change values which are stored in registers. These registers record the current state of the machine. When the display processor of the PS 390 encounters an attribute node in a display structure, the contents of the node are used to check and sometimes to change the register representing that attribute. For example, an attribute node which sets depth clipping can enable or disable depth clipping, depending on the Boolean value contained in the node.

There are three classes of attributes: appearance attributes, structure attributes, and picking attributes.

6.2 Appearance Attributes

Appearance attributes govern the following aspects of an object when it is displayed.

- The colors of lines that form the image.
- The intensity at which lines are drawn.
- Whether or not depth clipping is performed on the image.
- The character font for any text in the image.

6.2.1 Displaying Objects in Color

Objects or parts of objects can be displayed in different colors. Color is specified as a hue and a saturation. The hue is the color itself. There are 360 hues to choose from. These correspond to values on a color wheel as shown in Figure 2-69.

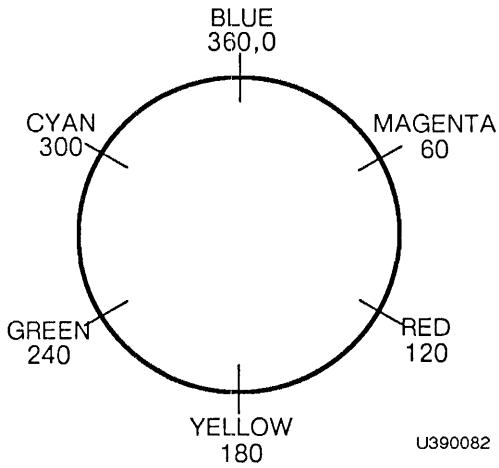

Figure 2-69. The Color Wheel

Blue has a value of 0 and 360, red is 120, and green is 240. The saturation is the amount of color versus the amount of white in the hue, and is specified as a range from 1 to 0. Blue at high saturation is deep toned. At low saturation, it is sky blue, and at 0 saturation it is white.

6.2.2 Displaying All Vectors in the Same Color

Color is applied to an object using the SET COLOR command. A cube can be colored red by applying the following command to Cube.

```
Red_Cube := SET COLOR 120,1 APPLIED TO Cube;
```

When Red_Cube is displayed, the lines that form the cube will appear in full-bodied red on the screen.

With complex objects, different parts of the object can be displayed in different colors. Each SET COLOR command creates an operation node in the display structure for the object. Consider the mechanical arm discussed in Section *GT2.4*. A simplified display tree is as shown in Figure 2-70.

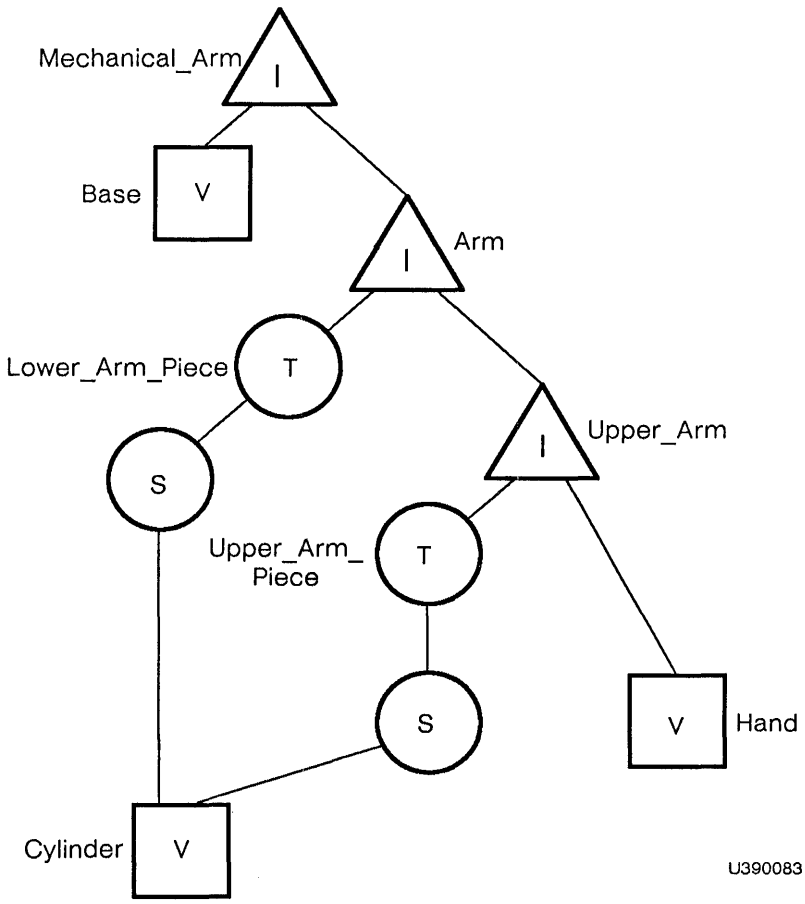

Figure 2-70. A Simplified Display Tree for the Mechanical Arm

You can use the SET COLOR command to color the parts of the model separately. For example, the base can be colored red, the arm pieces blue, and the hand green. The display tree with the SET COLOR nodes added is as shown in Figure 2-71.

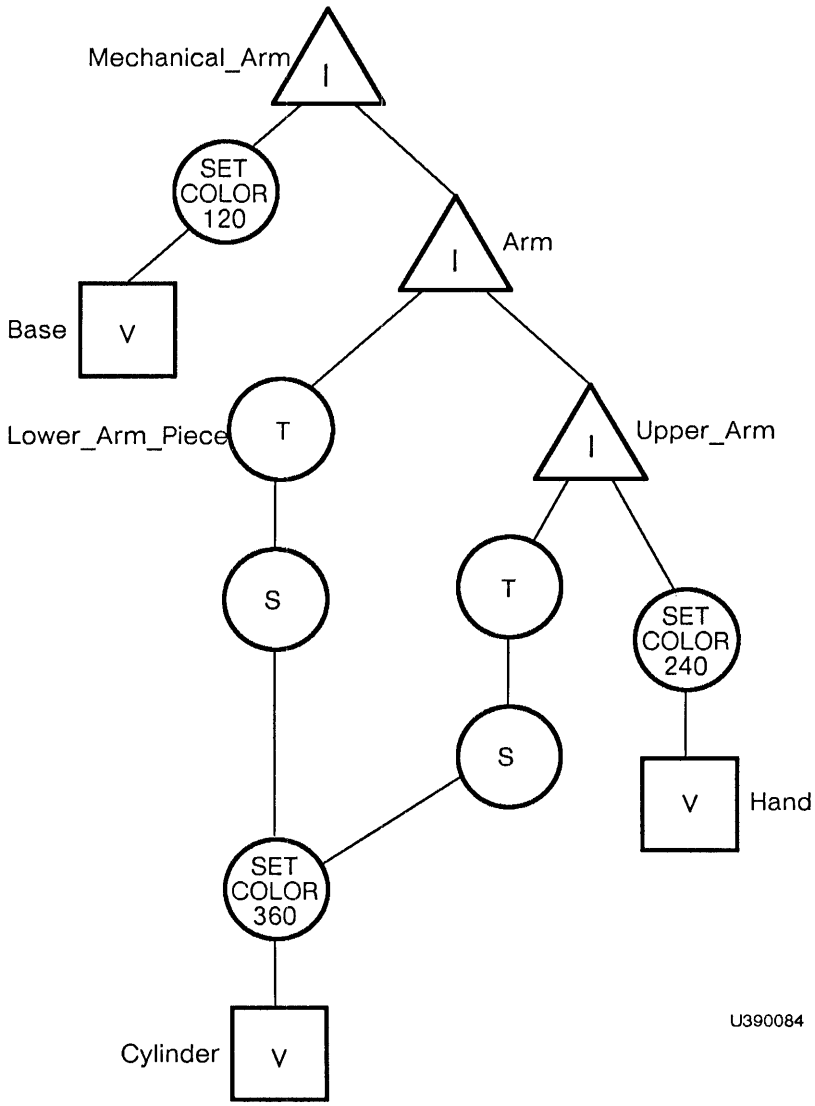

Figure 2-71. Display Tree With Color Nodes

For more information on color nodes, refer to the section called Setting Color in Section *GT8 Viewing Operations*.

6.2.3 Setting and Changing Intensity Levels

The PS 390 can be programmed to vary the intensity at which line segments are drawn between endpoints. This ability is used to good effect in the process known as depth cueing. Depth cuing enhances the illusion of three-dimensional views by varying the intensity of any line that recedes in the positive Z axis. Lines in an image which are "farther away" from the viewer appear dimmer.

Intensity levels are associated with dynamic viewports. An option of the VIEWPORT and LOAD_VIEWPORT commands allows you to specify the intensity variation for lines drawn within the dynamic viewport. A minimum and a maximum intensity are specified as values from 0 to 1. When objects enclosed in an orthographic or perspective window are mapped to the viewport, lines closest to the front boundary of the window are drawn at maximum intensity, and lines closest to the back boundary are drawn at minimum intensity.

The PS 390 also has a SET INTENSITY command which allows intensity to be specified as a separate attribute of an object. The command creates an attribute operation node in a display tree which overrides the intensity specification of the VIEWPORT or LOAD_VIEWPORT command.

A SET INTENSITY node in a display tree is often used as an interactive node. The node has two inputs. One accepts a Boolean value to enable or disable the effect of the node. The other accepts a 2D vector to change the intensity range. Thus a SET INTENSITY node in a display tree can be used to interactively change the intensity setting of a displayed image. The following command creates a node named Change_Intensity.

```
Change_Intensity := SET INTENSITY OFF 0.0:0.5 APPLIED TO Car;
```

The display tree which contains this node might be structured as in Figure 2-72.

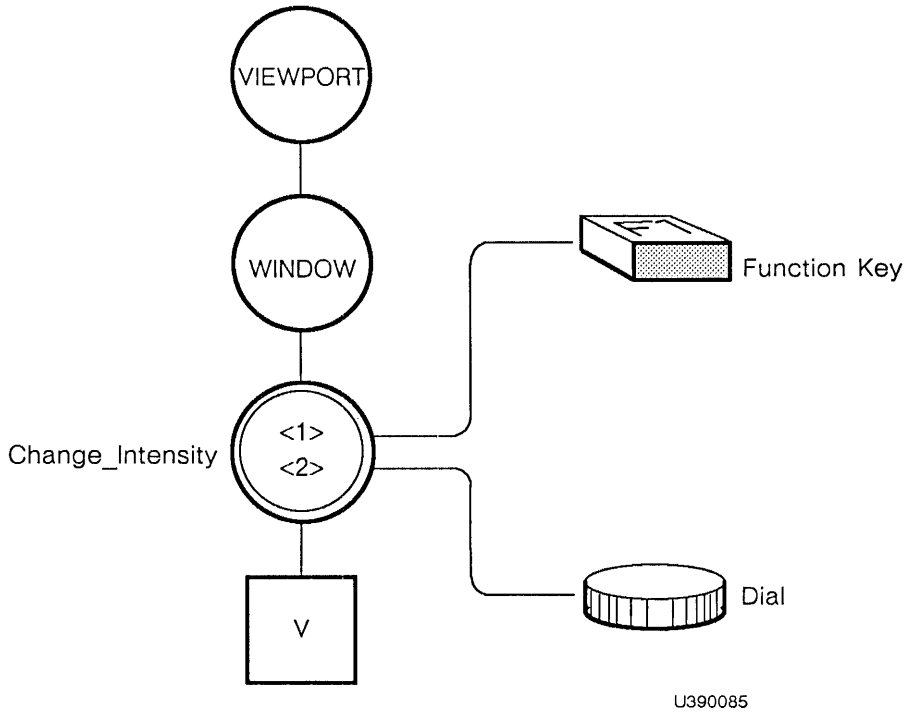

Figure 2-72. An Interactive Intensity Node

Function networks connect the two inputs of the node to interactive devices. Until the SET INTENSITY node is enabled, the intensity setting of the dynamic viewport (the default setting of 0:1) is in effect. A Boolean TRUE sent to input <1> from a function key will enable the SET INTENSITY node. New intensity settings can then be supplied from a dial, so that the operator can interactively change the intensity setting while viewing an image.

For more information on setting intensity, refer to Section *GT8 Viewing Operations*.

6.2.4 Enabling and Disabling Depth Clipping

Depth clipping is the operation of clipping (removing from the screen) objects or parts of objects that extend outside the viewing area in Z. The PS 390 automatically clips objects or parts of objects which extend beyond the X and Y boundaries of a window. Depth clipping (or Z clipping) is an optional feature which is not in effect when the system is initialized. It is specified as an attribute of an object.

Orthographic and perspective windows are defined with front and back boundaries or Z-clipping planes. When depth clipping is enabled, only objects or parts of objects that lie within the area bounded by the Z-clipping planes will be displayed in the viewport. This is illustrated in Figure 2-73.

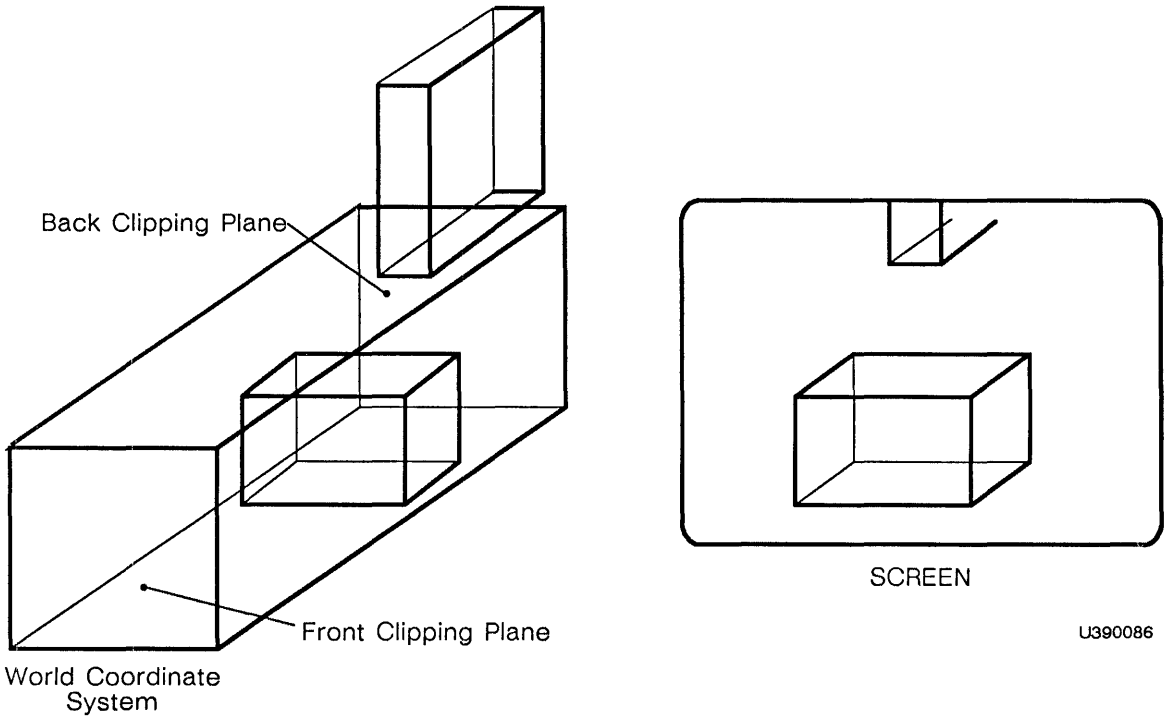

Figure 2-73. Depth Clipping Enabled for a Viewing Area

When depth clipping is disabled, objects that lie outside the Z-clipping planes in the positive or negative Z axis will be visible. Consider the objects in Figure 2-74.

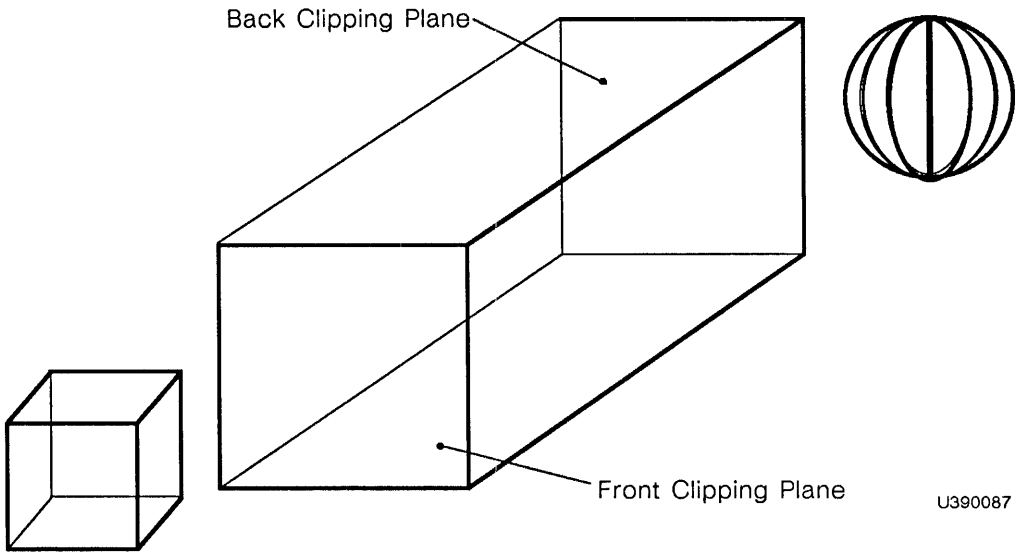

Figure 2-74. Objects Outside the Front and Back Boundaries

The cube and the sphere will not be displayed if depth clipping is on, because they lie outside the front and back boundaries. When depth clipping is turned off, however, they will be displayed.

Objects in front of the front boundary, such as the cube, will be displayed at maximum intensity. Objects behind the back boundary, such as the sphere, will be displayed at minimum intensity.

The following command enables depth clipping for an object called Rotated_Car.

```
Z_Clip := SET DEPTH_CLIPPING ON APPLIED TO Rotated_Car;
```

A display tree into which the SET DEPTH_CLIPPING node is inserted is shown in Figure 2-75.

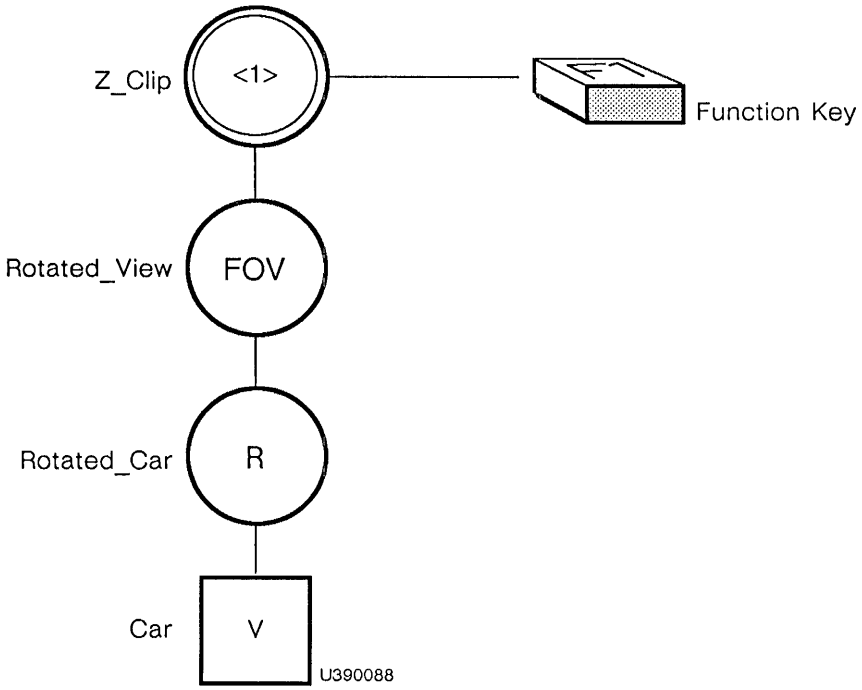

Figure 2-75. Display Tree With Depth-Clipping Node

The node can be turned on or off interactively. It has one input which accepts a Boolean TRUE or FALSE. TRUE turns depth clipping on; FALSE turns it off. A function key can be connected to the node to toggle depth clipping on and off.

6.2.5 Choosing a Character Font for Text

If text forms part of an object as a label, a menu item, or annotation, for example, you can add attribute nodes in the display tree to allow different character fonts to be used.

The PS 390 has a standard character font in which all text appears. You also have the ability to create alternate fonts. There is a command which allows you to design any number of other character fonts. This command (BEGIN_FONT .... END_FONT;) lets you enclose up to 128 separate vector lists defining characters within a named structure. Each vector list defines a letter, character, or number in the character font. For more information on the BEGIN_FONT ... END_FONT; command, consult Sections *RM1 Command Summary* and *GT10 Text Modeling and String Handling*. Also, in Section *TT3 Data Structure Editor* there is a user's guide to MAKEFONT, a graphi-

cal character font editor program. This program allows you to create new character fonts, to combine fonts, and to change existing fonts.

Once an alternate font has been created, it can be used by setting an attribute node in the display tree. Suppose that the alternate fonts Italic and Modern have been created, and that character strings in a display tree are to be displayed in the standard font and in Italic and Modern. Consider the display tree in Figure 2-76 for a group of labeled objects.

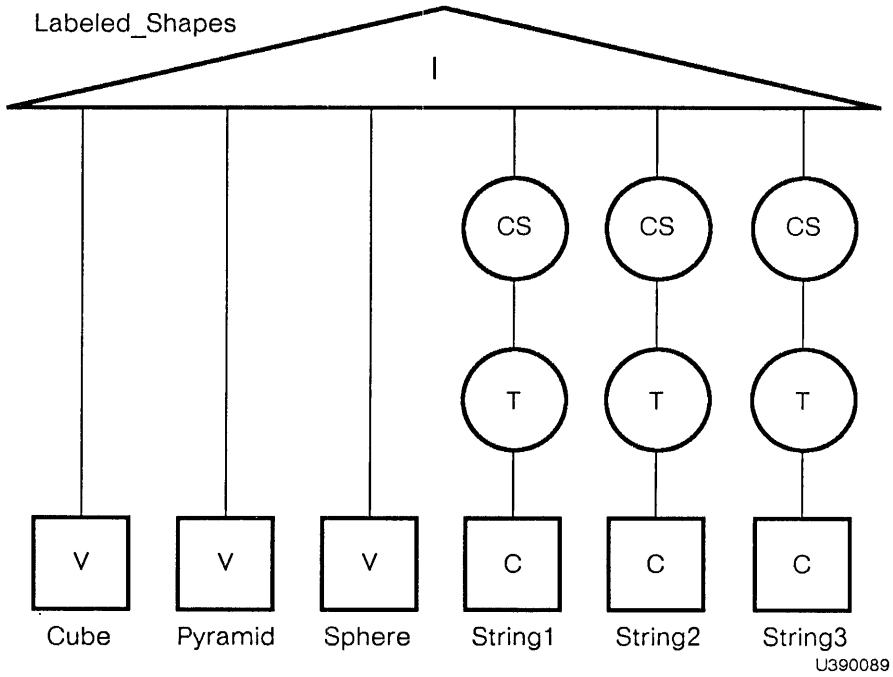

Figure 2-76. Display Tree for a Group of Labeled Objects

The instance node Labeled_Shapes groups vector lists for three objects (a cube, a sphere, and a pyramid) and character strings ("Cube", "Sphere", and "Pyramid") to label the objects. Each character node is created by the CHARACTERS command. The character nodes are preceded by a CHARACTER SCALE and a TRANSLATE node to scale the characters and move them to their correct location. When Labeled_Shapes is displayed, the three objects will appear labeled in the standard font.

Suppose you want the word "Cube" (String 1) to appear in the Italic font and "Sphere" (String 3) to appear in Modern. Two CHARACTER FONT nodes must be inserted above the data nodes for the cube and sphere labels. The following commands create those nodes.

```
Cube_Label := CHARACTER FONT Italic APPLIED TO String 1;
Sphere_Label := CHARACTER FONT Modern APPLIED TO String 3;
```

The modified display tree with alternate fonts specified is structured as shown in Figure 2-77.

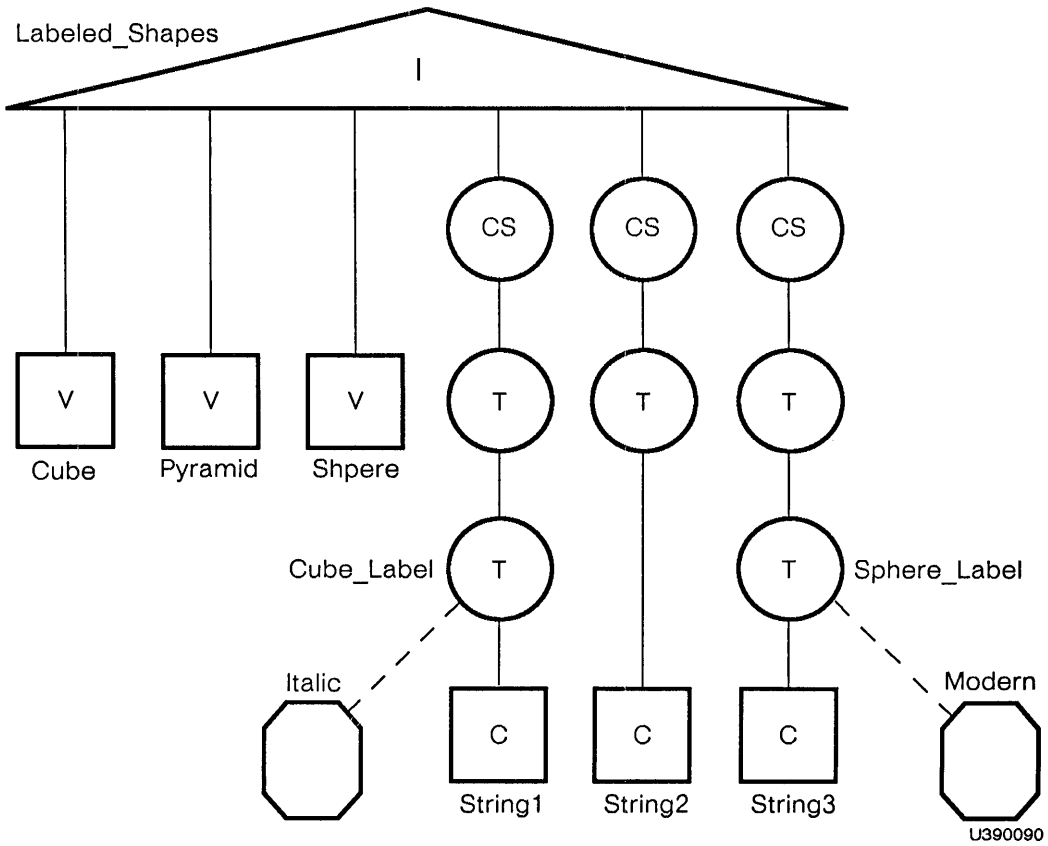

Figure 2-77. Display Tree With Character Font Nodes

The CHARACTER FONT nodes called Cube_Label and Sphere_Label are pointers to the fonts called Italic and Modern. The branch of the tree which ends at the CHARACTERS node for labeling the pyramid has no CHARACTER FONT node in it, so the string "Pyramid" will appear in the standard font.

6.3 Structure Attributes

A display tree for an object is composed of branches which determine the paths that the display processor must take when the object is being dis-

played. Each branch is unconditionally traversed during each display processing cycle. Structure attributes create nodes in a display tree at which "branching" may occur only if certain conditions are met. These attributes allow you to:

- Reference objects or parts of objects by setting conditional bits and testing those bit settings further down the display tree.
- Add or remove detail from an object by setting level-of-detail bits and testing for them further down in the display tree.
- Control blinking or alternate displaying of images by setting a rate and an on/off phase, then testing for the phase further down the display tree.

6.3.1 Conditional Referencing

Conditional referencing is generally used to display or blank parts of a complex structure by selectively traversing or bypassing branches of a display tree. Two commands are needed to set up and use conditional referencing. The SET CONDITIONAL BIT command sets any of fifteen conditional bits numbered 0 to 14. This creates a SET CONDITIONAL BIT node, or SET node for short, in the display tree. Below the SET node, an IF CONDITIONAL BIT node, or IF node, is created. This node tests a conditional bit setting and branches to the name it is APPLIED TO if the condition is met.

For example, consider a display tree for a car which, for simplicity, consists of four wheels, a chassis, and a body, as shown in Figure 2-78.

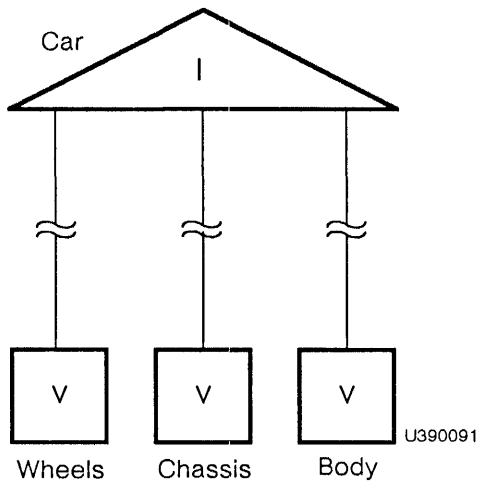

Figure 2-78. Simplified Display Tree for a Car

For some reason, you want to be able to display or blank the car body at your whim. Use the SET command and IF command to create a pair of SET and IF nodes in the branch which ends with Body.

```
Set_Condition := SET CONDITIONAL_BIT 1 ON THEN Condition_Met;
Condition_Met := IF CONDITIONAL_BIT 1 IS ON THEN Body;
```

Notice that the THEN form of the command is used. This is synonymous in all cases with the APPLIED TO form of the command, but makes more syntactic sense to readers.

Figure 2-79 shows the display tree with conditional referencing nodes added.

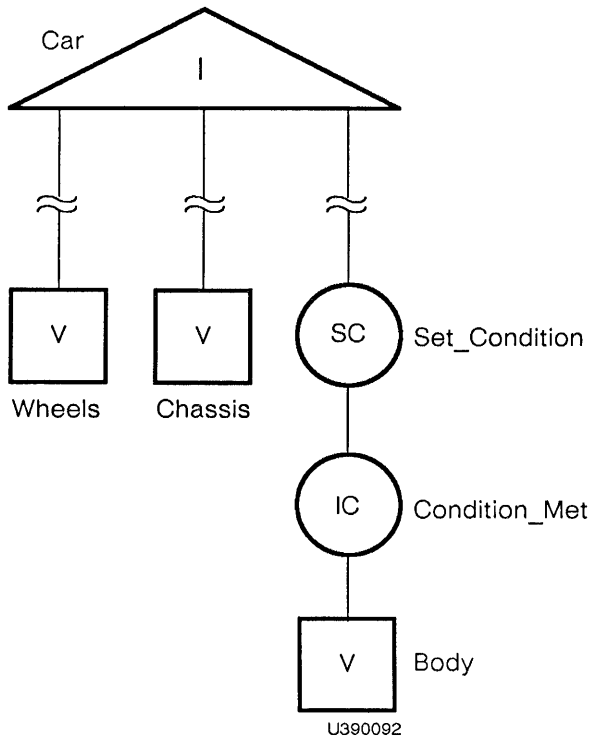

Figure 2-79. Display Tree With Conditional Referencing Nodes

Initially, when Set_Condition is displayed, all the components of the car, including Body, will be displayed. The condition that bit 1 be set on is met and the path to the data node Body is made. The ON/OFF clause lets you control the display of the car body. A function key can be connected to Set_Condition to turn it ON (Boolean TRUE) or OFF (Boolean FALSE). When the bit is off, the car body will not be displayed.

Refer to the section *Using Conditional-Bit Attribute Settings* in Section *GT9 Conditional Referencing* for more examples of this sort.

6.3.2 Level of Detail

Level of detail is another form of conditional referencing that is built into a display tree using pairs of SET and IF nodes. This form of conditional referencing is normally used to unfold detail in a complex display. For example, a display for a geological or seismological application might show various levels in the earth's crust. SET and IF level-of-detail nodes can be placed in the display tree to allow the picture to be displayed or blanked layer by layer.

Unlike conditional-bit referencing where 15 bits may be set, level of detail uses only one variable. This is an integer from 0 to 32767. The SET LEVEL_OF_DETAIL command creates a SET node in the display tree. The IF LEVEL_OF_DETAIL command creates an IF node to test the level-of-detail setting and complete the path to a named entity accordingly.

Consider as an example a display tree for a three-dimensional contour map of an area of land. You want to be able to turn a dial and add contour lines in 50 foot increments from sea level to 250 feet. Before any level-of-detail nodes are added, the display tree is simply a collection of vector lists, one for each contour line, under a single instance node, as shown in Figure 2-80.

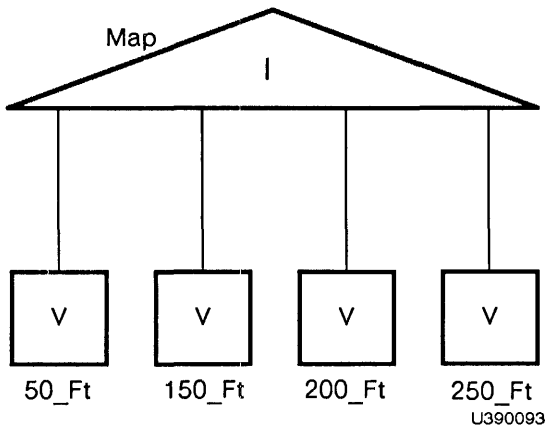

Figure 2-80. Display Tree for a Contour Map

This structure was created by the following command which grouped the vector lists.

```
Map := INSTANCE OF 50_Feet, 150_Feet, 200_Feet, 250_Feet;
```

Begin allowing for level-of-detail displays by adding a SET node at the top of the display tree.

```
Set_Level := SET LEVEL_OF_DETAIL TO 1 THEN Map;
```

Each branch of the display tree out of the instance node Map can now be prefixed by an IF node. Unlike conditional-bit referencing IF nodes, LEVEL_OF_DETAIL nodes do not test an on/off state, but a relationship. These relationships are as follows.

```
Less Than                 <
Less Than or Equal To     <=
Equal To                  =
Not Equal To              <>
Greater Than or Equal To  >=
Greater Than              >
```

A different value can be assigned to the IF node for each contour line in the map. If the level of detail is 1 or greater, the fifty-foot contour is displayed. If it is 2 or greater, the hundred-foot contour is displayed, and so on. For example, the following command creates a node called If_1 which tests whether or not the level of detail is 1 or greater and completes the path to the 50-foot contour line.

```
If_1 := IF LEVEL_OF_DETAIL >= 1 THEN 50_feet;
```

The complete tree with all IF nodes is as shown in Figure 2-81.

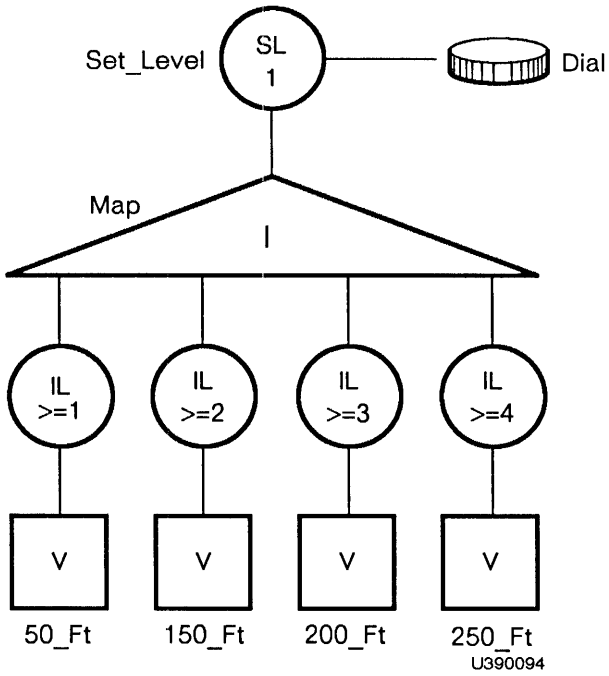

Figure 2-81. Display Tree With Level-Of-Detail Nodes

A function network can be connected to the SET node to supply new values to the level-of-detail setting from a dial. As the dial is turned and the level-of-detail changes, more of the contours will be displayed.

For more examples of this sort, refer to the section on *Using LEVEL_OF_DETAIL* in Section *GT9 Conditional Referencing*.

6.3.3 Blinking or Alternating Displays

Making an object blink or alternating the display of different objects is another form of conditional referencing which involves SET nodes and IF nodes in the display tree. The SET node sets a rate for displaying and blanking the object. This rate can be under control of the refresh rate of the PS 390 display, an internal PS 390 clock, or an external clock generated by a function network or the host computer. The IF node determines what will be displayed during the on phase and what will be displayed during the off phase. The commands are SET RATE and SET RATE EXTERNAL (for an external clock), and IF PHASE.

The SET RATE commands specify durations for the on phase and the off phase, an optional initial state (either on or off), and an optional clause

called the delay, which specifies the number of refresh frames in the initial state. The IF PHASE command determines what will be displayed during the on phase and what will be displayed during the off phase using the APPLIED TO or THEN clause to indicate a path to a named structure.

For example, to cause the label associated with an object to blink by being displayed for 120 refresh frames and blanked for 60, the following commands can be used.

```
Blink_Rate := SET RATE 120 60 THEN Phase;
Phase := IF PHASE ON THEN Object_Label;
Object_Label := CHARACTERS 'THIS IS THE OBJECT YOU CHOSE';
```

These nodes would be placed in a display tree as shown in Figure 2-82.

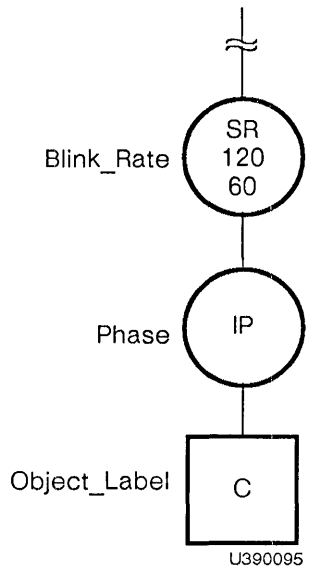

Figure 2-82. Conditional Nodes for Blinking

The words "THIS IS THE OBJECT YOU CHOSE" will be displayed for 120 refresh cycles (about two seconds) and blanked for 60 (about one second) when this tree is traversed.

The SET RATE and IF PHASE commands can also be used to display alternately two different objects. A display tree can be created with SET and IF nodes to display one object during the on phase and another during the off phase. Figure 2-83 shows such a display tree.

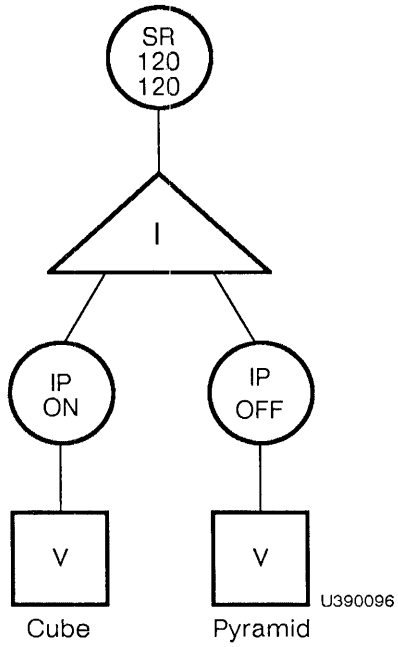

Figure 2-83. Display Tree for Alternate Display of Two Objects

During the on phase, the cube will be displayed for two seconds. During the off phase, the pyramid will be displayed for two seconds. Refer to Section *GT9 Conditional Referencing* for more information on blinking.

6.4 Picking Attributes

In computer graphics terms, picking means selecting by means of a stylus, a puck, or some other pointing device, a line, set of lines, or piece of text in a display. When the pick occurs, the computer generates information in the form of a pick list which identifies the line(s) or text picked no matter how the object may be oriented on the screen. This information is reported for programming purposes. For example, in the tutorial demonstration package, when a menu item is picked, the information returned by the pick is used to run the correct demonstration program.

Picking attributes must be assigned to an object before it or any part of it can be picked from a screen display. These attributes are nodes in the display which:

- Mark objects or parts of objects as candidates for picking and turn picking on or off.
- Assign a name (pick identifier) which will be reported as a text string when a pick occurs.

The highest attribute node in the display tree must be the node that turns picking on and off for the object. For example, to make an object called Space_Shuttle capable of being picked from the screen, the following command can be used.

```
Pick := SET PICKING ON APPLIED TO Space_Shuttle;
```

Assuming that Space_Shuttle is an instance node grouping the various parts of the craft, the top level of the display tree will be structured as shown in Figure 2-84.

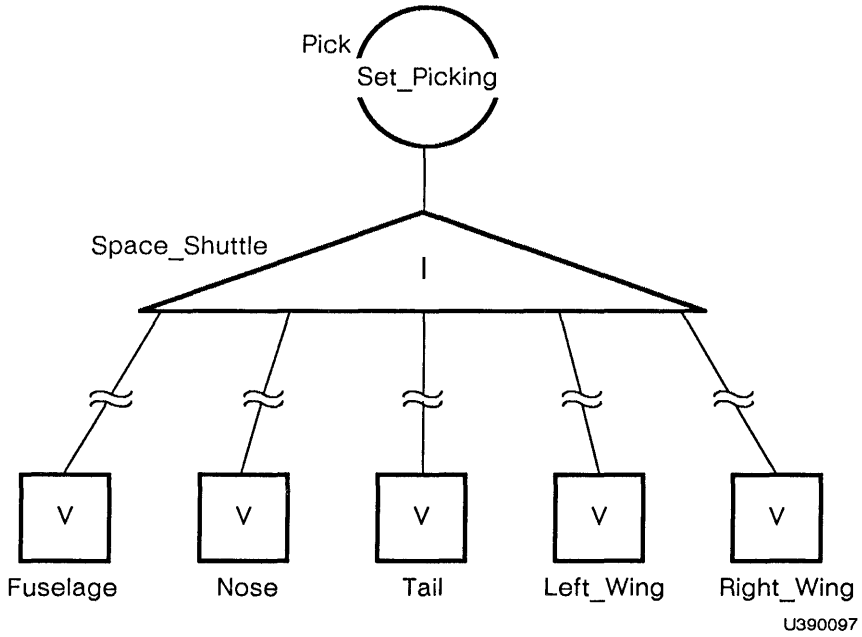

Figure 2-84. The SET PICKING ON/OFF Node

This node can be used interactively and should be created in the OFF setting. Picking is enabled by a Boolean TRUE sent to the node through a function network.

The node created in the command above makes the whole object called Space_Shuttle capable of being picked. If you want the separate components of the object to be pickable, nodes must be included in the display tree as shown in Figure 2-85.

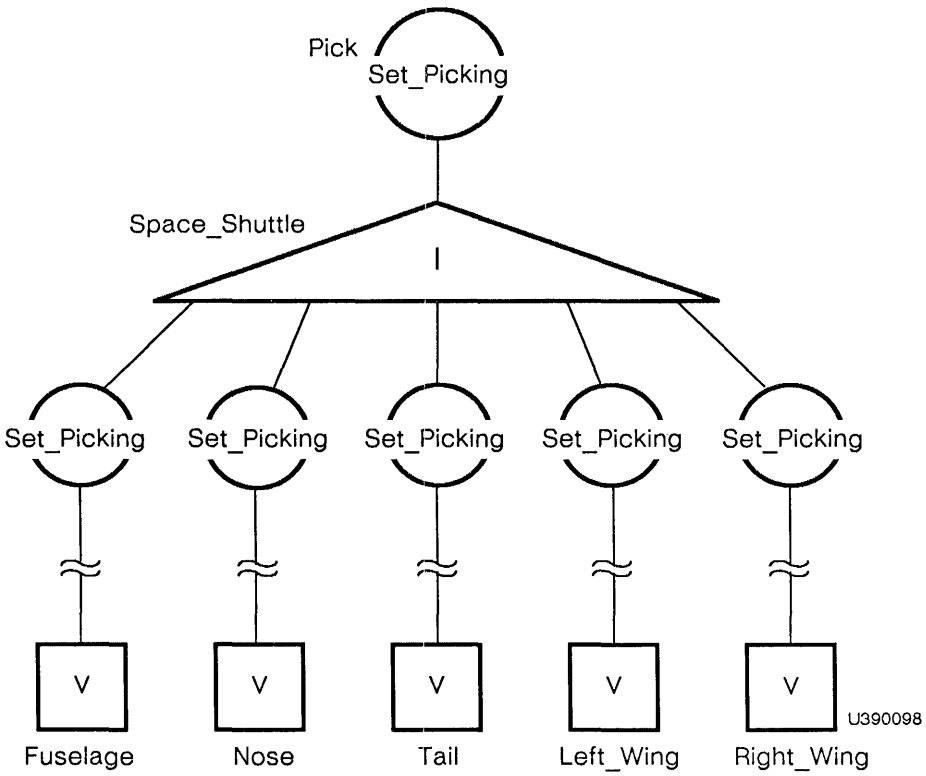

Figure 2-85. Making the Components Pickable

Now the fuselage, nose, tail, left wing, and right wing can be made individually pickable.

The other attribute node that must be added to the display tree assigns the pick identifier (or pick ID) that will be reported in the pick list when a pick occurs. Two names identify a picked object.

The first is the pick ID—a character string assigned by the SET PICKING IDENTIFIER command. The second name is the name of the data node that contains the line or character that was picked from the screen.

The following command, for instance, assigns a pick ID to the fuselage.

```
Fuselage_Pick := SET PICKING IDENTIFIER = Shuttle_Fuselage
                 APPLIED TO Fuselage;
```

If any line in the fuselage section of the space shuttle is picked when picking is enabled, the system will generate a pick list which reports the pick ID as Shuttle_Fuselage and the data node as Fuselage. To use picking with the

PS 390, function networks must be built to report any picks that occur. Refer to Section *GT11 Picking* for complete information on setting up picking networks.

6.5 Summary

New Information Presented

1. An attribute node is another type of operation node in a display tree. It allows you to specify characteristics of the displayed image of the models you create.

2. There are three types of attributes: appearance attributes, structure attributes, and picking attributes.

3. Attribute nodes differ from transformation nodes in a display tree. Transformation nodes create transformation matrices which are applied to the geometrical data in the data nodes. Attributes, however, are non-matrix operations. They set and change values in registers in the PS 390.

What Next?

You have now seen all of the types of nodes that can be included in a display tree. Data nodes define primitive shapes. Modeling operation nodes shape and position parts of complex models in the world coordinate system. Instance nodes group separate primitives and transformations into larger named entities. Viewing operation nodes create views of objects from any angle and from any perspective and specify areas of the screen in which the view will be displayed. Attribute operation nodes change aspects of the model's appearance, allow conditional referencing, and set up picking.

In the next section, you will see how the interactive devices of the PS 390 are programmed to allow interactive manipulation of models. Function networks are created to complete the path between the devices and interaction nodes in the display tree. These networks take values from the control dials, function keys, and so on, and convert them to the correct type of data for the interactive node they are connected to.

7. Interacting With the Picture

A display tree contains three types of operation nodes. Modeling nodes represent translation, rotation, and scale transformations that are applied to primitive data to shape and position the parts of a model in the world coordinate system. Viewing nodes transform the model through viewing matrices to create numerous views of the model from different vantage points. Attribute nodes determine aspects of the model's appearance on the screen, control which parts of a model will be displayed, and set up picking.

Operation nodes can be set up for modeling purposes or for interaction.

For modeling purposes, translation, rotation, and scale nodes; viewing nodes; and attribute nodes are all created with fixed values. For example, a primitive might be rotated 60 degrees around the X axis to a permanent location in the coordinate system. Or a model might have a permanent perspective view imposed on it with a viewing angle of 45 degrees. Or the intensity range might be fixed at .5 to 1, and separate parts of the model might be designated as always pickable.

Interaction nodes, on the other hand, are put in the display tree to allow you to interactively manipulate the entire model or any separate part of it. To achieve this interactive manipulation, the contents of these nodes must be updated with new values. These values are supplied from a physical device such as a dial through data-handling software called a function network to the interactive node. The network might feed a rotation node with a series of new rotation matrices, a viewing node with a new viewing matrix, or an attribute node with information to change its function.

7.1 Evans & Sutherland and Interactive Graphics

At Evans & Sutherland, interaction has always been the most important feature of graphics systems. For E&S, interaction means the ability to change the picture being displayed in an easy manner and in real time.

The PS 390 provides ease of manipulation through offering a variety of interactive devices. A data tablet and stylus can be used to control a cursor on the screen for pointing at and selecting parts of the display. Eight control dials can be programmed to translate, rotate, and scale objects and to zoom and pan. A bank of 32 function buttons can be programmed to select differ-

ent displays or change details of the same display. Twelve programmable function keys can act as toggle switches between different functions. These devices are all easy and natural to use and can be arranged comfortably at your work place. Refer to Section *RM13 Interactive Devices* for more information.

Real time interaction means that the effect of an interactive device—for example, turning a dial or pressing a button—is seen instantly in the picture. If a dial is correctly programmed to rotate a model around the Y axis, then you perceive no delay between turning the dial and seeing the model respond. If you turn the dial slowly the model turns slowly, and if you turn it fast the model turns fast. When the devices are correctly programmed, minute, precise changes can be made to the orientation of a model on the screen as you watch.

Since every owner of an interactive graphics system has a different reason for using interactive graphics and different requirements and expectations of the machine, the interactive devices must be programmed to suit individual needs. Users themselves decide how they want to interact with the models they have created, and they program the devices accordingly.

In Evans & Sutherland systems previous to the PS 300 product line, the host computer controlled the interactive devices as well as running the application programs and calling the routines that created the graphics. Interactive devices were checked regularly by the host computer programs to see if their state had changed. If the state had changed, the host program had to determine how and what to do about it.

The PS 390 unburdens the host by handling the interactive devices locally. The host computer never has to intervene in setting up the devices or interpreting data from them. In addition, each device contains its own microprocessor. This distribution of some intelligence to the devices themselves in turn unburdens the Joint Control Processor (JCP) of the PS 390. Devices send data that has already been interpreted to the JCP. So, for example, instead of the control dials unit sending a stream of data whenever a dial is turned, it sends significant information only (such as which of the eight dials was turned) at significant times (every sixteenth of a turn, for instance).

7.2 Programming the Interactive Devices

The common end product of programming an interactive device is to have it change the displayed picture in some way or send information back to the host. For example, you might want the object being displayed to start and stop blinking when you press function key F3. Or you might want dial 2 to rotate only the wrist joint of a mechanical arm, and dial 4 to translate the whole model from left to right across the screen. Or when you pick an object on the screen, you may want information from the pick to be reported back to an application program on the host.

7.2.1 Planning for Interaction

The first step in planning for interaction is designing the display tree for the model. You must decide what sort of interaction you want and structure the display tree accordingly. For most applications of interactive graphics, you will want to interactively translate, rotate, and scale the model. For other purposes, you may also want to change the viewing matrices dynamically. And in many cases you will want to use conditional referencing, level-of-detail, and picking in interactive operations.

Interactive nodes, unlike modeling operation nodes, are created with values that will later be updated from an interactive device. Consider, for example, the simple display tree in Figure 2-86 for a star that can be rotated interactively.

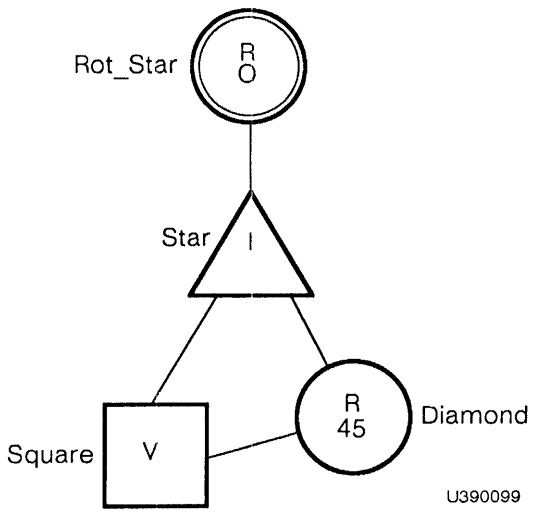

Figure 2-86. Display Tree for Simple Interaction

The instance node called Star groups a data node called Square and a rotation node called Diamond. The rotation node is a modeling node. It applies a 45 degree rotation matrix to the Square to create a diamond shape. Its contents never change. The rotation node Rot_Star, however, is not in the display tree for modeling purposes. It is drawn as a double circle to indicate that it is an interaction node. This rotation node is initially created with a rotation of zero degrees, so that at first it will not have an effect on the structure. Its contents will eventually be updated with a new rotation matrix from a function network as a dial is turned.

The following commands will create the display tree shown in Figure 2-86.

```
Rot_Star := ROTATE 0 APPLIED TO Star;
Star := INSTANCE OF Diamond, Square;
Diamond := ROTATE IN Z 45 APPLIED TO Square;
Square := VECTOR LIST N=5 .5,.5 .5,-.5, -.5,-.5, -.5,.5, .5,.5;
```

7.2.2 Updating a Node

Not every node in a display tree can be updated and so not every node can be an interactive node. Instance nodes, for example cannot be updated. Their function is to point to other places in the structure of the display tree. An instance node can be redefined using the INCLUDE and REMOVE commands, but new values cannot be sent to an instance node through a function network because instance nodes do not contain data.

Operation nodes, however, do contain data, in the form of matrices, vectors, numbers, and Boolean values. Most operation nodes can have their contents changed as long as those nodes have a direct name by which they can be accessed. Data nodes contain vector lists, polygon lists, special vector lists for curves, and text in various forms. There are ways to change the contents of these nodes interactively too.

Section *RM1 Command Summary* shows the type of node a command creates and indicates if that node has inputs which allow it to be updated. Figure 2-87 shows a representation of the SET DEPTH_CLIPPING node.

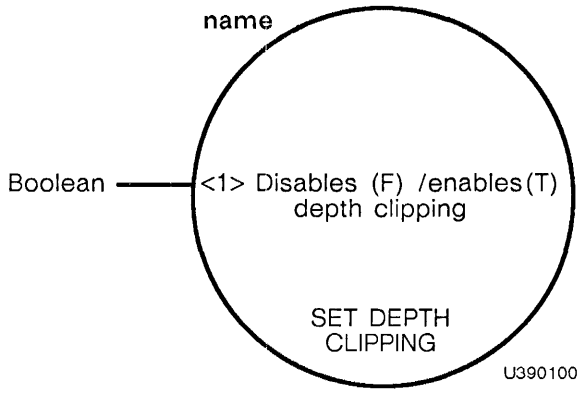

Figure 2-87. The SET DEPTH_CLIPPING Node

This node has one input which accepts a Boolean TRUE or FALSE. A TRUE enables depth clipping for an object and a FALSE disables it.

7.2.3 Supplying the Correct Type of Data

The Boolean value which the SET DEPTH_CLIPPING node requires is supplied by an interactive device. Logically, a two-state device such as a function key or function button would be programmed to act as a toggle switch, setting depth clipping on the first time it is pressed and setting it off when it is pressed again. However, when a function key is pressed it generates an integer which identifies the key, not a Boolean value. Some method is needed of programming a path between the function key and the SET DEPTH_CLIPPING node, and of converting the integer to a Boolean value.

7.3 PS 390 Functions

With the PS 390, interactive devices are not programmed using a standard programming language. Instead, the PS 390 uses functions which are combined into function networks. The individual functions which compose a network are actually Pascal procedures, but can be thought of as "black boxes" with numbered input queues and outputs, as shown in Figure 2-88.

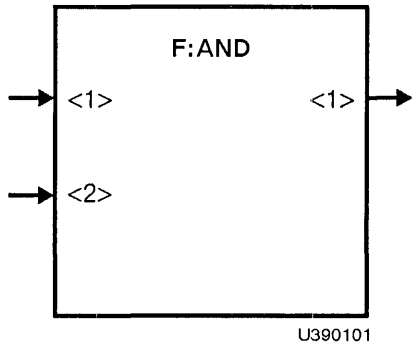

Figure 2-88. Representation of a Function

Each function accepts data on its input queues, performs a mathematical, logical, data conversion, routing, or selecting operation, and sends data out of its outputs. Inputs accept data from interactive devices, from the host, or from the outputs of other functions. Outputs connect to inputs of other functions or interactive nodes in a display tree.

Functions are chosen and combined so that the final network will accept data from a device and manipulate and convert the data into types that will be accepted by the interactive nodes. There are nine categories of functions available with the PS 390. These are as follows.

- Data Conversion

  Data conversion functions change matrices into rows, rows into scalar elements, and real numbers to integers or vectors. Data can be output in decimal or exponential format.

- Arithmetic and Logical

  These functions perform all arithmetic operations (add, divide, subtract, multiply, square root, sine, and cosine) and logical operations (and, or, exclusive-or, and complement).

- Comparison

  Comparison functions test whether values are greater than, less than, equal to, not equal to, greater than or equal to, and less than or equal to other values.

- Data Selection and Manipulation

  These functions are used to selectively switch functions, choose outputs, and route data.

- Viewing Transformation

  Viewing transformation functions connect to viewing operation nodes in display trees to interactively change line-of-sight, window size, and viewing angle.

- Object Transformation

  Object transformation functions connect to modeling operation nodes in display trees to interactively rotate, translate, and scale objects.

- Character Transformation

  These functions are used to interactively position, rotate, and scale text.

- Data Input and Output

  These functions set up and control the interactive devices (dials, function keys, function buttons, data tablet, and keyboard) and output values to the optional LED labels on the control dials and function keys.

- Miscellaneous

  Other functions set up and control picking, clocking, timing, and synchronizing operations.

The complete set of functions is loaded into memory when the PS 390 is booted. Sections *RM2 Intrinsic Functions* and *RM3 Initial Function Instances* are a reference to all available functions.

There are three types of functions: intrinsic functions, initial function instances, and user-written functions.

7.3.1 Intrinsic Functions

Intrinsic functions are the set of master functions which you can instance to create networks. Their names reflect the operation they perform, and are preceded by F:, for instance, F:AND, F:ROUTE, F:MATRIX.

Functions are instanced using the NAME := F:function_name command. For example, the following command creates an instance of the ADD function (F:ADD) and assigns it the unique name Adder.

```
Adder := F:ADD;
```

Intrinsic functions are always instanced in this way. The intrinsic function name itself, in this case F:ADD, is never used in the network. The name of the function instance (i.e., Adder) is used instead.

7.3.2 Initial Function Instances

When the PS 390 is booted, the system itself instances (i.e., names) certain functions as initial function instances. Among other things, these functions connect to the interactive devices, connect to the host, and connect to error detection logic. For example, inputs to the initial function instance called DIALS are connected to the control dials unit at system initialization. DIALS has eight outputs on which it sends real numbers from one to eight, corresponding to the numbers of the eight dials. It sends values generated by the dials out of the output that corresponds to the number of the dial.

Unlike intrinsic functions, which must always be assigned a unique name, initial function instances are used with their system-assigned name. The name reflects the operation the function performs, but is not preceded by F: (for example, TABLETIN, WARNING, KEYBOARD).

7.3.3 User-Written Functions

You are not limited to the set of intrinsic functions and initial function instances supplied with the system. If the functions that are available do not suit all your needs, you can write your own using the optional user-written function facility. User-written functions are instanced in the same way as intrinsic functions. E&S provides documentation on writing Pascal proce-

dures to create user-written functions and documentation and software files that aid in producing and transporting these procedures from the host to the PS 390. To understand user-written functions, you should know Pascal well and you should have experience in programming PS 390 function networks. For complete information, refer to the *Advanced Programming* volume of the *PS 390 Document Set*.

7.3.4 Creating Networks

Networks are created by connecting initial function instances, instances of intrinsic functions, and interactive nodes in display trees using the CONNECT command. For example, the following group of commands create a simple network to rotate the star diagrammed in Figure 2-86 around the Z axis.

```
Rotate := F:DZROTATE;
CONNECT DIALS<2>:<1>Rotate;
CONNECT Rotate<1>:<1>Rot_Star;
```

The first command

```
Rotate := F:DZROTATE;
```

creates an instance of the intrinsic function F:DZROTATE named Rotate. This intrinsic function is represented in Figure 2-89.

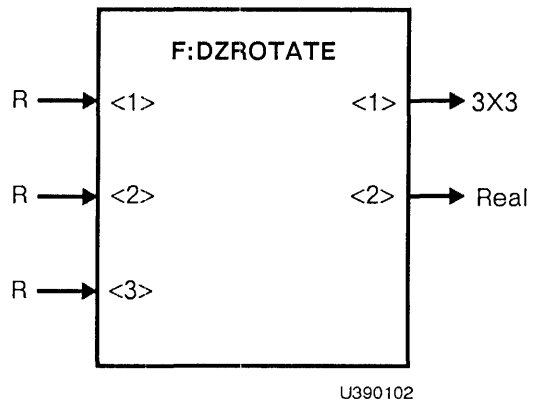

Figure 2-89. The F:DZROTATE Function

This function has three inputs. Input <1> accepts real numbers, usually directly from the initial function instance DIALS. Input <3> is a magnification factor. The very small numbers (from 0 to 1) that arrive at input <1> from the dial are multiplied by this factor. Input <2> is an accumulator set for the values received on input <1>. The function creates a matrix from an angle of rotation, which is derived from the accumulator contents on input <2> multiplied by the scale factor on input <3>. The matrix is sent on output <1>. Output <2> contains the accumulator contents from input <2>.

The second command

```
CONNECT DIALS<2>:<1>Rotate;
```

connects output <2> of the initial function instance DIALS to input <1> of Rotate. The initial function instance DIALS is diagrammed in Figure 2-90.

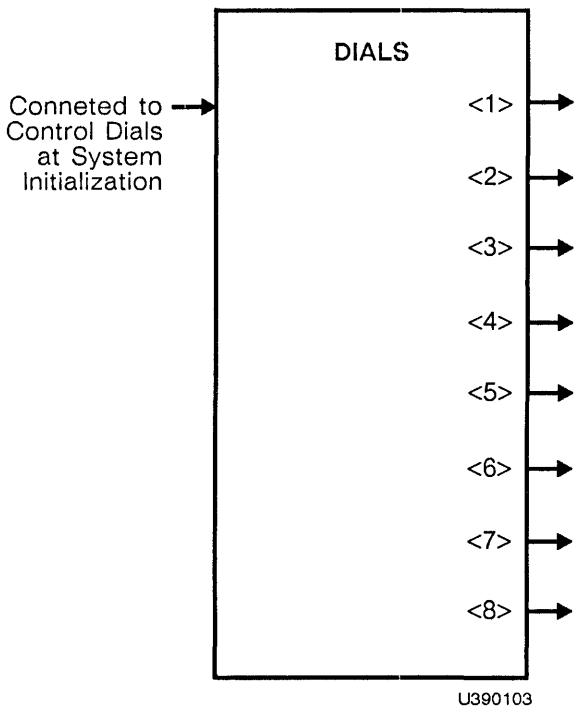

Figure 2-90. The Initial Function Instance DIALS

This initial function instance is connected to the control dials unit when the PS 390 is booted. It produces a real number on each of its eight outputs. Every output corresponds to one of the eight dials. Connecting output <2> of DIALS to input <1> of Rotate feeds values into the Rotate function from dial 2 whenever the dial is turned.

The third command

```
CONNECT Rotate<1>:<1>Rot_Star;
```

connects output <1> of Rotate to input <1> of an interaction node called Rot_Star. Figure 2-91 represents a rotation node in a display tree.

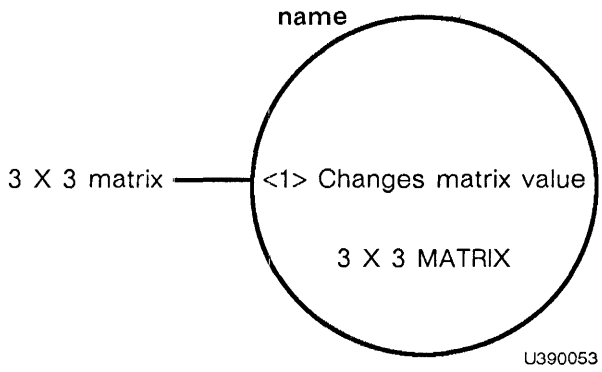

Figure 2-91. Inputs to a Rotate Node

This connection feeds the rotation matrix from the Rotate function to the interactive rotation node. Figure 2-92 is a diagram of the simple Z-rotation function network which the commands create.

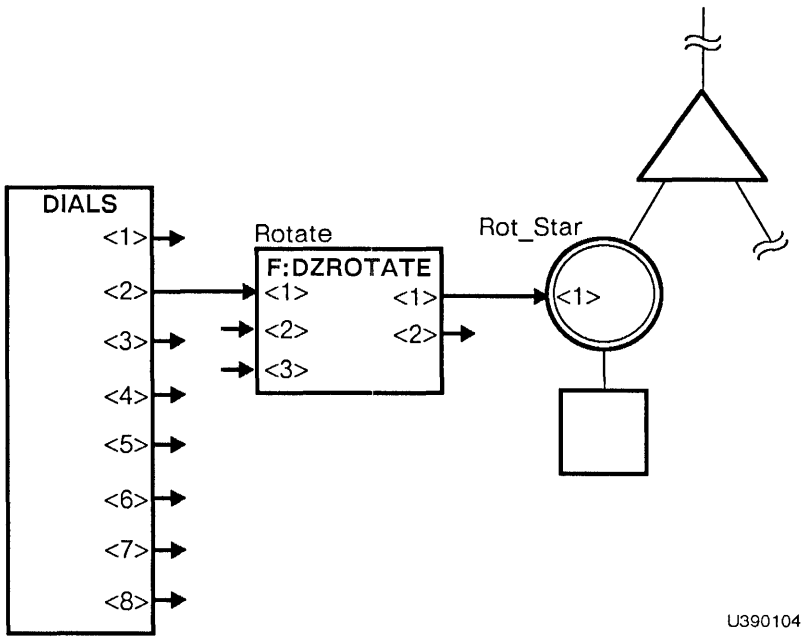

Figure 2-92. Simple Z-Rotation Network

Before the network will start to accumulate values from the dials correctly, however, inputs <2> and <3> on Rotate must be primed. The SEND command is used to send a magnification value of 50 to input <3> and an initial value of 0 to input <2> to set the accumulator to an initial value.

The final command file, with comments in braces, might read as follows.

```
Rotate := F:DZROTATE;              {Instance of Z-rotate function}
CONNECT DIALS<2>:><1>Rotate;     {Connect dial 2 to rotate function}

CONNECT Rotate<1>:<1>Rot_Star; {Connect output of rotate function}
                               {to rotate node}

SEND 0 TO <2>Rotate;               {Set accumulator to zero}
SEND 50 TO <3>Rotate;              {Multiply values from dial by}
                                    {magnification factor of 50}
```

7.3.5 Active and Constant Inputs

A function instance can have active or constant input queues. An active input receives data from an interactive device or from the output of another function instance. Input <1> of F:DZROTATE is an active input, for example. Each datum or token that arrives on an active input is a trigger for the function to execute. When the function is triggered, the datum is consumed. Constant input queues, however, are primed with a value, usually by the SEND command, and that value remains on the input queue until it is replaced by another constant value from another SEND command. For example, inputs <2> and <3> of F:DZROTATE are constant inputs. The values that are sent to those inputs prime the function. The value on input <2> sets the accumulator to an initial value. The value on input <3> is a scale factor which is used to magnify the real numbers sent from the dial.

Section *RM2 Intrinsic Functions* indicates whether a function has active or constant inputs: an input followed by a "C" in the "Intrinsic Functions" diagrams is a constant input. There is also a command named SETUP CNESS, which allows you to change the constant or active nature of function instance inputs. Refer to Section *RM1 Command Summary* for details.

7.3.6 Data-Driven Networks

Individual functions and the networks they comprise are data driven. This means that a function only becomes active when data arrive at its inputs to be processed. Once a function has executed its task, it dormant again until another set of tokens arrives. An entire network is dormant until activity occurs at the interactive device to which it is connected. As long as values are being sent out from the device, the network is active, converting and routing the data.

7.3.7 Why Function Networks?

Data driven function networks differ from conventional programming languages in that they are active only when an event occurs which produces data to be processed. Conventional programming languages are best suited for data treated as values to be looked at if necessary. Whenever data exist as asynchronous events and when the arrival of such events causes an operation to occur, then data are best handled by data-driven programs, such as function networks. Conventional programs written to handle input from interactive devices must regularly poll all the available devices to see if any activity has occurred. Once activity is detected, the type of activity has to be determined and data have to be processed accordingly.

A PS 390 with a tablet, 8 control dials, 12 function keys, 32 function buttons, a keyboard, and a communications line to the host has a total of 55 independent devices which can input data. Programming in a conventional language requires each device to be polled regularly to determine if its status has changed. Function networks, however, capitalize on the fact that few of these devices are ever used at the same time. A human user of the system has only two hands and typically uses only one or two of the devices at a time. The data-driven nature of function networks schedules operations so that devices which are unused at any time do not burden the central processing unit of the PS 390, the Joint Control Processor.

Function networks are designed to filter data and perform data formatting and selection. They filter input data, for example, reducing a stream of data indicating tablet positions to just those data when the the tip switch of the stylus is pressed. They reformat input data, converting a dial's value, for

instance, into a rotation matrix. And they select and route data, by connecting to a node in a display tree, for example, or transmitting data back to the host application program. They do not operate like conventional computer programs, as single processes whose parts communicate via subroutine calls. Instead, they are collections of autonomous, cooperative processes whose parts communicate via packages of information which are sent out while the originator of the information goes on to do something else.

7.3.8 Creating Function Networks

Function networks are created as ASCII files. They can be entered by hand or generated automatically from the graphical function network editor program, NETEDIT. This program is documented in Section *TT4 Function Network Editor*. Briefly, networks are created using a drawing program which lets you select and place symbols which represent functions. Connections are made by routing arcs between outputs and inputs, much like a wiring diagram. When a network drawing is complete, code can be generated automatically.

A network debugging aid, NETPROBE, is also available. It is documented in Section *TT5 Function Network Debugger*. For more information on networks and their use, refer to Sections *GT6 Function Networks I* and *GT7 Function Networks II*.

7.4 Summary

New Information Presented

1. Most operation nodes in a display tree can have their contents changed. Nodes that are set up for interaction have their contents updated with values from an interactive device.

2. The path between a device and a node is a function network. The network, composed of individual functions, receives data from a physical device such as a dial, manipulates those data, and produces the correct data type to update the node.

3. Networks are data driven. This means that they are only active when there is data to process.

4. Programming with PS 390 functions allows you to customize the operations of the interactive devices to suit any programming needs.

What Next?

Realtime interactive manipulation of models can be accomplished by the use of function networks, which are used to complete the path between the interactive devices and the interaction nodes in the display tree.

The next section describes how polygonal models can be rendered. The options of the POLYGON command will be described as well as a discussion of the rendering operations available with the PS 390 rendering firmware.

8. Polygonal Rendering

The PS 390 has the capability of multiple rendering operations, yielding both calligraphic quality wireframe renderings as well as shaded models. There are two types of rendering operations that may be applied to polygons; those performed in the dynamic viewport, and those performed in the static viewport. Dynamic viewport rendering operations include backface removal, sectioning by a section plane, and cross-sectioning. Static viewport rendering operations include hidden-line removal, wash, flat, Gouraud, and Phong shading.

Rendering operations have effect on polygonal models only. Vector list, text, and curve primitives are not affected by rendering operations.

Renderings are created from collections of polygons defined by the POLYGON command. A polygon is defined by the coordinates of its vertices, with the edges defined by the lines that connect those vertices. Polygons in the PS 390 are limited to a minimum of three vertices and a maximum of 250, all of which must lie in the same plane.

8.1 Defining Polygonal Objects

Polygons are defined by the POLYGON command, which defines a data node in the data structure of an object. The POLYGON command consists of one or more polygon clauses, which define an individual polygon or face of an object by specifying the coordinates of its vertices. By definition, polygons are closed implicitly, so the first vertex is not repeated when defining a polygon.

Each polygon of an object must be defined with a POLYGON clause. A POLYGON command can contain an unlimited number of polygon clauses. Each polygon clause has 3 different options which associate characteristics or attributes with the individual polygons. The vertex definition in the POLYGON command also has options to specify additional characteristics.

The POLYGON command is:

```
Name := <polygon> <polygon> ... <polygon>;
```

where each polygon clause has the definition:

```
<polygon> = [WITH ATTRIBUTES name1] [WITH OUTLINE h] [COPLANAR]
             POLYGon  <vertex> ... <vertex>
```

Following is a brief description of each of the parameters in the command, and of the vertex definition contained in the command.

WITH ATTRIBUTES is an option that assigns the attributes defined by name1 for all polygons until superseded by another WITH ATTRIBUTES clause. This option is used to specify color, diffuse reflection, specular highlights and the degree of transparency for polygons to be rendered in the static viewport. Attributes may be specified for both the front and back sides of a polygon.

WITH OUTLINE is an option that specifies the color of the outlines overlaid on polygon borders of shaded images, and the color of polygon edges in hidden-line renderings. The specifier (h) in the WITH OUTLINE clause is an index into the Spheres and Lines Attributes table.

COPLANAR declares that the specified polygon and the one immediately preceding it have the same plane equation. This option is used when defining polygons that represent cavities or holes in an object.

A <vertex> definition has the form [S] x,y,z [N x,y,z] [C h[,s[i]]]

where:

S indicates that the edge drawn between the previous vertex and the current one represents a soft edge of the polygon. If S is specified for the first vertex in a polygon definition, the edge connecting the last vertex with the first is soft.

N indicates a normal to the surface with each vertex of the polygon. Normals are used only in smooth shaded renderings. Normals must be specified for all vertices of a polygon or for none of them. If normals are not specified for a polygon, their values default to the values for the normal to the plane in which the polygon lies.

x,y, and z are coordinates in a left-handed Cartesian system.

C indicates a color to be assigned to the vertex. This color will be interpolated across the polygon to the other vertices during shading operations in a static viewport. Color must be specified for all vertices of a polygon or for none of them.

h,s,i are coordinates of the Hue/Saturation/Intensity color system.

For a more detailed explanation of the POLYGON command and its options refer to Section *GT13 Polygonal Rendering*.

8.1.1 Constructing Surfaces and Solids

There are two classes of polygons which may be defined: surfaces and solids. Solids enclose a volume of space while surfaces do not. Different types of rendering operations require specific types of models, either surfaces or solids. For example, cross-sectioning a polygonal model requires that it be defined as a solid, whereas shading a polygonal model can be done on either a surface or a solid.

Surfaces can have edges belonging to just one polygon, or edges common to three or more polygons (Figure 2-93).

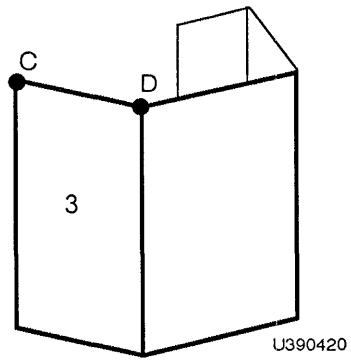

Figure 2-93. Surface Object

In a solid, each edge of a polygon must coincide with the edge of an adjacent polygon, and cannot have three or more polygons that have a single edge in common (Figure 2-94).

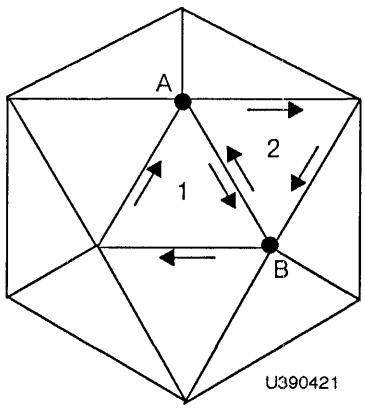

Figure 2-94. Solid Object

Determining the nature of a polygonal object, either surface or solid, is accomplished not only by the construction, but by its placement beneath a rendering node determined by the SURFACE_RENDERING and SOLID_RENDERING commands. These commands are discussed in Section 8.4.

8.2 Specifying Vertices for Surfaces and Solids

In solids, the direction in which the vertices are ordered within each polygon clause has important consequences for rendering operations. The listing of the vertices (as indicated by the order in the polygon clause) should move in a clockwise direction.

Also important is the direction of the edges in common edge pairs. In all correctly defined solids, each edge is repeated in two different polygons. For each pair of adjacent polygons, the common edges should run in opposite directions. This is true for any edge of any correctly defined solid (Figure 2-95).

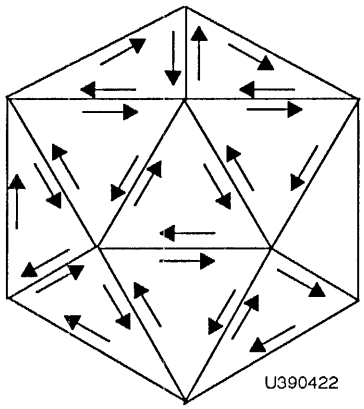

Figure 2-95. Correctly Constructed Icosahedron

For surfaces, the vertex ordering rule is less stringent. Vertices in surfaces do not have to be ordered in a clockwise direction, although if so defined, provide for easy upgrade to solids. Although the vertices of a surface do not need to be ordered in a clockwise direction, they should be ordered so that common edges of adjacent polygons run in opposite directions.

8.3 Memory Requirements

Rendering operations require a large block of mass memory be available as working storage. Before the rendering process can execute, a workspace must be reserved in mass memory. The PS 390 can automatically calculate the required working storage for you, or you may explicitly reserve it yourself. To have the system calculate the working storage for you, enter the command:

```
RESERVE WORKING STORAGE 0;
```

The PS 390 will automatically calculate the amount of memory required, and will display the total memory used at the completion of the rendering operation.

System calculation of working storage is more efficient in memory usage, but requires extra time during the rendering process. To avoid this, working storage may also be reserved explicitly. The best time to reserve working storage is immediately after booting, when large requests can be filled easily.

Between 200,000 to 400,000 bytes of working storage should be reserved when you begin a session. This is also done with the RESERVE_WORKING_STORAGE command. The command syntax for reserving working storage is:

```
RESERVE_WORKING_STORAGE n;
```

where the current working storage is replaced with another containing at least n bytes.

8.4 Creating Renderings

A polygonal object must be defined as either a surface or solid before rendering operations can be applied to it. The commands to do this are:

```
SURFACE_RENDERING
SOLID_RENDERING
```

The SURFACE_RENDERING command creates an operation node in the data structure. The default value of this command declares that all of its descendant polygon data nodes define surfaces.

The SOLID_RENDERING command also creates an operation node in the data structure. The default value of this command declares that all of its descendant polygon data nodes define solids.

A POLYGON data node can be displayed by itself. However, if the object is to be rendered, it must have a rendering node as an ancestor. All rendering and display operations involving the object are done with the rendering node rather than the data node itself.

Syntax for the rendering commands is:

```
Name := SURFACE_RENDERING APPLIED TO Name1;
Name := SOLID_RENDERING APPLIED TO Name1;
```

where:

Name1 names either (a) a POLYGON node, or (b) an ancestor of one or more POLYGON nodes. If (b) is the case, then any rendering referring to Name is performed on all of the POLYGON objects descended from Name1 at once.

An appropriate integer sent to a SOLID_RENDERING or SURFACE_RENDERING node produces a rendering of that node's descendant polygonal object. Refer to Sections *RM1 Command Summary* and *GT13 Polygonal Rendering* for more information on the rendering commands.

8.5 Rendering Operations

There are two types of rendering operations available with the PS 390. Rendering operations are divided into those performed in the dynamic viewport and those performed in the static viewport. Rendering operations performed in the dynamic viewport include the following:

- Backface removal (for solid wireframe polygonal models)
- Sectioning (for solid or surface wireframe polygonal models)
- Cross-sectioning (for solid wireframe polygonal models)

8.5.1 Backface Removal

Backface removal provides an approximation of a hidden-line rendering's appearance. In backface removal, all polygons facing away from the viewer are removed. Because the backface removed rendering resembles an unfinished hidden-line rendering, it can be used to give a rough idea of the hidden-line rendering.

Only solids can be subjected to backface removal; the operation has no visual effect on surfaces.

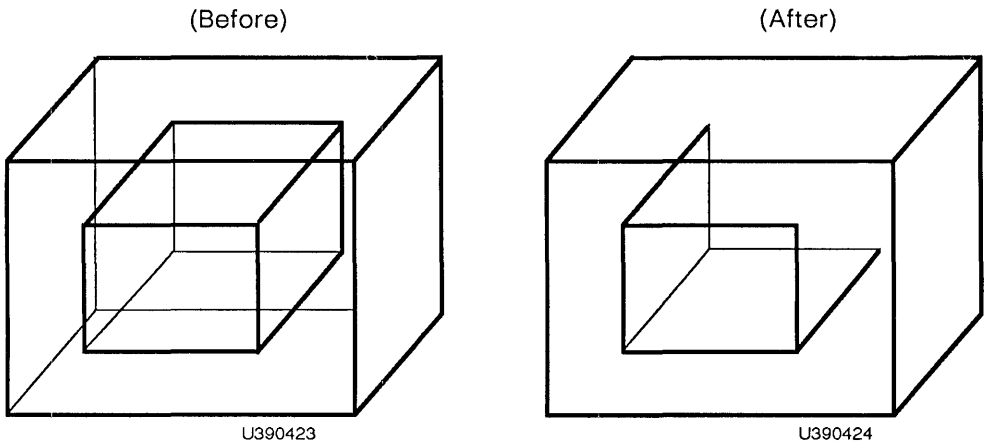

Figure 2-96. Object Before and After Backface Removal

8.5.2 Sectioning

Sectioning makes use of a sectioning plane that passes through an object and divides the object into two pieces. This operation yields a "cutaway view" of the object. The part of the object that is behind the plane is discarded and only the front section of the object is displayed.

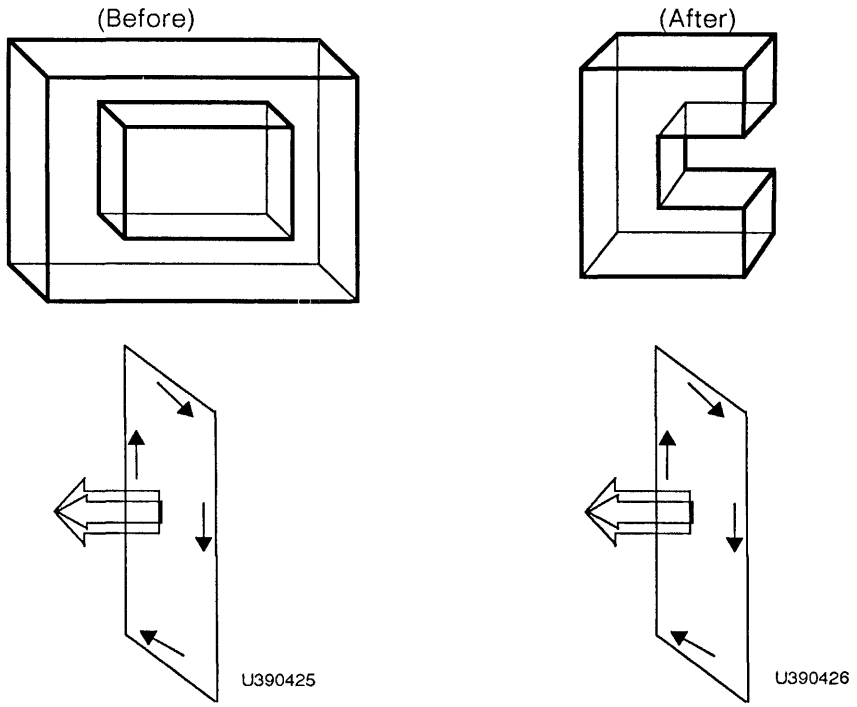

Figure 2-97. Object Before and After Sectioning

A sectioned object may be saved and then subjected to further rendering operations such as resectioning, or backface removal.

8.5.3 Cross-sectioning

The cross-sectioning operation makes use of a defined sectioning plane to create a cross section of an object. When this operation is used, both sides of the object are discarded and only the slice defined by the sectioning plane remains. Cross-sectioning has effect on solid polygonal models only.

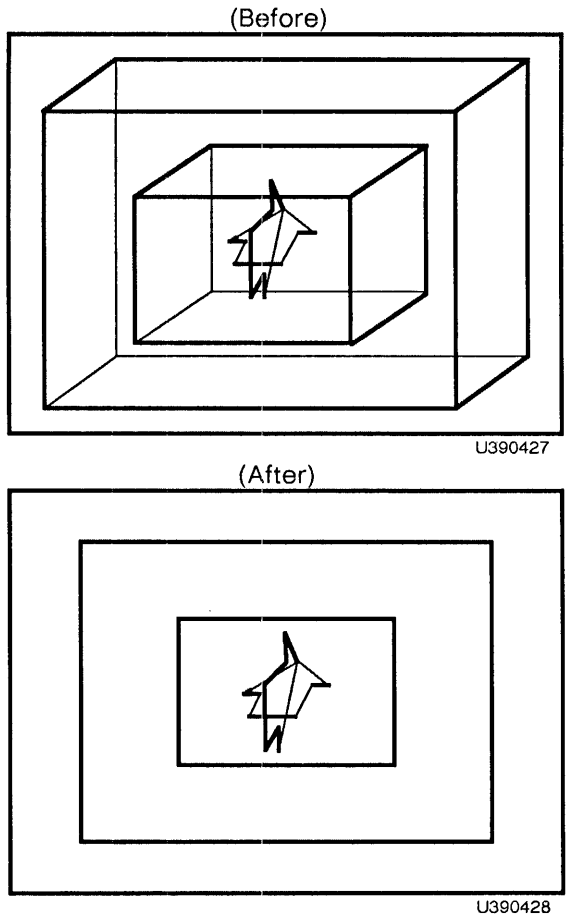

Figure 2-98. Object Before and After Cross-Sectioning

8.5.4 Static Viewport Renderings

Rendering operations that apply to objects in a static viewport include hidden-line removal, wash shading, flat shading, Gouraud shading, and Phong shading.

8.5.5 Hidden-Line Removal

Hidden-line removal generates a view in which only the unobstructed portions of an object are displayed. All polygon edges or parts of edges that would be obscured by other polygons are removed.

Hidden-line removal may be performed on both solids and surfaces.

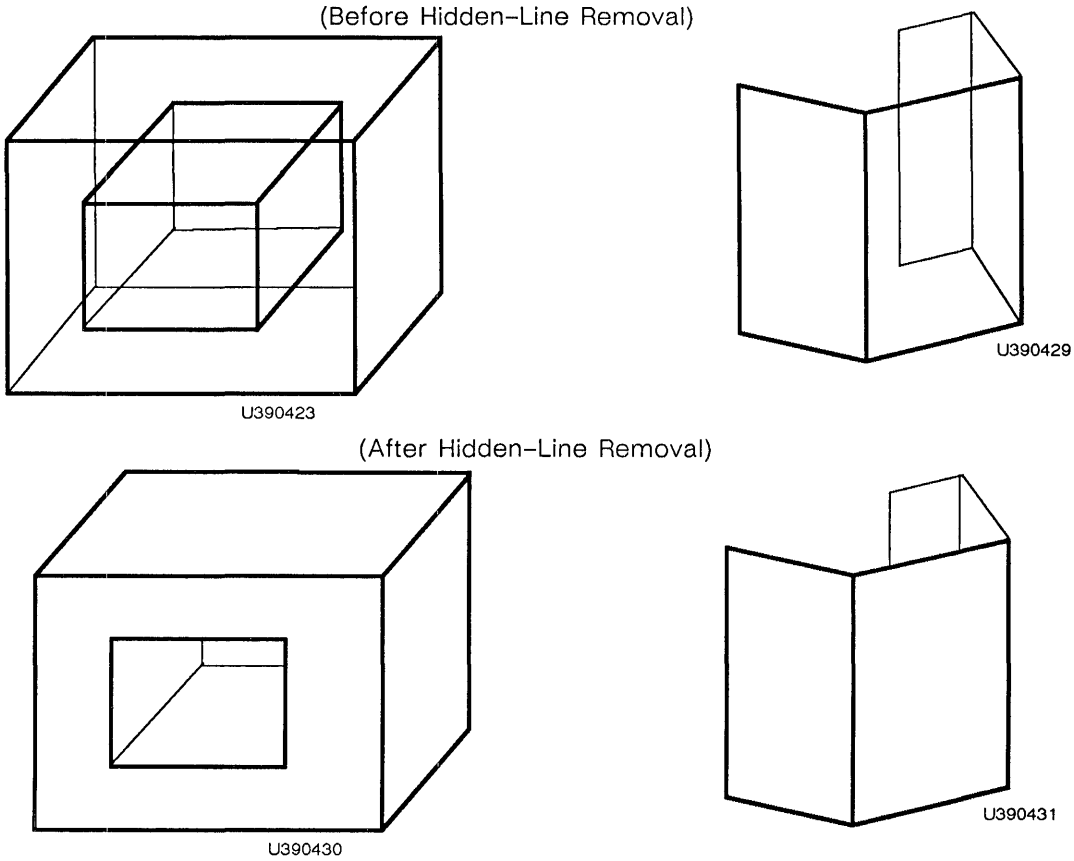

Figure 2-99. Object Before and After Hidden-Line Removal

8.5.6 Wash Shading

Wash shading is the quickest and most simple of the shading operations. Wash shading produces an object with area-filled colored polygons ignoring normals, light sources, all lighting parameters, and all depth cuing parameters. This operation does not produce objects that simulate a curved surface.

8.5.7 Flat Shading

Flat shading considers color, one light source, and depth cuing to shade the polygons in the object accordingly. Flat shading produces a faceted surface.

8.5.8 Gouraud and Phong Shading

Gouraud and Phong shading are both examples of smooth shading. These shading processes are the most complex of all the shading styles. The color of a polygon is varied across its surface, considering the normals at the vertices of the polygon, the direction and color of various active light sources, the attributes of the polygon (both color and highlights), and depth cueing. Objects that simulate a curved surface can be produced with both Phong and Gouraud shading.

8.6 SHADINGENVIRONMENT Function

The initial function instance SHADINGENVIRONMENT allows you to control various non-dynamic factors of shaded renderings. This function controls factors that affect the total environment in which shading operations are performed, as well as specific polygonal characteristics. Things such as background color, viewport specification, polygon edge enhancement, edge smoothing, and transparency are controlled by the SHADINGENVIRONMENT function.

For more information on rendering operations and the SHADINGENVIRONMENT function, refer to Section *GT13 Polygonal Rendering*.

8.7 Summary

1. Polygons are defined by the POLYGON command, which defines a data node in the data structure of an object. Polygonal objects are the only objects eligible for rendering operations.

2. The POLYGON command has the syntax:

```
Name := <polygon> <polygon> ... <polygon>;
```

   where each polygon clause has the definition:

```
<polygon> = [WITH ATTRIBUTES name1] [WITH OUTLINE h] [COPLANAR]
            POLYGON  <vertex> ... <vertex>
```

3. A polygon must be defined as a surface or solid before rendering operations can be applied. The commands to do this are:

```
SURFACE_RENDERING
SOLID_RENDERING
```

4. All types of rendering operations require an ancestral rendering node. The syntax for the rendering commands is:

```
Name := SURFACE_RENDERING APPLIED TO Name1;
Name := SOLID_RENDERING APPLIED TO Name1;
```

   where Name1 names either a POLYGON node or an ancestor of one or more POLYGON nodes.

5. Rendering operations require a large block of mass memory. This working storage may be reserved automatically by the system or you may reserve it explicitly. To have the system allocate working storage, the command is:

```
RESERVE_WORKING_STORAGE 0;
```

   To explicitly reserve a block of memory, the syntax of the command is:

```
RESERVE_WORKING_STORAGE n;
```

   where n is the size of the block you wish to reserve.

6. Dynamic viewport renderings include backface removal, sectioning by a section plane, and cross-sectioning.

7. Static viewport renderings include hidden-line removal, and wash, flat, Gouraud, and Phong shading styles.

8. The initial function instance SHADINGENVIRONMENT controls factors affecting the total environment in which shaded renderings occur, as well as specific polygonal characteristics.

GT3. TUTORIAL DEMONSTRATIONS

PS 390 TUTORIAL DEMONSTRATIONS

LIMITED SUPPORT DISCLAIMER

The PS 390 Tutorial Demonstrations are distributed by Evans & Sutherland as a convenience to customers and as an aid to understanding the capabilities of the PS 390 graphics systems. Evans & Sutherland Customer Engineering supports the Tutorial Demonstrations to the extent of answering questions concerning the installation and operation of the programs, as well as receiving reports on any bugs encountered while the programs are running. However, Evans & Sutherland makes no commitment to correct any errors which may be found.

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GT3. PS 390 TUTORIAL DEMONSTRATIONS

CONTENTS

Section GT3
PS 390 Tutorial Demonstrations

1. Introduction to the Tutorial Demonstrations

The eight Tutorial Demonstration programs are designed to clarify graphics programming concepts explained in the tutorial sections of the *PS 390 Document Set*.

The programs display images you can interact with using the data tablet, control dials, and function keys. Typically, the keys and dials are programmed to translate, rotate, and scale the objects displayed and to change the values in the PS 390 graphics programming commands that are being illustrated. Programmed operations are shown in the LED displays above each control dial or function key.

The following concepts are illustrated in the programs.

- **Programming the PS 390**

  In three separate areas of the screen, you are shown a sequence of PS 390 commands, a representation of the structures these commands create in memory, and the picture that the commands produce on the screen. As you scroll through the commands, the contents of memory and the screen display are changed when each command takes effect.

- **Windows and Viewports**

  This program illustrates the mapping of an orthographic window in the world coordinate system to a viewport on the PS 390 screen. In one area of the screen, a sphere is shown enclosed in a window. In another, the sphere is shown as it appears when displayed on the PS 390 screen. To the side, the variables used in the WINDOW and VIEWPORT commands are listed. Using function keys and dials, you can change the dimensions of the window and the viewport and control the size and orientation of the sphere. The relation between windows and viewports is clearly shown in the resulting changes to the displayed image of the sphere.

- **The FIELD_OF_VIEW Command**

  To demonstrate the FIELD_OF_VIEW command, a sphere is shown enclosed in a perspective viewing area. In another portion of the display, the sphere is shown as it would appear on the PS 390 screen. The values entered in the FIELD_OF_VIEW command are listed to one side. Using dials you can change the viewing angle and front and back boundaries of the viewing area to see how the image of the sphere is affected on the screen.

- **The LOOK Command**

  This program shows how the LOOK command rotates and translates all points in the world coordinate system to simulate a vantage point and a line of sight towards an object. One area of the screen shows a collection of objects and an eye that can be moved in any direction to change values in the LOOK command. A second area shows the rotations and translations that are performed by the PS 390 to create the view specified in the LOOK command. A third area shows the screen display. Dials are programmed to change the "at" and "from" points in the LOOK command and to change the "up" vector.

- **Character Modes**

  The three ways in which characters can be used in an image are illustrated in this program. Three cubes are displayed with each of their faces labeled. The cubes can be rotated, translated, and scaled using control dials. The first cube contains world-oriented characters which are transformed with the cube. The second cube contains screen-oriented characters which always remain at the same size and in a plane parallel to the screen, so that they are always legible. The third cube contains screen-oriented characters which are "fixed" so that they do not vary in intensity as they move forwards and backwards (in the Z axis).

- **Level of Detail Settings**

  This demonstration shows how level-of-detail nodes can be used in a structure to display changing images of an object in response to changing values from a function network. A display structure is shown with a SET node connected to a network and IF nodes at the head of each of twelve hierarchial branches. As the value in the SET node is updated from the

network, a different branch is traversed. This produces an animation sequence of 12 frames in which the ends of a cylinder twist and untwist in opposite directions.

- **Execution of a Function Network**

  This program illustrates the relationship between interactive devices, function networks, interactive nodes in a display structure, and a dynamically changing image. In one area of the screen, an object is shown which consists of two wheels and a tie-bar. A display structure is shown for the structure of this object. The structure contains interactive rotation and translation nodes connected to a dial through a function network. As you turn the dial to rotate the wheels, the function network is shown accepting data, converting it to matrices, and updating the nodes in the display structure.

- **Picking**

  To illustrate picking, this program shows a collection of objects consisting of two cubes, a B-spline curve, a character string and a labels block. The display structure for these objects is shown with the required SET PICKING node and pick identifier nodes. A picking network is connected to the display structure. When a vector, character, or label is picked, the branch traversed in the display structure is highlighted and the information returned from the pick on the outputs of the function F:PICKINFO is shown.

This manual explains how to install the Tutorial Demonstrations and how to run each of the programs.

The first section describes the components of the Tutorial Demonstrations and explains the interactive devices and host computer requirements for running the demonstrations.

The second section explains how to install the Tutorial Demonstration programs on your system.

The third section gives complete operating instructions for each of the programs.

1.1 The Components of the Tutorial Demonstration Package

The PS 390 Tutorial Demonstration package consists of several files distributed on magnetic tape.

The tape contains control networks, the Tutorial Demonstrations Menu from which programs are chosen, the programs themselves, and several character fonts. Also included are the vector lists for the primitives used in the tutorial sections of the *PS 390 Document Set*.

1.2 Required Interactive Devices

The following interactive devices are required to run the Tutorial Demonstration programs.

- Data Tablet and Stylus
- Keyboard with Function Keys
- Control Dials

The data tablet and stylus are used to pick programs from the menu and to interact with the objects displayed by some of the programs. The function keys and control dials are programmed through function networks to perform various graphical operations such as scaling, rotating, and translating the images displayed and to change dynamically the values in the PS 390 commands being illustrated. The operation controlled by each function key and control dial is displayed in its red LED label.

1.3 Host Computer Requirements

The eight programs that comprise the Tutorial Demonstrations are run locally on the PS 390. There are no host computer requirements for running the programs.

The files that are distributed on the tape must be loaded onto a host computer and then transferred to the PS 390. There are two requirements for the host computer for storing and transferring the files. First, it must have sufficient memory to contain the files on the tape: approximately 1166K bytes are needed. Second, the host must be able to communicate with the PS 390 so that the files can be transferred.

2. Accessing the Tutorial Demonstrations

The complete Tutorial Demonstrations package takes between 15 and 20 minutes to transfer from the host to the PS 390, depending on the current work load on the host.

2.1 Using the Tutorial Command File

Individual sites will need to set up a method on the host computer to gain access to the Tutorial Demonstrations as well as the objects that are required by some of the tutorial sections and the sample programs. A command file displaying the following menu should be available.

```
                PS 390 GRAPHICS PROGRAMMING TUTORIAL

Set to be loaded          First used in section ...

1. Demonstrations
2. Sports Car             GT5. "PS 390 Command Language"
3. Molecule               GT9. "Conditional Referencing"
4. Complete Robot         GT6. "Function Networks I" & GT7.
                               "Function Networks II"
5. Sphere and Cylinder    GT5. "PS 390 Command Language" & GT9.
                               "Conditional Referencing"
6. Sample Programs        GT16. "Sample Programs"

Enter the number of the selection you want. Loading is complete when
the host operating system prompt is displayed again.
```

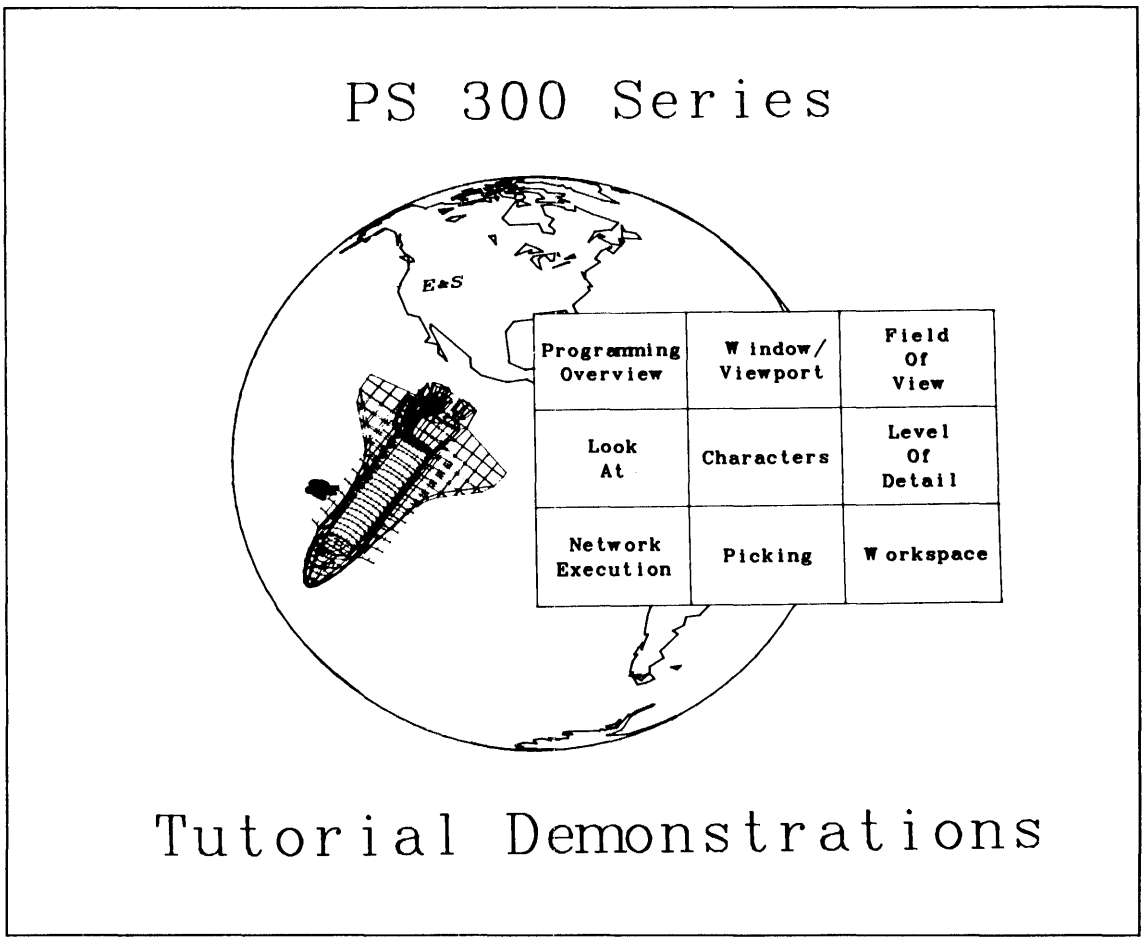
3. Running the Tutorial Demonstration Programs

This section describes how to run each of the Tutorial Demonstration programs. Each description is organized as follows.

Typical screen displays are illustrated. An abstract points out some of the features of the PS 390 that are shown in the demonstration. The programmed functions and the LED labels that appear on control dials and function keys are listed. Notes on usage give instructions for running the program.

3.1 Program: TUTORIAL DEMONSTRATION MENU - GLOBE AND SHUTTLE

Typical Program Display



Abstract

This program serves both as a demonstration in itself and as the menu from which the other Tutorial Demonstration programs are picked. Several windows and viewports are combined to produce a very complex dynamic image. In the center of the screen is the earth spinning on its axis. Orbiting the earth is a Space Shuttle, and closely hugging the shuttle in a tight orbit of his own is one of the crew in a Manned Maneuvering Unit. Overlapping the globe to the right is the menu from which the programs are selected.

Programmed Functions

Control Dials	Function Keys
D1 - OS X ROT (globe and shuttle)	F10 - STRT/STP
D2 - OS Y ROT (globe and shuttle)	F11 - RESET
D3 - OS Z ROT (globe and shuttle)	

Notes on Usage

To use this program as a menu, pick the demonstration you want to run by positioning the cursor over the name and pressing the stylus down on the data tablet. Whenever you exit from a program by pressing F12, you are returned to this display.

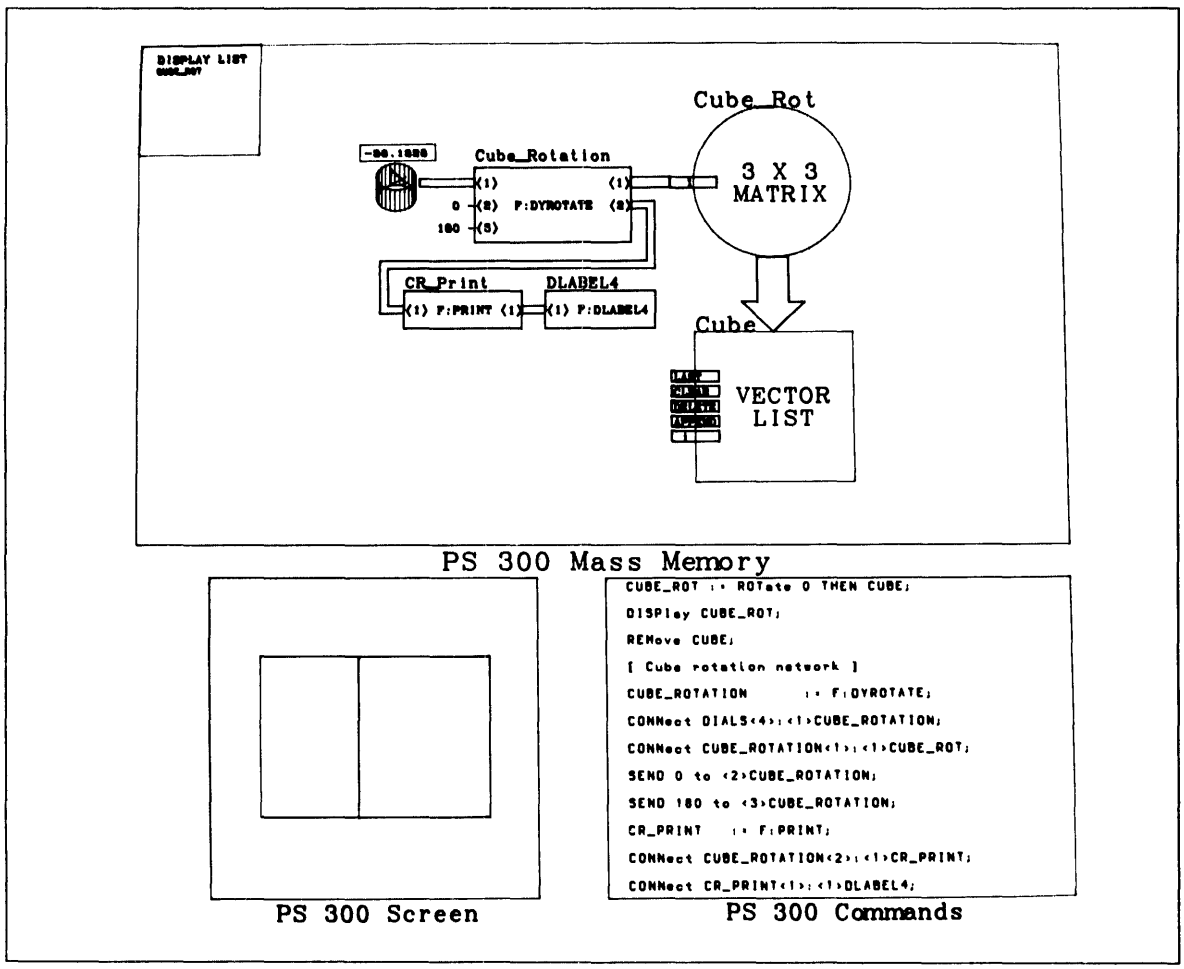
The function keys and dials let you interact with the spinning globe and space shuttle displayed in the center of the screen. Dials 1 through 3 let you rotate the globe and shuttle around the X, Y, or Z axes. The "OS" in the dial labels stands for Object Space. An object rotates in Object Space when it rotates about a set of axes which are different from the world coordinate system axes.

Function key F10 starts and stops the rotation of the globe and shuttle.

Function key F11 resets the orientation of the globe and shuttle.

3.2 Program: PROGRAMMING

Typical Program Display



Abstract

This is a graphical introduction to programming the PS 390 with commands and function networks. It illustrates how PS 390 commands create structures in memory and affect images being displayed, as well as how some of the interactive devices are programmed with simple networks.

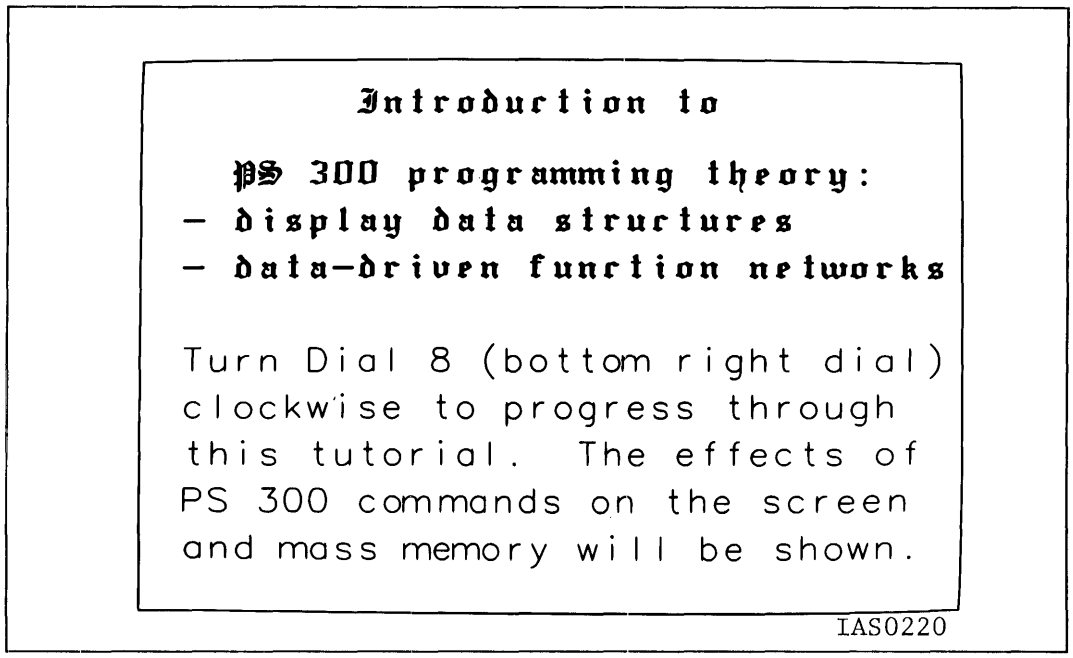
After an initial introductory message, the screen is divided into four viewports representing the contents of the display list, the contents of mass memory, the PS 390 screen, and commands which are entered. When you turn control dial 8, commands appear in the Commands viewport. Each time a complete command is displayed, the display in the other viewports is changed to reflect updates to mass memory, the display list, or the PS 390 screen.

Programmed Functions

Control Dials	Function Keys
D4 - (rotate the object displayed)	F1 - (used with conditional
D8 - (progress through program)	F2 - referencing commands)
	F11 - RESET
	F12 - EXIT

Notes on Usage

When the Programming demonstration is chosen, the following message is displayed.



Dial 8 controls your progress through this program. As you turn the dial, the PS 390 commands will scroll in the lower right viewport of the screen. As the semicolon terminator for each command becomes visible, the effect of the command will be reflected in the other viewports on the screen. Function keys F1 and F2 and control dial 4 become active as the commands controlling them become visible.

Notes on Usage (continued)

The program starts by showing how the VECTOR_LIST command creates a data node (shown as a square) called CUBE in memory. Nothing appears on the screen or in the Display List, however, until the DISPLAY command is used. A rotation node (shown as a circle) called CUBE_ROT is created in memory using the ROTATE command. Since this command is applied to CUBE, the node becomes part of the same display structure. The two entities are displayed simultaneously as one bright cube, because the display processor is traversing both nodes. CUBE is then removed from the display list and CUBE_ROT is displayed alone.

Next, the capability of the PS 390 to do graphical manipulations locally is shown through the use of functions. An instance of the Y-rotation function F:DYROTATE is created and connected to control dial 4. This dial can now be turned to rotate the cube displayed in the PS 390 Screen viewport. To see the value of the rotation, an instance of the print function (F:PRINT) is created and connected to dial label 4. When dial 4 is turned, the value of the rotation will now be displayed in dial 4's LED and in the mass memory viewport.

A scale node named CUBE_S is now created and applied to CUBE. This shows how one vector list can be displayed in two different ways, one through CUBE_ROT, and one through CUBE_S. Now an instance node (a triangle) called VIEW is created, the display is initialized, and VIEW is displayed. At first, VIEW groups nothing more than the rotation node CUBE_ROT and the data node CUBE. Then the INCLUDE command is used to include CUBE_S in VIEW also, so both CUBE_ROT and CUBE_S are displayed with the one display command.

CUBE_S is then redefined as a 2x2 scaling matrix applied to CUBE_CHAR, a null structure which has not yet been defined. CUBE_CHAR is then defined as the character string "PS 390", which is displayed on the screen. CUBE_S is now redefined to be a special 2x2 skewing matrix to italicize the characters. Using an alternate character font, the string is then displayed in an Old English character set.

Notes on Usage (continued)

The LOOK command is used to view the structure being displayed from an arbitrary point in space. The use of BEGIN_STRUCTURE ... END_STRUCTURE is shown as an alternative to naming every command. The FIELD_OF_VIEW command is applied to the structure to create a perspective view of the cube.

The display structure is next enhanced to include conditional references to different branches of the hierarchy. Function keys are connected to the SET LEVEL_OF_DETAIL node. F1 controls display of one branch of the hierarchy, F2 controls display of the other. A similar operation is performed with the SET CONDITIONAL_BIT node, but now the objects can be displayed independent of each other, as determined by the CONDITIONAL_BIT test. The cube is displayed if conditional bit one is set, the text if bit two is set. Another way to conditionally branch is shown, using the SET RATE node. The number of refresh frames on and off are given, and a phase attribute is set so that for 20 frames, the phase attribute is on and for 40 frames it is off. By doing a test of the phase attribute, the cube is displayed for 20 frames and the text for 40 frames.

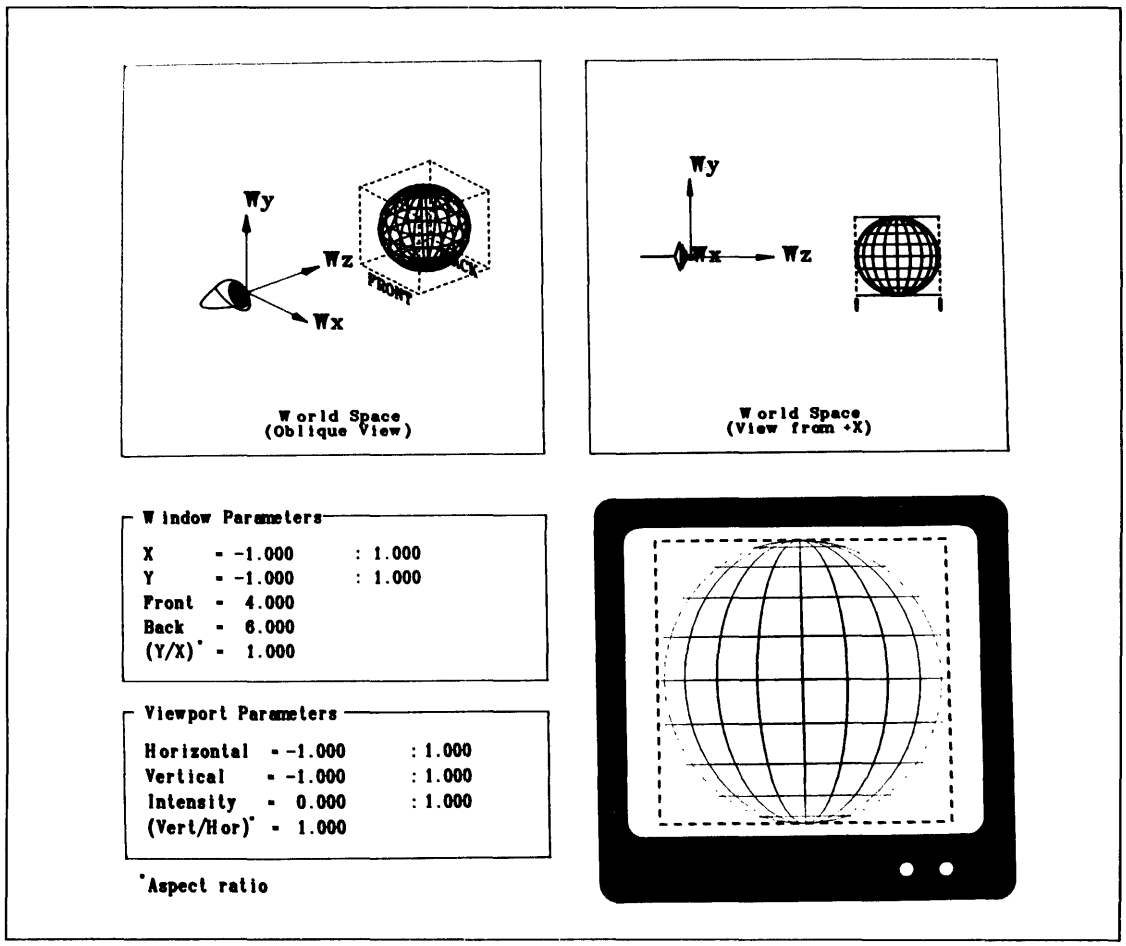
Note that you can go back through the program by turning dial 8 in the opposite direction.

Function key F11 resets the screen to the initial display.

Function key F12 leaves this program and displays the Tutorial Demonstrations Menu again.

3.3 Program: WINDOW/VIEWPORT

Typical Program Display



Abstract

This program shows the relationship between windows and viewports and illustrates the use of the WINDOW and VIEWPORT commands.

Two areas of the screen show two views of the world coordinate system, one from the +X axis, and one from an oblique angle. A sphere is shown in the world coordinate system enclosed in an orthographic window. Another area of the screen shows the sphere as it would de displayed on the PS 390 screen in a full-screen viewport. Values for the WINDOW and VIEWPORT commands are shown to the left.

Abstract (continued)

In one mode of operation, dials let you change the X and Y values of the window and the location of the front and back boundaries. In another mode, the dials change the horizontal and vertical values of the viewport and the intensity setting. The aspect ratio for the window (X/Y) and for the viewport (vertical/horizontal) are also shown.

Programmed Functions

Mode 1

Control Dials

```
D1 - WIN XMIN (window's minimum X value)
D2 - WIN YMIN (window's minimum Y value)
D3 - WIN ZMIN (window's minimum Z value)
D4 - unused
D5 - WIN XMAX (window's maximum X value)
D6 - WIN YMAX (window's maximum Y value)
D7 - WIN ZMAX (window's maximum Z value)
D8 - unused
```

Mode 2

Control Dials

```
D1 - W X CENT (move window along X axis)
D2 - W Y CENT (move window along Y axis)
D3 - W Z CENT (move window along Z axis)
D4 - unused
D5 - OBJ XROT (rotate objects around the X axis)
D6 - OBJ YROT (rotate objects around the Y axis)
D7 - OBJ ZROT (rotate objects around the Z axis)
D8 - OBJ SIZE (scale objects)
```

Mode 3

Control Dials

```
D1 - VP H MIN (viewport's minimum horizontal value)
D2 - VP V MIN (viewport's minimum vertical value)
D3 - VP I MIN (viewport's minimum intensity value)
D4 - VP HCENT (move viewport along X axis)
```

Programmed Functions (continued)

Control Dials

```
D5 - VP H MAX (viewport's maximum horizontal value)
D6 - VP V MAX (viewport's maximum vertical value)
D7 - VP I MAX (viewport's maximum intensity value)
D8 - VP VCENT (move viewport along Y axis)
```

Function Keys

```
F1 - MODE 1
F2 - MODE 2
F3 - MODE 3
F4 - DEPTH CL (depth clipping)
F11 - RESET
F12 - EXIT
```

Notes on Usage

In Mode 1 (when function key F1 is pressed) the dials change the window's X, Y, and Z minimum and maximum values.

In Mode 2 (when function key F2 is pressed) the dials let you move the window along the X, Y, and Z axes and rotate and scale the sphere.

In Mode 3 (when function key F3 is pressed) the dials let you change the vertical and horizontal minimum and maximum values for the viewport and the minimum and maximum values for the intensity range. In this mode of operation, you can also move the viewport along the X and Y axes.

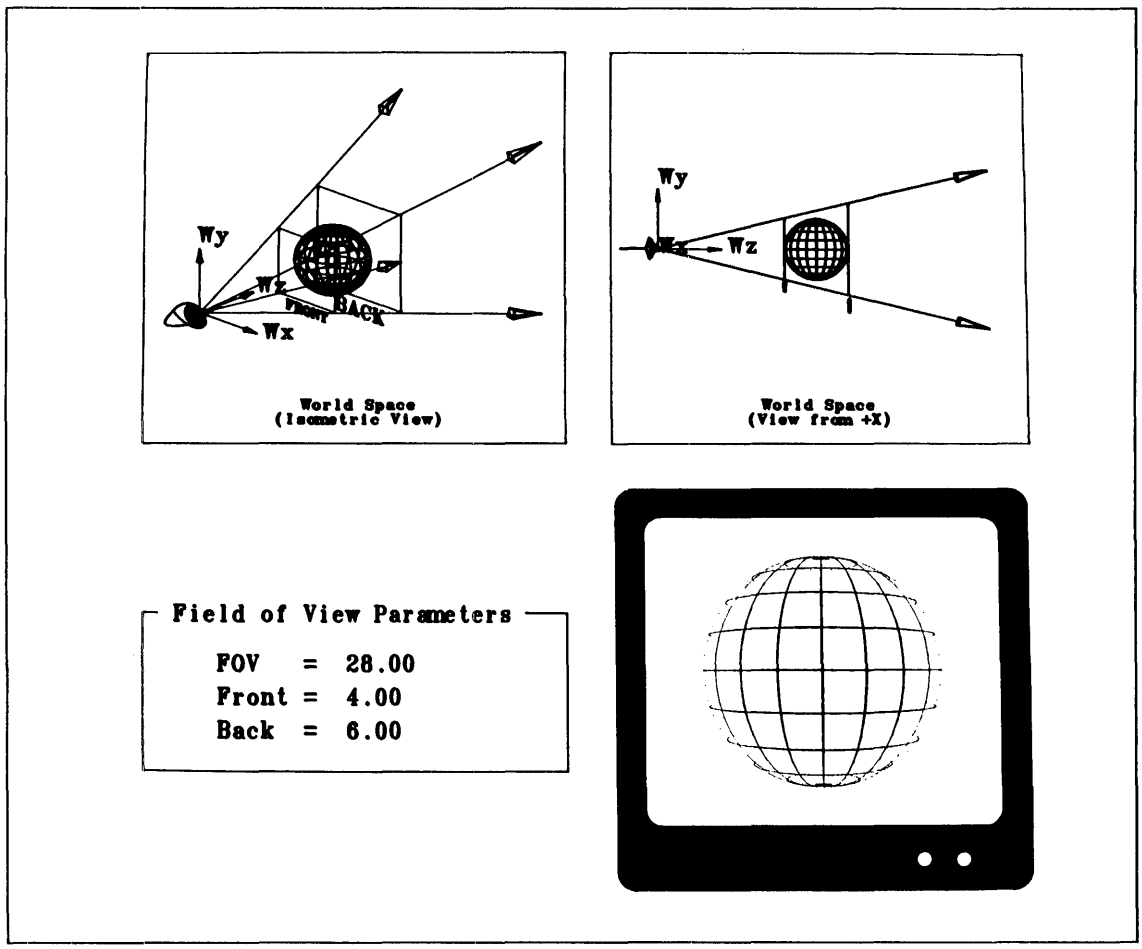
Depth clipping is on when the program is first called. Use function key F4 to turn it on and off.

Function key F11 resets the program.

Function key F12 leaves the program and displays the Tutorial Demonstrations Menu again.

3.4 Program: FIELD_OF_VIEW

Typical Program Display



Abstract

Perspective views of objects are created using the FIELD_OF_VIEW command. This program illustrates how to use that command. Two viewports show the world coordinate system from two different vantage points. In each, a sphere is shown enclosed in a perspective viewing area. A third viewport shows the sphere as it would be displayed on the PS 390 screen. Values for command variables (viewing angle and front and back boundaries) are also shown. Dials allow you to change the viewing angle, the location of front and back boundaries, and the size and orientation of the sphere.

Programmed Functions

Control Dials	Function Keys
D1 - WS X ROT	F11 - RESET
D2 - WS Y ROT	F12 - EXIT
D3 - WS Z ROT	
D4 - SCALE	
D5 - FOV ANGL (field-of-view angle)	
D6 - FRONT	
D7 - BACK	
D8 - BOTH	

Notes on Usage

The FIELD_OF_VIEW command (abbreviated to FOV) encloses an object in a viewing space shaped like a frustum (a section of a pyramid). The eye point, established by the LOOK command, is at the apex of the pyramid. The top and bottom planes of the frustum are the front and back boundaries in the FOV command.

Dials 1 through 4 manipulate the sphere, allowing you to rotate and scale it.

Dial 5 controls the viewing angle. Notice that as the angle increases, the size of the image on the screen shrinks and vice versa. A larger viewing angle encloses more of the coordinate system in the viewing space, a smaller viewing angle encloses less.

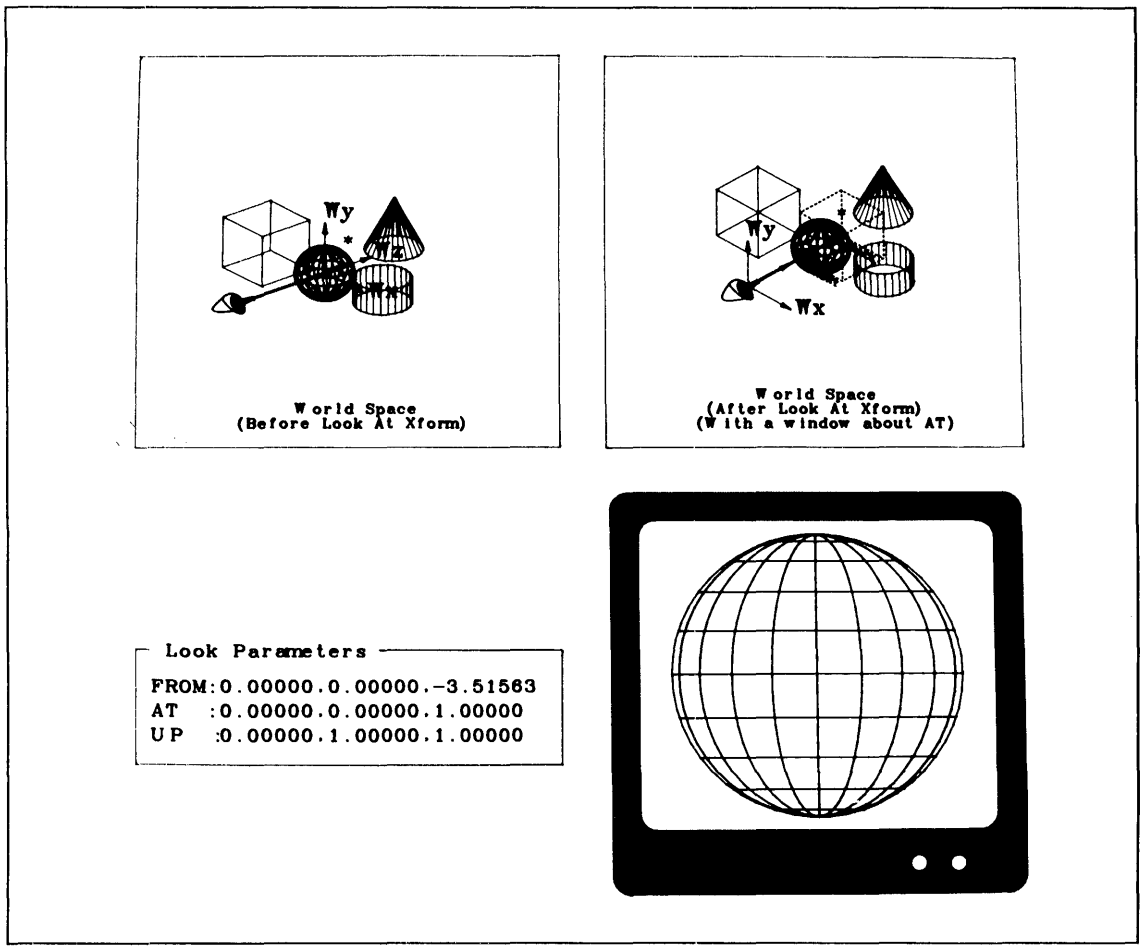
Dials 6 through 8 move the front and back boundaries (clipping planes) of the viewing area. Dial 8 moves both boundaries together.

Function key F11 resets the program.

Function key F12 leaves the program and displays the Tutorial Demonstrations Menu again.

3.5 Program: LOOK AT

Typical Program Display



Abstract

This deceptively simple program illustrates how the LOOK command works. In one viewport, the world coordinate system is shown containing a cube, sphere, cone, and cylinder, the three axes, and an eye. This viewport represents the world coordinate system before the LOOK transformation is applied to the objects. A second viewport shows the coordinate system after the transformation has taken place. A third area shows the values for the "from," "at," and "up" points. A fourth area shows the PS 390 screen and the objects being displayed.

Mode 1

Control Dials

```
D1 - FROM X
D2 - FROM Y
D3 - FROM Z
D4 - WS Y ROT (world space Y rotation)
D5 - DOLLY X (rotate eye point around the X axis)
D6 - DOLLY Y (rotate eye point around the Y axis)
D7 - DOLLY Z (rotate eye point around the Z axis)
D8 - FOR/BACK (move eye point forward and back along Z axis)
```

Mode 2

Control Dials

```
D1 - AT X
D2 - AT Y
D3 - AT Z
D4 - unused
D5 - OBJ XROT (rotate objects around the X axis)
D6 - OBJ YROT (rotate objects around the Y axis)
D7 - OBJ ZROT (rotate objects around the Z axis)
D8 - OBJ SIZE (scale objects)
```

Mode 3

Control Dials

```
D1 - UP X
D2 - UP Y
D3 - UP Z
D4 - unused
D5 - OBJ XTRAN (translate objects along the X axis)
D6 - OBJ YTRAN (translate objects along the Y axis)
D7 - OBJ ZTRAN (translate objects along the Z axis)
D8 - unused
```

Programmed Functions (continued)

Function Keys

```
F1 - MODE 1
F2 - MODE 2
F3 - MODE 3
F4 - DEPTH CL (depth clipping)
F5 - MOVE UP (move/don't move "up" point with the eye point)
F11 - RESET
F12 - EXIT
```

Notes on Usage

The LOOK transformation is a 4x3 transformation matrix. It applies a translation and rotation to every point in the world coordinate system to produce a view which corresponds to the "from," "at," and "up" points given in the LOOK command.

All points are translated so that the eye is at the origin, and rotated so that the "at" point is in the positive Z axis and the "up" vector is in the YZ plane. These transformations are shown in the second viewport.

A window is built around the "at" point in the second viewport so that whatever is being looked at will appear on the PS 390 display in the third viewport. Initially, the sphere is displayed. As you manipulate the "at" point, the window is moved also to maintain a display on the simulated PS 390 screen.

The "up" point is shown as an asterisk. Function key F5 is a toggle which lets you move or not move the "up" point with the "from" and "at" points.

Function key F4 is a toggle which lets you turn depth-clipping on and off.

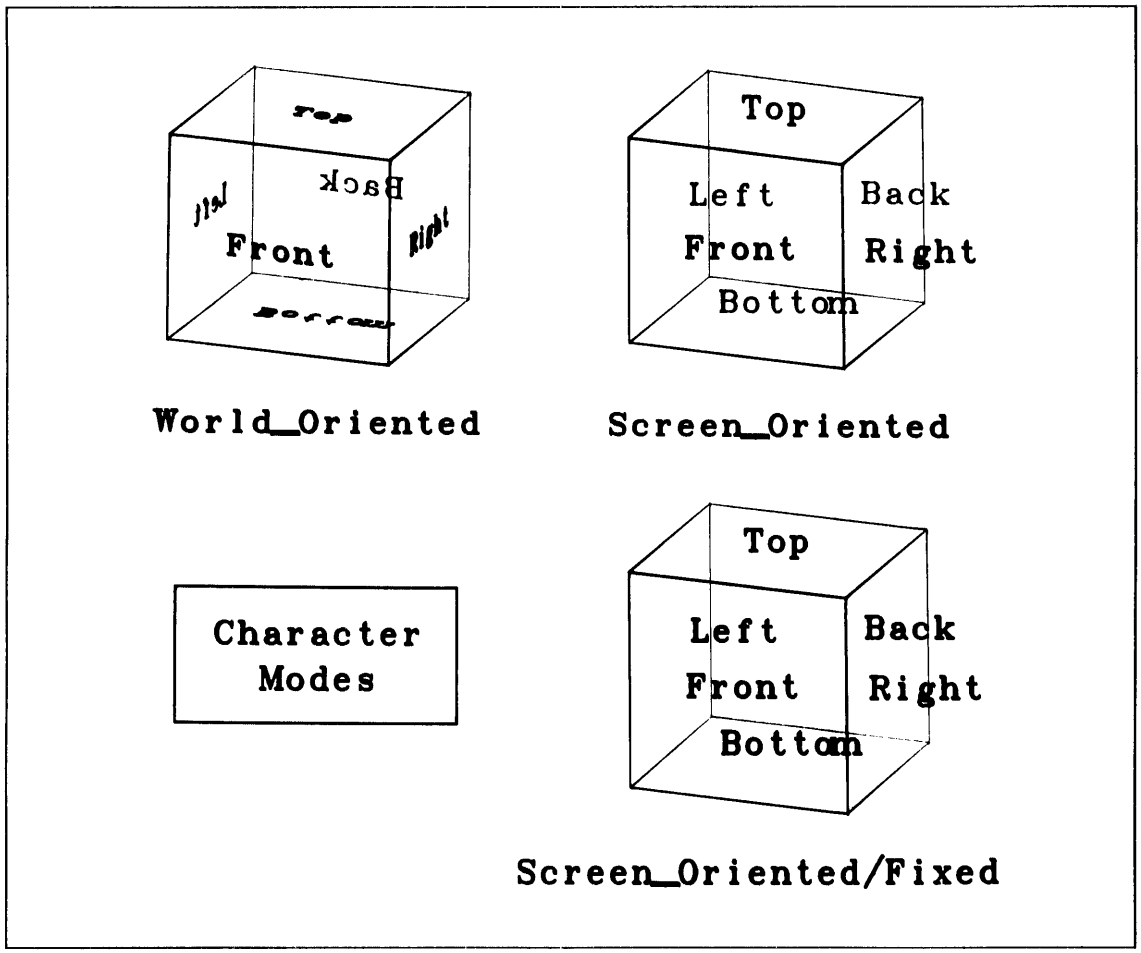
Dial 2 in Mode 1 rotates the objects and the eye in the first viewport so you can see better where the eye is located.

Function key F11 resets the program.

Function key F12 leaves the program and displays the Tutorial Demonstrations Menu again.

3.6 Program: CHARACTERS

Typical Program Display



Abstract

This program illustrates the concept of character orientation discussed in Section TU10. "Text Modeling and String Handling." It shows the three ways in which characters can be defined with the SET CHARACTERS command. Three cubes are displayed with their faces labeled. Characters in the first cube are created with the WORLD_ORIENTED clause (the default). They are transformed as an intrinsic part of the cube as if they were painted on the cube's faces. Characters in the second and third cubes are created with the SCREEN_ORIENTED clause (the default setting). No matter how the cube is rotated, these characters always remain in a plane parallel to the

Abstract (continued)

screen. Character size is unaffected by scaling. In addition to being screen-oriented, the characters in the third cube have an additional FIXED clause. This maintains the characters at full intensity, no matter where they are located in the Z axis.

Programmed Functions

Control Dials	Function Keys
D1 - OS X ROT	F11 - RESET
D2 - OS Y ROT	F12 - EXIT
D3 - OS Z ROT	
D4 - SCALE	
D5 - TRANS X	
D6 - TRANS Y	
D7 - TRANS Z	
D8 - unused	

Notes on Usage

As you manipulate the cubes with the control dials, note that the screen-oriented characters remain in a plane parallel to the screen but that they do move along the Z axis when the cubes are rotated in X and Y. Also, when the cubes are scaled, the screen-oriented characters remain the same size but the starting location of each character string responds to the scaling.

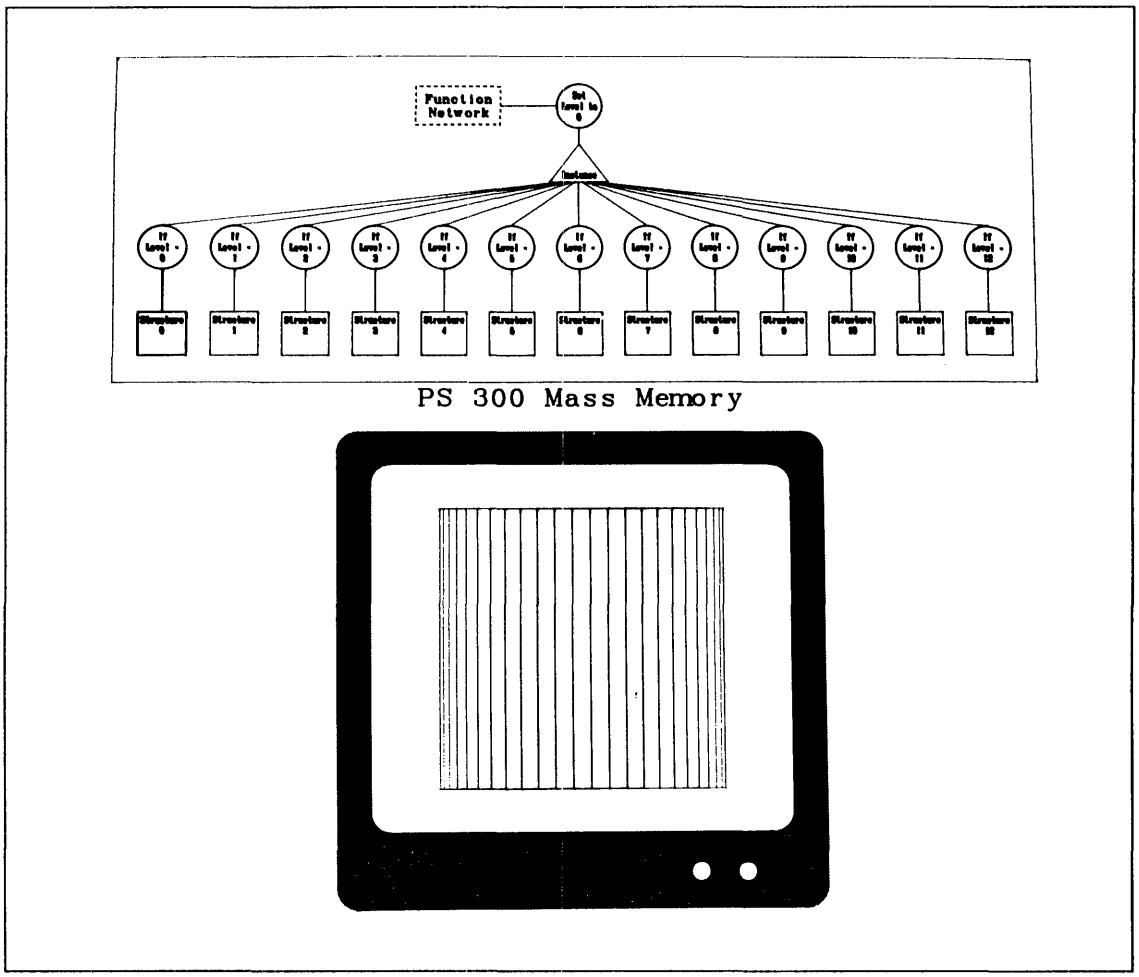
To see more clearly the difference between SCREEN_ORIENTED and SCREEN_ORIENTED/FIXED characters, turn down the intensity of the PS 390 display. If you turn it low enough, only the "fixed" characters will be visible.

Function key F11 resets the orientation of the cubes.

Function key F12 leaves the program and displays the Tutorial Demonstrations Menu again.

3.7 Program: LEVEL OF DETAIL

Typical Program Display



Abstract

This program shows how level-of-detail commands are used to set up conditional branching in a display structure.

In one area of the screen, a display tree is shown with a SET LEVEL node at the top. Thirteen different paths are grouped under one instance node following the SET node. Each branch contains an IF LEVEL node and a "structure." To keep the diagram simple, the structure is shown as a square data node, but it actually consists of a vector list and a color node. The IF nodes contain values from 0 to 12. The SET node is connected to a function network.

Abstract (continued)

As new values from 0 to 12 are received from the network, different branches out of the instance node are traversed. The effect of this is seen in the lower part of the display, where a representation of the PS 390 screen is shown. Each of the thirteen structures is a "frame" in a sequence which shows a cylinder whose top and bottom twist and untwist in opposite directions.

Programmed Functions

Control Dials

D1 - WS X ROT
D2 - WS Y ROT
D3 - WS Z ROT
D4 - SCALE
D5 - X TRAN
D6 - Y TRAN
D7 - Z TRAN
D8 - LEVEL

Function Keys

F10 - STRT/STP
F11 - RESET
F12 - EXIT

Notes on Usage

Dials 1 through 7 are just for fun. They let you manipulate the cylinder while it is cycling through its animation sequence.

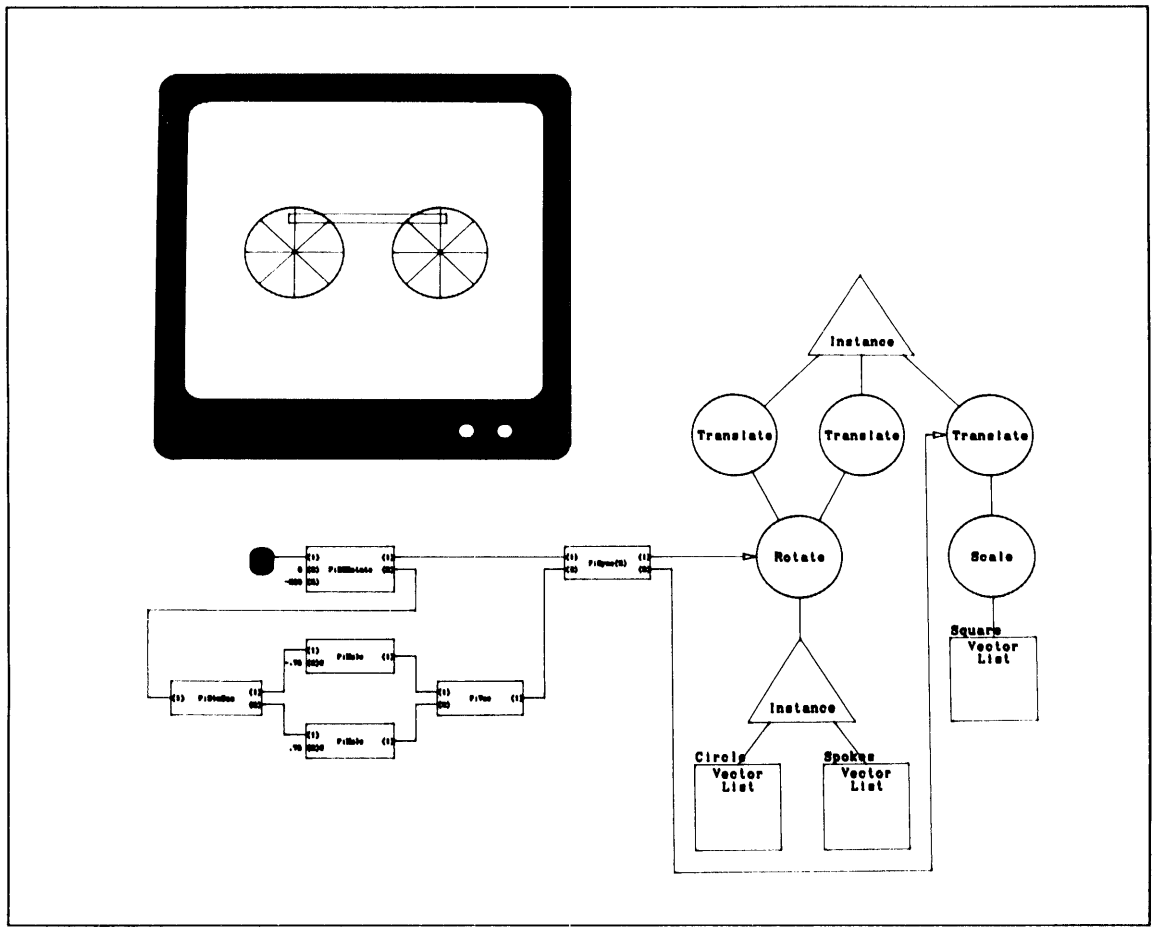
Function key 10 starts and stops the animation. When the motion is stopped, you can use dial 8 to change the level of detail by one value at a time to step through the animation sequence. Note that the "WS" in the LEDs for dials one, two, and three stands for World Space. Rotations of this sort happen about the world coordinate axes.

Function key F11 resets the program.

Function key F12 leaves the program and displays the Tutorial Demonstrations Menu again.

3.8 Program: NETWORK EXECUTION

Typical Program Display



Abstract

This program shows the sequence of activities when a function network accepts data from a dial, processes the data through the functions that make up the network, and updates interaction nodes in a display tree with the resulting transformation matrices.

A representation of the PS 390 screen is shown in one viewport, displaying the object defined by the display tree: two wheels connected by a tie bar. In another viewport, the display tree is shown with the interactive rotation and translation nodes that will supply motion to the object connected to a function network.

Abstract (continued)

The network connects to dial 8. As you turn the dial, the values received from it are passed through the network, converted to the correct data types, and fed into the interactive rotation and translation nodes at the end.

Programmed Functions

Control Dials	Function Keys
D8 - WHEELROT	F11 - RESET
	F12 - EXIT

Notes on Usage

There are two parts to the network which supplies new values to the interactive rotation and translation nodes. One part handles the simultaneous rotations of the two wheels; the other part handles the synchronized translation of the tie bar with the motion of the wheels.

The rotation network consists of the function F:DZROTATE connected to dial 8. The magnification value on input <3> of this function increases each tiny value received from the dial by two hundred to create significant numbers to accumulate. The accumulator on input <2> is initially set to zero. As the function accumulates values, it converts them to a Z-rotation matrix which is sent out of output <1>. The accumulator contents are sent out of output <2>.

The translation network calculates the amount in X and Y by which the center of the tie bar must be translated to be synchronized with the motion of the wheels. The accumulator contents from the F:DZROTATE function (representing degrees of rotation around the Z axis) are fed into F:SINCOS. This function calculates the sine and cosine of the angle of rotation. These values are output by F:SINCOS and are multiplied by a constant value of .75 in one case and -.75 in the other to calculate the displacement of the tie bar. (The value is .75 because the center of the tie bar is initially located at 0 in X and .75 in Y.) The resulting values are fed into the F:VEC function and are converted to a 2D translation vector.

Notes on Usage (continued)

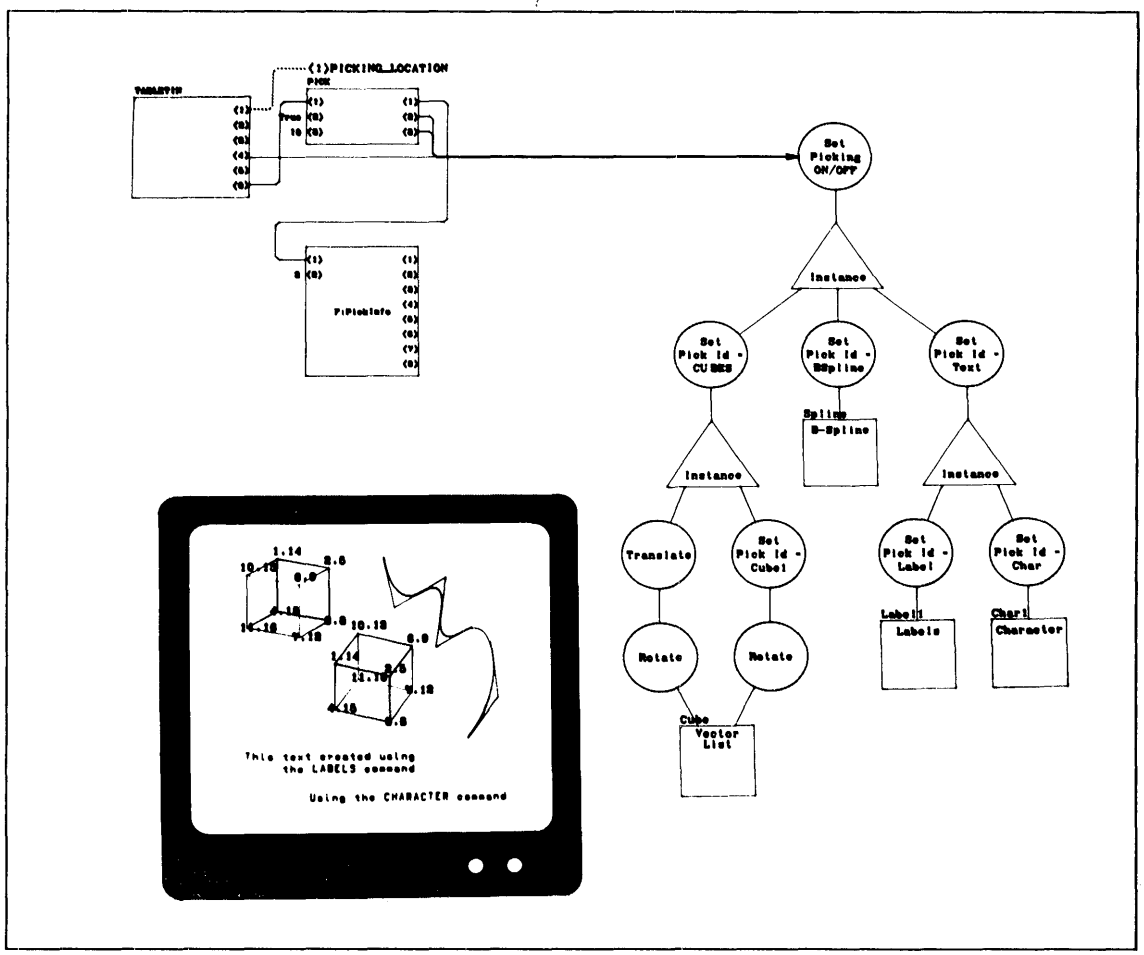
The outputs of F:VEC and F:DZROTATE are fed into F:SYNC(2). This synchronizes the updating of the rotation node and the translation node.

Function key F11 resets the display.

Function key F12 leaves the program and displays the Tutorial Demonstrations Menu again.

3.9 Program: PICKING

Typical Program Display



Abstract

This program shows graphically how picking can be performed on a vector list, a curve, a character string, or a label in a labels block.

Picking requires nodes in a display structure to set picking on and off, and nodes to identify the object that was picked (picking identifiers or pick IDs). A picking network must also be built so that a pick can be performed with the data tablet and information about the picked object can be returned for programming purposes.

Abstract (continued)

In one viewport, a representation of the PS 390 screen is shown displaying two cubes, a B-spline curve, a character string, and two labels. In another viewport, the display structure for this group of objects is shown. A SET PICKING ON/OFF node heads the display structure. This node is connected to the picking network. When you pick one of the vectors in the cube or B-spline, one of the characters in the string, or one of the two labels in the block, the path traversed in the display structure will brighten, and the function F:PICKINFO will show on its outputs the information returned by the pick.

Programmed Functions

Control Dials	Function Keys
None	F11 - RESET F12 - EXIT

Notes on Usage

The display structure shows that there are two requirements for an object to be a candidate for picking. The display structure must have a SET PICKING ON/OFF node that can be enabled, and the object must be identified with a pick ID.

The picking network consists of the initial function instances TABLETIN and PICK, the initial structure PICK_LOCATION, and an instance of the function F:PICKINFO.

As you move the pen over the tablet, notice that output <1> of TABLETIN sends X and Y coordinate values to PICK_LOCATION. This is positioning the invisible pick-box so that it is centered exactly where the cursor appears on the screen.

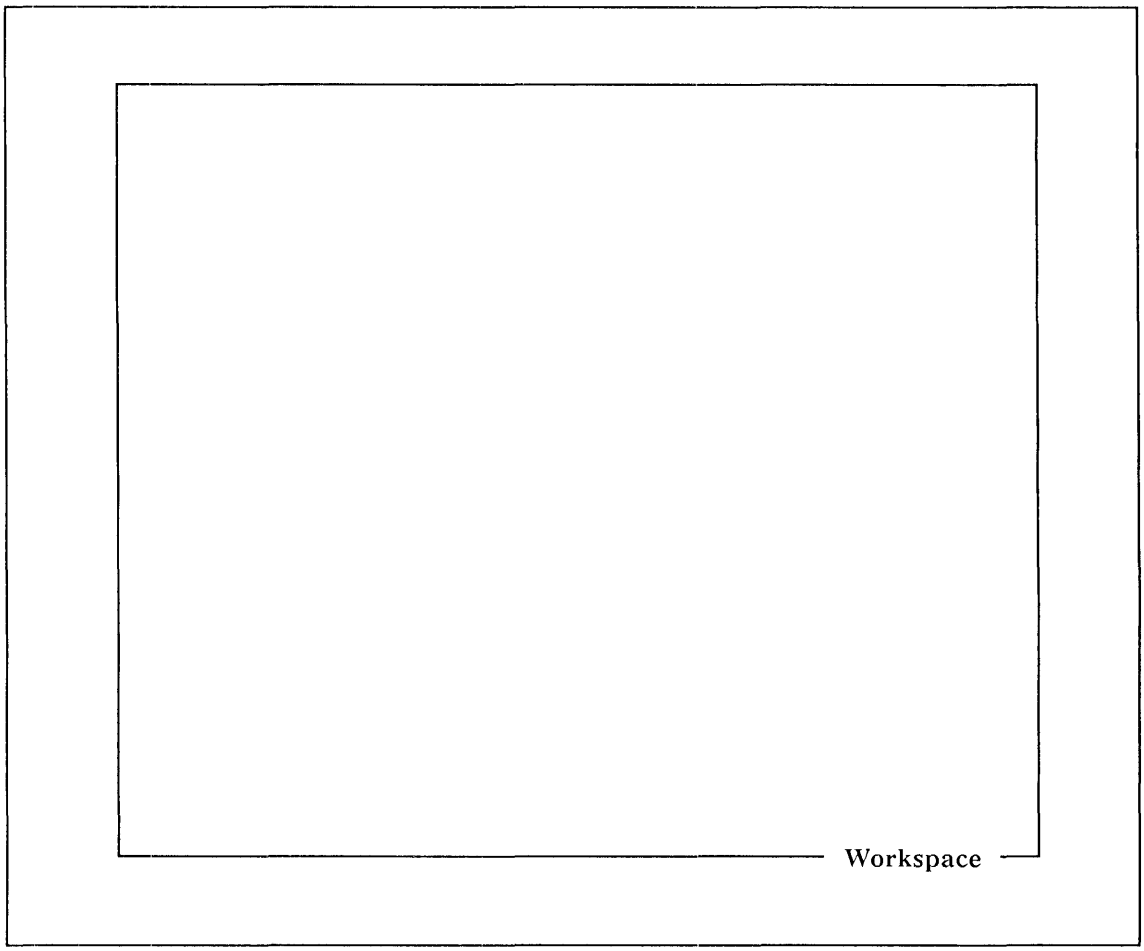
When a pick occurs, the path traversed in the display tree is momentarily brightened, and the outputs of F:PICKINFO show the information returned about the vector picked.

Function key F11 resets the display.

Function key F12 leaves the program and displays the Tutorial Demonstrations Menu again.

3.10 Program: WORKSPACE

Typical Program Display



Abstract

The work space is not truly a demonstration program, but a blank screen for you to use with the tutorial sections of the PS 390 Document Set GENERAL TUTORIAL VOLUME. Choose this selection from the menu when you are studying a Section such as GT8. "Viewing Operations", or GT10. "Text Modeling and String Handling" that requires you to display and manipulate objects.

The work space is simply a border with the word "WorkSpace" at the bottom right.

Programmed Functions

Control Dials	Function Keys
None	F12 - EXIT

Notes on Usage

When you go to the work space, you will probably be entering commands to create and display structures as directed in the Tutorial Modules. If you create any other structures on your own, be aware that the names you assign may conflict with named entities in the Tutorial Demonstration files. We recommend that you avoid this by prefixing any name of your own devising with your initials or some other two-letter code.

Here is a reminder of the three modes of operation of the the PS 390 and the key sequences that enter those modes.

Command Mode	CONTROL/LINE LOCAL	Enter PS 390 commands at the "@@" prompt.
Interactive Mode	SHIFT/LINE LOCAL	Use the interactive devices to perform programmed functions.
TE Mode	LINE LOCAL	Enter commands on the host at the host prompt (PS 390 is emulating a host terminal).

When you leave the work space, enter the following command.

```
INITIALIZE NAMES;
```

This will clear all object names and function instance names you have created in Command Mode but will not affect names that are contained in the Tutorial Demonstration files. Remember that an INITIALIZE command is specific to a communications line. In other words, structures created through the keyboard in Command Mode can only be initialized with a local command from the keyboard, and structures transferred from the host can only be initialized with a command sent from the host.

If you use the INITIALIZE DISPLAY command, you will have to display the Tutorial Demonstration Menu and programs again. To do this, type the command

```
DISPLAY TUTORIAL_DEMOS;
```

when you are finished at the work space.

Use Function key F12 to exit and return to the Tutorial Demonstration Menu.

GT4. MODELING

DESIGNING A CONCEPTUAL MODEL

CONTENTS

ILLUSTRATIONS

TABLES

Section GT4
Modeling
Designing A Conceptual Model

Introduction

One of the benefits of the PS 390 is the ease with which you can create a model for display. Essentially, there are three steps to creating a model which can be manipulated interactively on the screen.

- The first step is to design the model on paper, taking into account what it will look like and how it will move.
- The second step is to write the PS 390 code using that conceptual model as a blueprint.
- The last step is to make the model interactive by connecting it to interactive devices. This section details the first step, designing a conceptual model.

Designing a conceptual model is in many ways like creating an outline or blueprint of your model. Like any outline, it allows you to organize your material in a logical, sequential manner. It also helps you design a complex model one step at a time.

Once the conceptual model is completed, it can be analyzed more easily for errors, repetitions, omissions, or flaws in logic because you can see its organization as a whole. Should you find an error, it is easy to correct at this stage of design.

Designing a conceptual model allows your attention to be focused on the problems of design. You need not be concerned with operating procedures for the PS 390 or with the PS 390 command language. In fact, once the model is designed, you already have the framework for the commands necessary to create that model in the PS 390.

Inherent in the design process of any model is the consideration of not only what the model looks like, but also what it does. This is because the way in which you interact with a model is built into the design as part of its organization. Not only can you interact with the model as a whole, you can manipulate different parts of it as well.

Consequently, the model is organized as a hierarchy of interrelated parts. Building this hierarchy entails:

- Knowing what the object to be modeled looks like.
- Dividing the object into the pieces that comprise it.
- Organizing these pieces according to movement or attributes.

The resulting hierarchy is a representation of the organization of the model.

Once you have the model organized into the pieces that comprise it, the next step is to detail the steps that would be necessary to create each piece in the world coordinate system of the PS 390.

To create a model in the world coordinate system, you perform a series of transformations (such as scales or rotations) on data primitives.

Using the hierarchy as your basis of organization for the pieces, you build each piece in the world coordinate system, performing whatever transformations are necessary; i.e., shaping a primitive into the desired piece, grouping the piece with other pieces according to their interdependencies, and then moving the pieces into their respective locations within the model.

Each of these steps is detailed in the display tree for the model. The modeled primitives are represented in the display tree as data nodes. The transformations you perform are represented in the display tree as operation nodes. There is a third type of node in display trees called an instance node which is used to organize and group the other two types of nodes. An instance node is placed wherever the display tree branches to more than one descending node.

When completed, the display tree represents all the information necessary to create the model, step by step. It even includes operation nodes which allow you to interact with the model as a whole or with any of its select pieces. The display tree can then actually be coded in the PS 390 via the PS 390 command language.

Objectives

This section details how to design a display tree for a model. You will learn how to:

- Design an organizational hierarchy.
- Design a detailed display tree.
- Design a complex model.

Prerequisites

Before reading this section, you should know basic computer graphics concepts, as developed in Section *GT2 Graphics Principles*. You should also have completed Section *GT1 Hands-On Experience*.

1. Designing An Organizational Hierarchy

The first step in building a display tree is to design an organizational hierarchy for the model.

Before you can design an organizational hierarchy, however, you must know exactly what the model will look like. The dimensions and proportions of the model may have been provided for you initially, or you may have to provide these yourself by drawing out a rough draft of the model on graph paper.

This rough draft can be used to divide the model into indivisible pieces. The basis for this division depends on what you want to do with the model.

One basis for division might be movement—what pieces you want to move individually. You will also want to consider attributes which might differentiate pieces, such as color, blinking, or level-of-detail. For example, you may want to show red fingers on a white hand. These attributes affect the way in which you design the model. It is much easier to make design allowances for them initially than to reconstruct the model later.

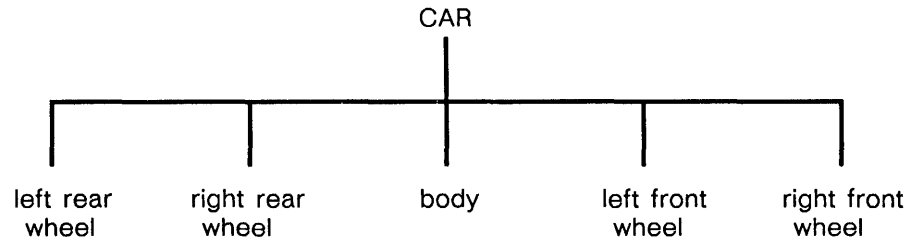
Of course it is possible that you may not want to differentiate all the pieces of a model. For example, suppose you are designing a sports car, and the only movable pieces are the four wheels. In this case, the whole car body can be thought of as one piece.

The model as a whole would then consist of five pieces:

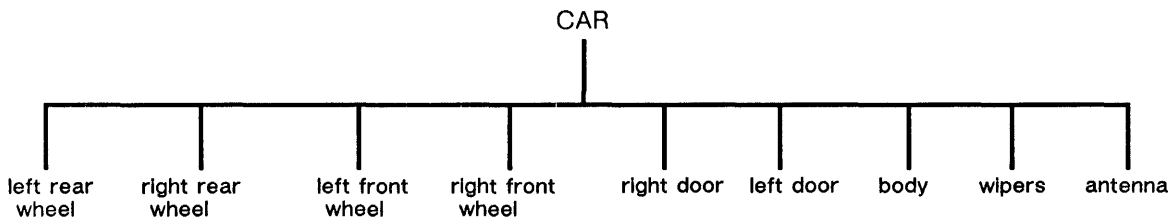
Pieces

1. right front wheel
2. left front wheel
3. right rear wheel
4. left rear wheel
5. car body

The resulting hierarchy would be:



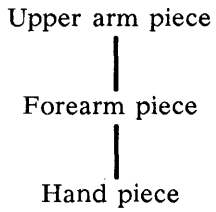
However, if you want the doors to swing open, the front windshield wipers to move, and an antenna to retract, each of these features is distinguished as a separate piece. The following hierarchy would then be:



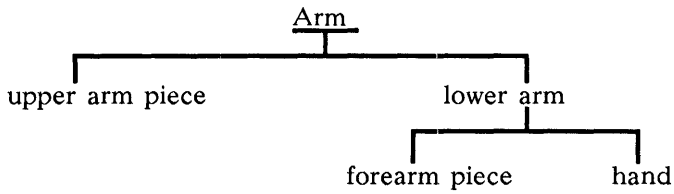
There are also times when you may want to interact with several pieces of the model collectively as well as individually or when the movement of one piece has a direct result on another piece. This kind of grouping or dependency affects the design of the hierarchy.

For example, if you were designing the arm of a robot, the arm could consist of three pieces: the hand, the forearm, and the upper arm. The hand piece can be moved individually. However, moving the forearm necessitates moving the hand, and moving the upper arm necessitates moving the both the forearm and hand. In this example, then, the three pieces have different degrees of independent movement.

Pieces are organized in a hierarchy according to this kind of sphere of influence. Those pieces which influence other pieces are above them in the hierarchy. So a simple hierarchy for the robot's arm might be:



To build the capacity for movement into this hierarchy, add two "grouping" names:



Grouping names are used when pieces act collectively. In this hierarchy, Lower Arm is the grouping name used when the separate pieces, forearm and hand, move collectively. Arm is the grouping name used when you want to move the upper arm piece and the lower arm.

Grouping names make collective movement of pieces easier. Moving Arm is easier than moving each of the three pieces simultaneously. Moving Lower Arm is easier than moving the forearm and hand pieces individually. Grouping names do not identify new pieces of the model—no ARM or LOWER ARM piece exists.

1.1 Exercise

Analyze the structure of the simplified mechanical arm in Figure 4-1 according to dependent and independent movement of pieces. Then organize these into a hierarchy accordingly. Use whatever grouping names are necessary.

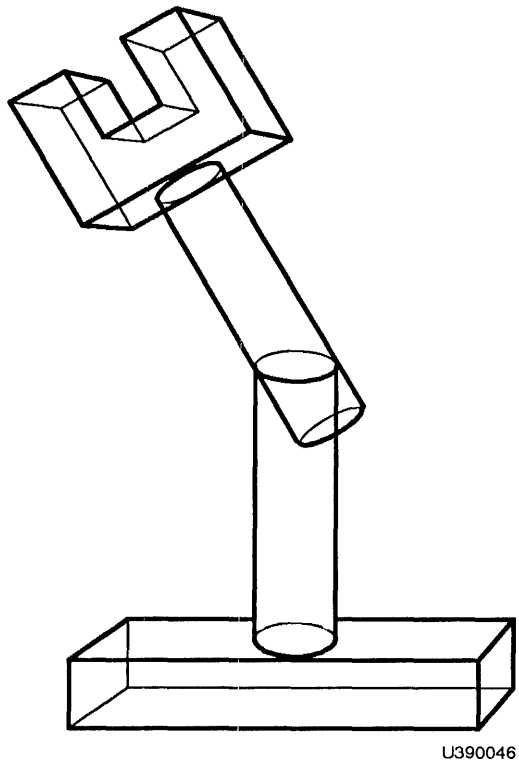


Figure 4-1. Mechanical Arm

The arm consists of a base, two jointed sections, and a hand. The base is fixed and cannot move. The whole arm can rotate at the base. The two arm pieces and hand are affected by this movement. The movement at the elbow affects the upper arm and hand only. Movement at the wrist only affects the hand.

So the pieces are:

base

lower arm

forearm

hand

The pieces can be grouped accordingly: the first movement that affects more than one piece is above the elbow. Group the forearm and the hand together to form UPPER ARM.

Pieces	Grouping Name
hand forearm	Upper Arm

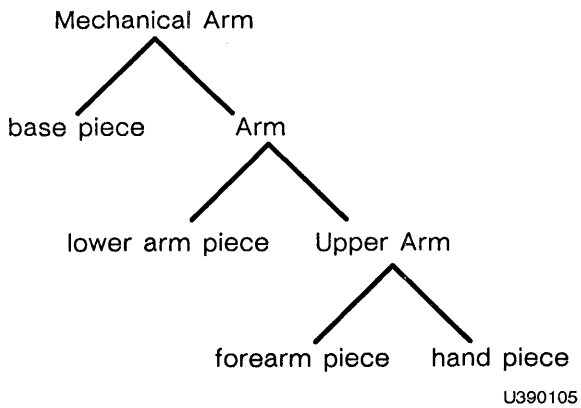
The upper arm moves with the lower arm piece when the whole arm rotates at the base. Group these together to form the Arm.

Pieces	Grouping Name
lower arm piece Upper Arm	Arm

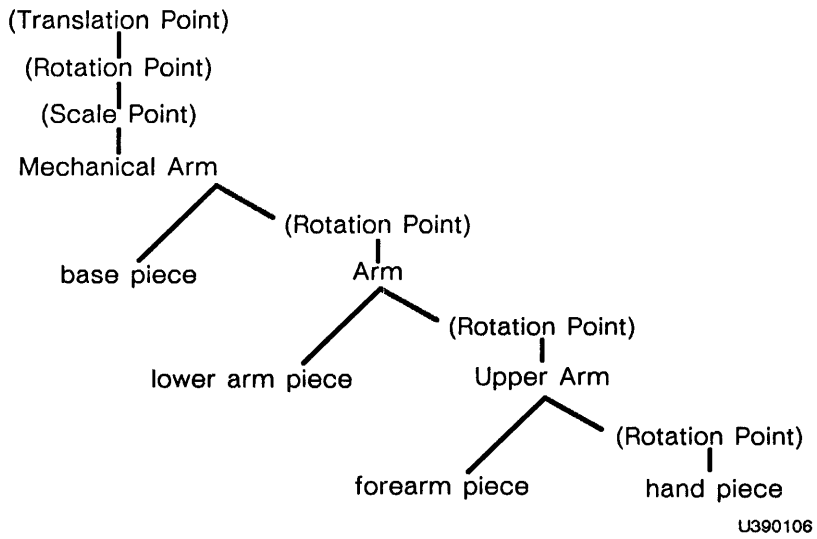
Finally, the base is a piece on its own. It is unaffected by the movement of the arm and the hand.

Piece
base

Once the pieces of the model have been identified and grouped, an informal hierarchy can be sketched out. The most inclusive pieces, in terms of influencing other pieces, are at the top of the hierarchy.



Since the pieces are divided according to how you can move them, it may be helpful at this point to note in the hierarchy those points where interaction will occur. So since Mechanical Arm in the above hierarchy is divided according to rotation movements, note the places where interactions would occur in the above hierarchy. The interaction points are shown in parenthesis in the following hierarchy for Mechanical Arm.



2. Designing A Detailed Display Tree

The informal hierarchy is used as the organizational outline for the actual display tree you will design in this section. This is reflected in the way the model is actually built in the world coordinate system: pieces that are grouped collectively down a hierarchical branch are often built collectively along an axis of the world coordinate system.

The display tree conceptually represents each of the steps performed to build each piece that comprises the model. As you identify each step necessary to build the model, you will draw a corresponding node in the display tree. In other words, modeling the pieces and designing the display tree are simultaneous procedures.

The modeling steps themselves are:

- Shaping the organizational hierarchy pieces from primitives. For information on how to create primitives, refer to Section *RM1 Command Summary.*
- Using modeling transformations to move pieces into position relative to other pieces that are grouped within the hierarchy.
- Adding interactions where needed.

First determine the primitives you want to use. These will depend on the kind of modeling you want to do.

- You may want an iconic model—one that looks as much as possible like the object it models. With this kind of model, each body piece is very distinctive and is modeled individually. For example, an iconic model of a man might have details such as facial features, hair style, fingernails, and so on. The designer can use vector lists or polygon lists to create the model. A very large vector list or polygon list is usually required to provide this kind of needed detail.

  With iconic modeling, not only is more detail needed for each piece, but more pieces are needed. This requires a great many vector lists or polygon lists, a time-consuming and often difficult programming task.

- You may be able to use a less detailed analog model. Analog models minimize your task by eliminating unneeded detail. You only define pieces that are really needed. An analog model may be as useful as an iconic one for certain applications. Use an analog model if you only want to show movement, or relative position or size, for example.

Most graphics programming is a compromise between these two types of modeling. A model needs to be iconic enough to be recognizable but analog enough to be useful.

For example, a robot model designed for movement might not require a great deal of realism. If there is no need to differentiate individual fingers on the hand, it could be designed as an oval shape. The vector list or polygon list to create this would be simpler than one to create a detailed hand with fingers. Both the left and right hands could be modeled from this vector list or polygon list.

In the same way, simpler primitive shapes, like cylinders and spheres, could be used repetitively by many different pieces of the robot. For example, a robot could be made from nothing but cylinders by defining a cylinder primitive and then transforming that shape to create each body piece. Changing the primitive from a cylinder to a sphere would change the appearance of the analog model.

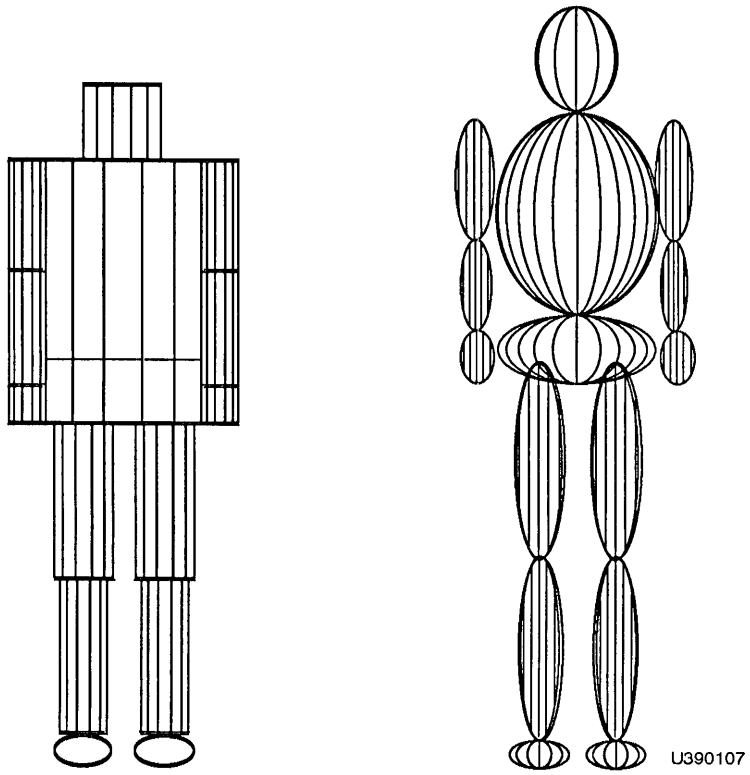


Figure 4-2. All-Cylinder Robot and All-Sphere Robot

However, both models illustrate movement, position, and size in exactly the same way. Both use only one primitive, easing the programming task immensely.

The model in Figure 4-3 is only slightly more complex. It uses a sphere primitive for the head and hands, and a cylinder primitive for the rest of the body pieces. Two primitives are required, but the result is more aesthetically pleasing.

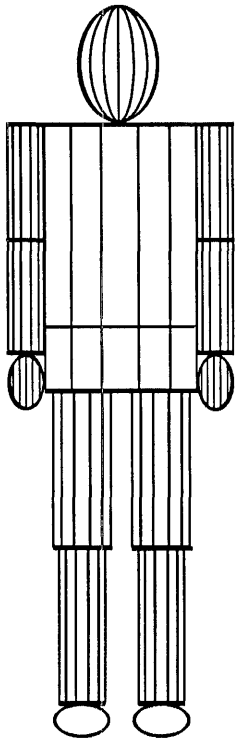


Figure 4-3. Robot Made of Cylinders and Spheres

Clearly, there are numerous ways to model an object. In any modeling application, there is flexibility in deciding how realistic the model will be and how many primitives will be required.

Once you have established what primitives the model will be shaped from, you will determine the actual dimensions and placement of the primitives in the world coordinate system. To do this, it is helpful to draw the model to scale on graph paper. The model serves as a visual aid as you determine how much to enlarge, reduce, or reshape primitives.

The dimensions of the primitive are often determined arbitrarily and are usually small, whole numbers. For example, it is easy to work with a sphere with a radius of one. If you need an oval four units high and two units wide, scale the sphere by 1 in X and 2 in Y.

When determining the initial position of primitives, consider where it is easiest to define a primitive, and what position it needs to be in most of the time to form pieces of the model. It is usually easiest to work with primitives located at the origin of the world coordinate system. One reason is that

rotations take place around coordinate system axes. To apply rotations correctly to a primitive, pieces of a model often need to be centered about, sit on, or hang from an axis.

Any model you create will be defined by coordinate system locations. When positioning the model, it is usually preferable to construct a model near the origin. One reason is that the initial view of the PS 390 world is centered on the origin. Another reason is that it is often easiest to establish symmetry if the model is centered about the X, Y, and Z axes. Finally, because rotations and scalings are performed relative to the origin, building the model there is easier.

Now that you know the dimensions of your model, its position in the world coordinate system, and the primitives which compose it, you are ready to design the display tree of the model.

A display tree represents several kinds of information. First, it includes the step-by-step information necessary to create the model in the world coordinate system. Second, it includes the capability to differentiate pieces of the model by attributes, such as color, or by movement. Finally, it includes the capacity for interaction with part or all of the model.

PS 390 display trees consist of up to three types of nodes.

- Primitive data, the "building blocks" for the model, are represented in the diagrams by square data nodes. Specifically, these nodes describe the collection of points, lines, polygons, and characters that define primitive data. Data nodes are always terminal nodes in a display tree.
- Any operations (such as scaling and rotation) which are performed on an object are represented in the display tree by a circle. These nodes are called operation nodes. An operation node can point to no more than one node below it.

  Operation nodes are used in two ways: for modeling and for interaction. Modeling operations are performed strictly to shape the "building blocks" of a model and move them into place. Interaction operations allow you to interact with a model. Any operation node can be either a modeling or an interactive node, or both kinds, depending on how it is used. In this section, interactive nodes are represented by a double circle; modeling nodes by a single circle.

Operation nodes are also distinguished by the fact that once they have been coded into the display tree, you can enable or disable them interactively. For more information on this, refer to Section *GT6 Function Networks I.*

- Instance nodes join one or more subparts, or hierarchical branches, into a whole, namable part. Instance nodes are represented by a triangle.

There is a special group of operation and data nodes that represent the commands that allow you to display labels and character strings. For details on these, refer to Section *GT10 Text Modeling and String Handling.*

In Section *GT1 Hands-On Experience,* each step you took to create and display the Star can be represented by one of the three types of nodes described above.

First, you created the square using a vector list:

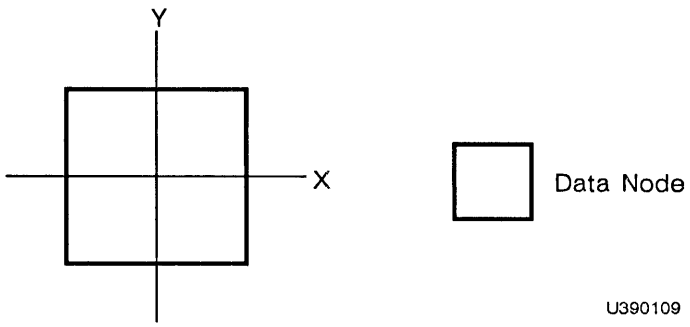


Figure 4-4. Square and Corresponding Display Tree

Then you displayed a rotated version of that square—Diamond:

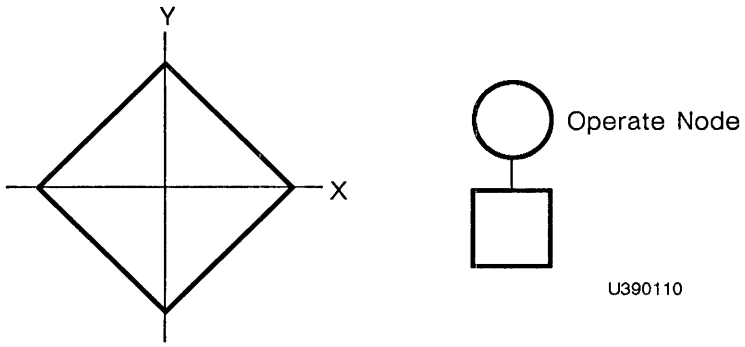


Figure 4-5. Diamond and Corresponding Display Tree

The diamond and the square were then linked together to form a star:

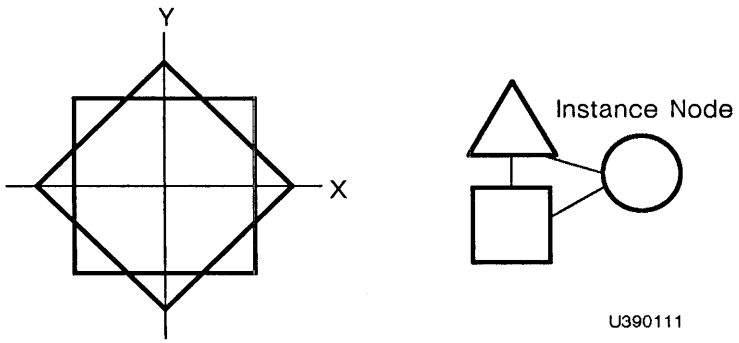


Figure 4-6. Star and Corresponding Display Tree

The other operations you perform on the star, scaling and translating, are represented in the display structure by these nodes.

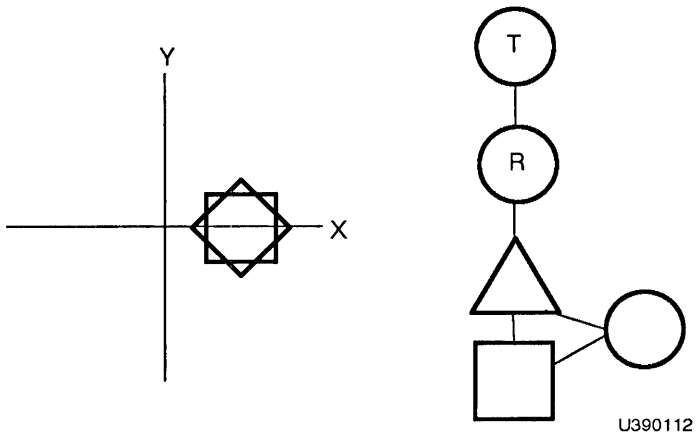


Figure 4-7. Transformed Star and Corresponding Display Tree

Display trees are designed beginning with the lowest nodes on the tree, the data nodes, and moving consecutively up the tree through each operation that is performed. This assures that the data are modified in the proper order by the PS 390. Operations such as scale, rotate, and translate are all performed using matrix multiplication. The non-commutativity of matrices means you must order transformations carefully.

The remainder of this section describes, step by step, how to design a display tree for the mechanical arm used in the first exercise. The mechanical arm and its dimensions are shown in Figure 4-8.

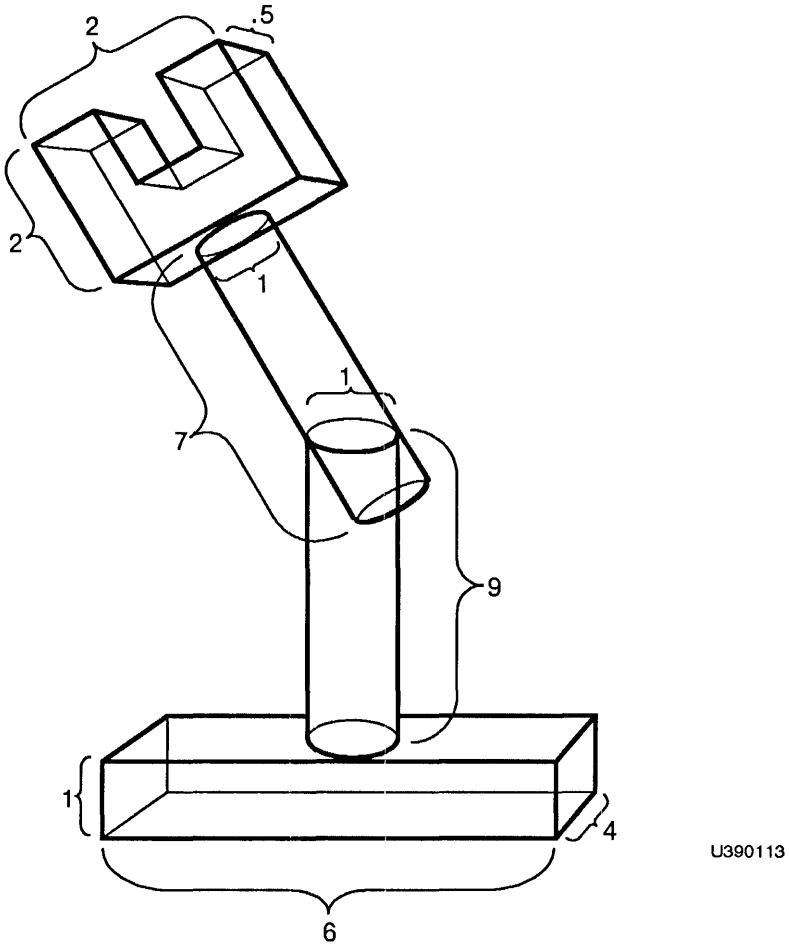


Figure 4-8. Mechanical Arm With Proportions

The mechanical arm is designed using these primitives:

1. A unit cylinder with its base on the XZ plane, centered on the positive Y axis, with a radius of 1 and height of 1. (Figure 4-9)

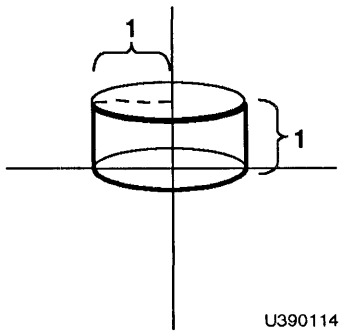


Figure 4-9. Cylinder Primitive for Mechanical Arm

2. A unit cube with its base on the XZ plane, centered on the positive Y axis, with a length, height, and width of 1. (Figure 4-10)

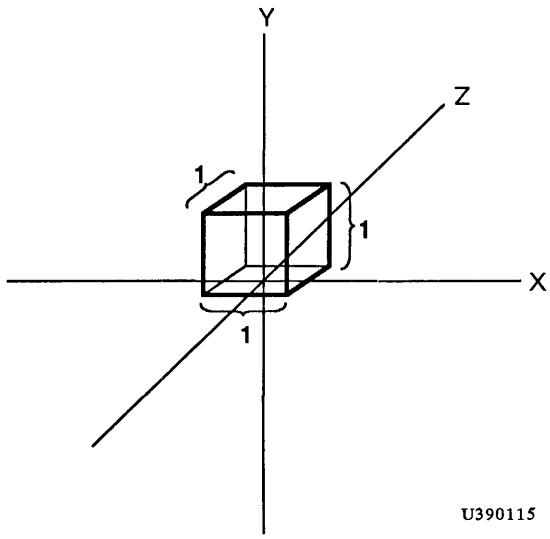


Figure 4-10. Cube Primitive for Mechanical Arm

3. A primitive consisting of lines which form the hand with its forks pointing up, with the base on the XZ plane, centered on the positive Y axis with a height of 2, width of 2, and depth of .5. (Figure 4-11)

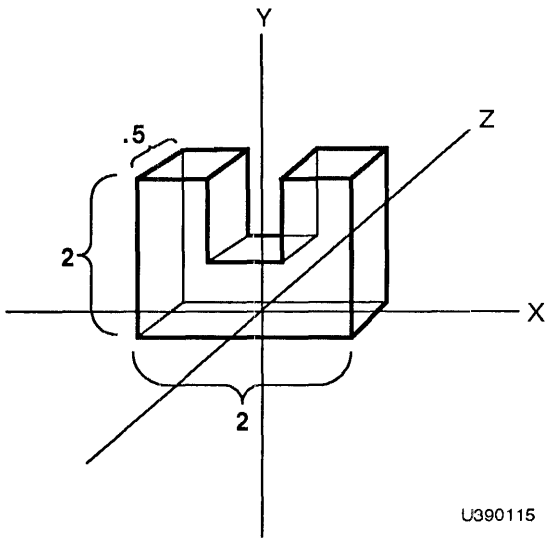
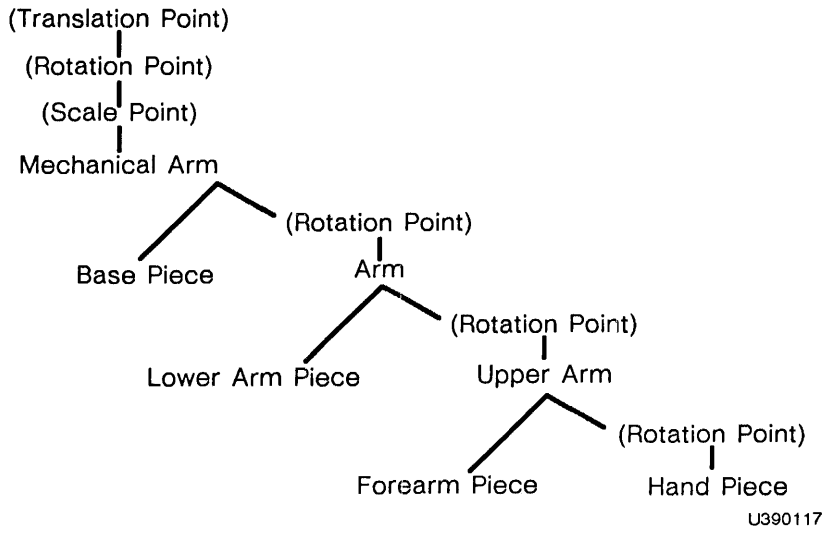


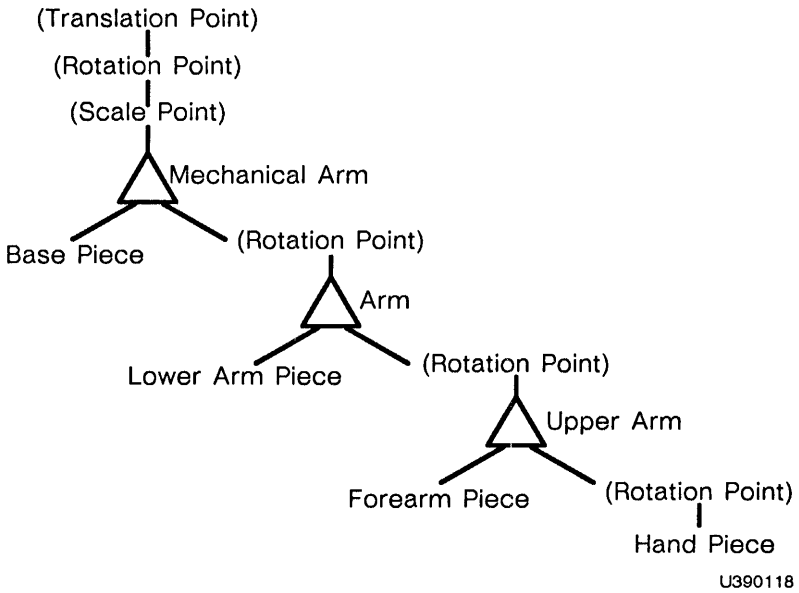
Figure 4-11. Hand Primitive for Mechanical Arm

As for initial position in the world coordinate system, the mechanical arm will be placed with its base on the XZ plane, centered on the positive Y axis. It will be easiest to build the model up the Y axis.

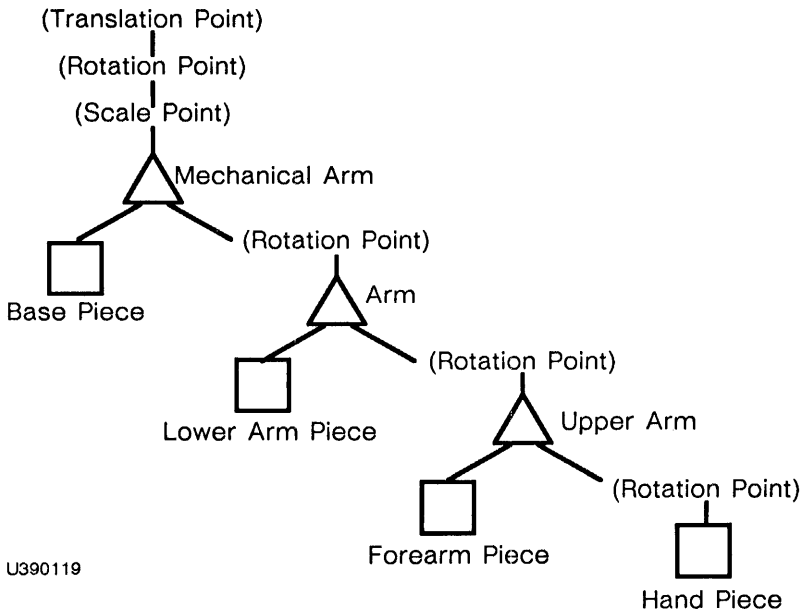
As you model the mechanical arm, create the corresponding display tree using the hierarchy as the basis:



Instance nodes are used to group other nodes in the display tree. The hierarchy branches at three places: where the mechanical arm is divided into a base and arm, where the arm is divided into a lower arm piece and an upper arm, and where the upper arm is divided into a forearm and a hand. The instance nodes are placed accordingly:



Next remember that all terminal nodes, those which define primitives, are represented with data nodes:



Finally, working up from the bottom of the display tree, we will detail the steps to model each of the primitives in the world coordinate system. Begin with the hand.

The primitive for the hand (data node) is designed so the hand is already the proper size and in the proper place, so no scaling or translating is necessary. According to the hierarchy, however, a rotation node is needed to allow rotation at the wrist. See Figure 4-12.

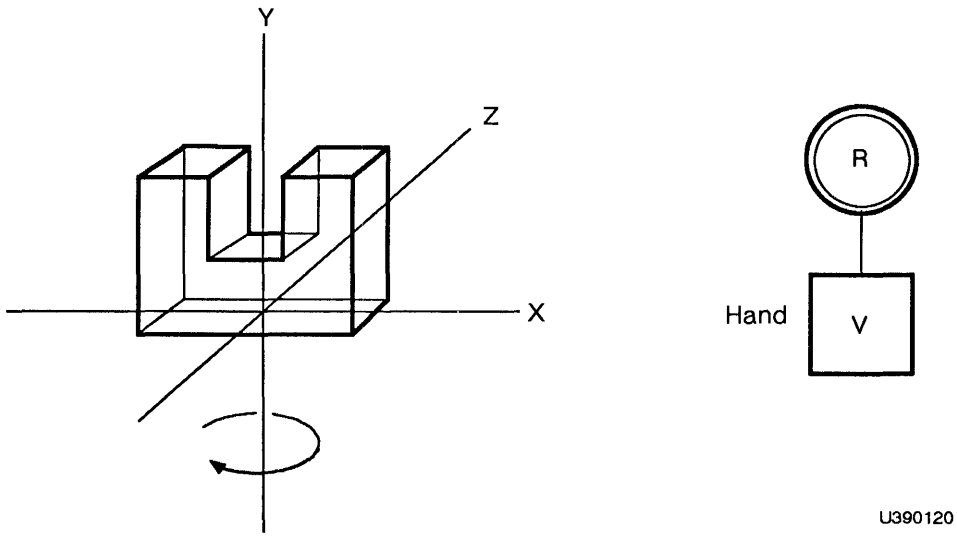


Figure 4-12. Mechanical-Arm Hand and Corresponding Display Tree

Now that the hand is built, it should be positioned so it can be grouped with the forearm piece. You might be tempted to translate the hand to its final position in the model, build the forearm piece, and then translate that piece into its final position. But if you do this, when you group these two pieces into upper arm and then rotate that upper arm, both pieces will "orbit" the axis rather than rotate at the elbow. For proper rotation of the upper arm, the hand must be grouped with the forearm and both rotated while the forearm rests on the axis. For more information about rotation, refer to Section *GT2 Graphics Principles*.

So next, translate the hand up the Y axis the length of the forearm piece, 7 units in +Y. Then build the forearm at the origin by scaling the cylinder (1,7,1), and group both the forearm and hand together as upper arm. Now if you apply a rotation to upper arm, it will rotate properly. See Figure 4-13.

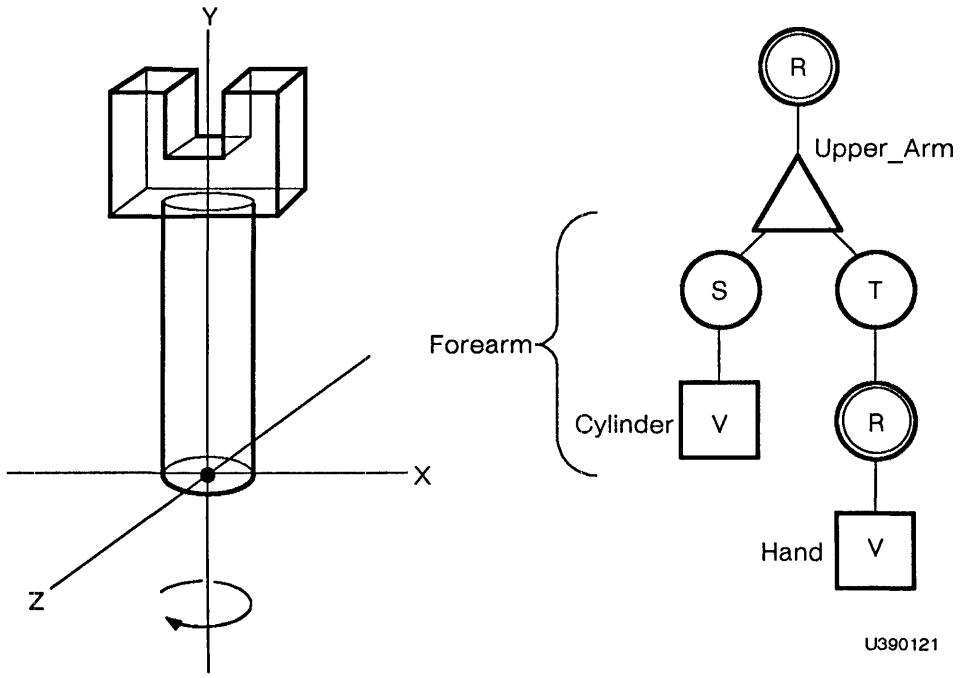


Figure 4-13. Mechanical-Arm Upper Arm and Corresponding Display Tree

A similar procedure is used to build the remainder of the arm. To assure proper rotation, move the upper arm up the Y axis the length of the arm, build the lower arm piece, and THEN apply the rotation to the whole arm. Pieces do not have to be grouped just along the Y axis. If it is easier to do so, you can build the pieces along the X or Z axis. The modeling steps can be summarized as follows:

1. Move the upper arm (forearm and hand pieces) 9 units up the +Y axis to make room for the lower arm piece.
2. Scale the cylinder to create the lower arm piece (1,9,1).
3. Group the lower arm and upper arm to form the whole arm.
4. Apply a rotation to the arm.
5. Scale the cube to create the base (6,1,4).
6. Allow for interactive manipulation of the whole mechanical arm (rotation, translation, scaling) with three interactive nodes.

The final display tree is shown in Figure 4-14.

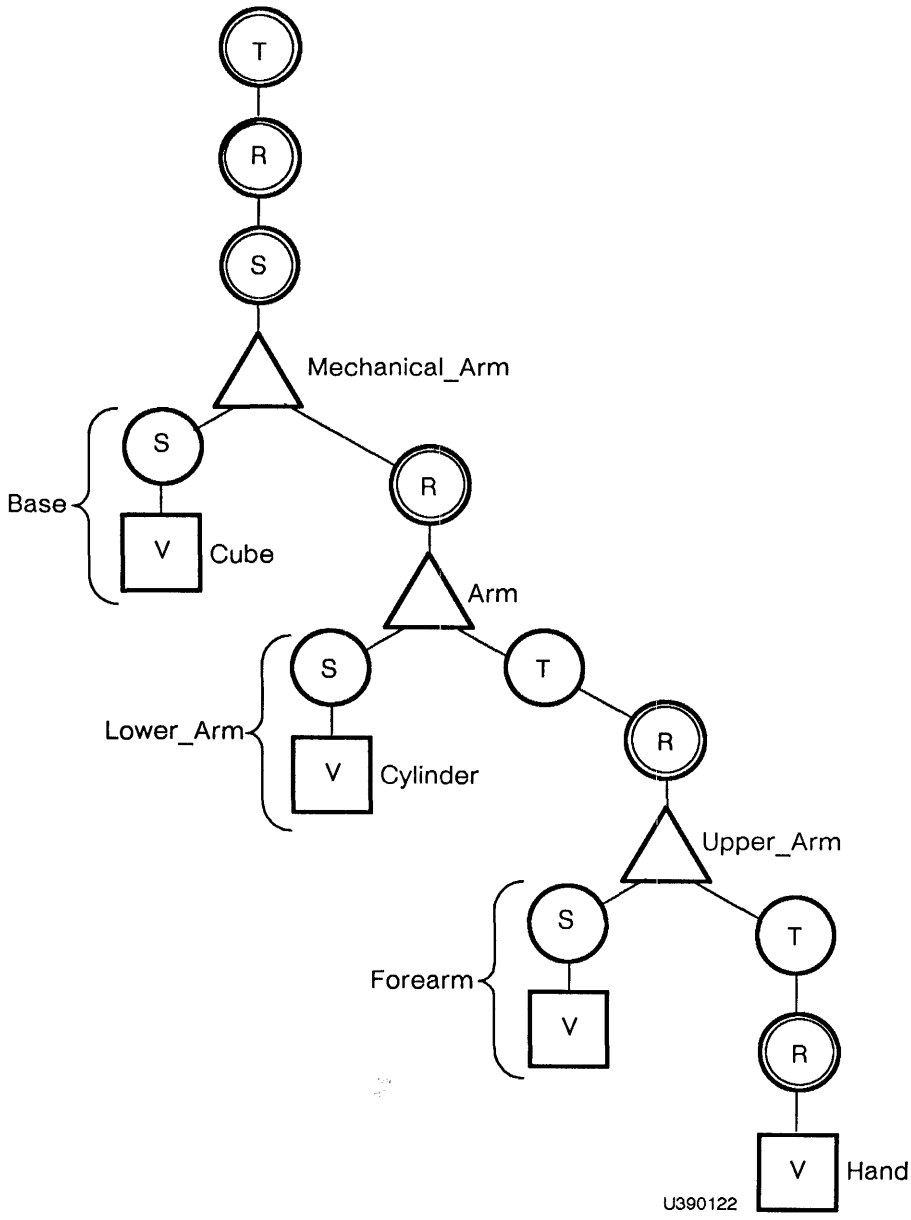


Figure 4-14. Mechanical-Arm—Final Display Tree

2.1 Exercise

Design the display tree for the sports car in Figure 4-15.

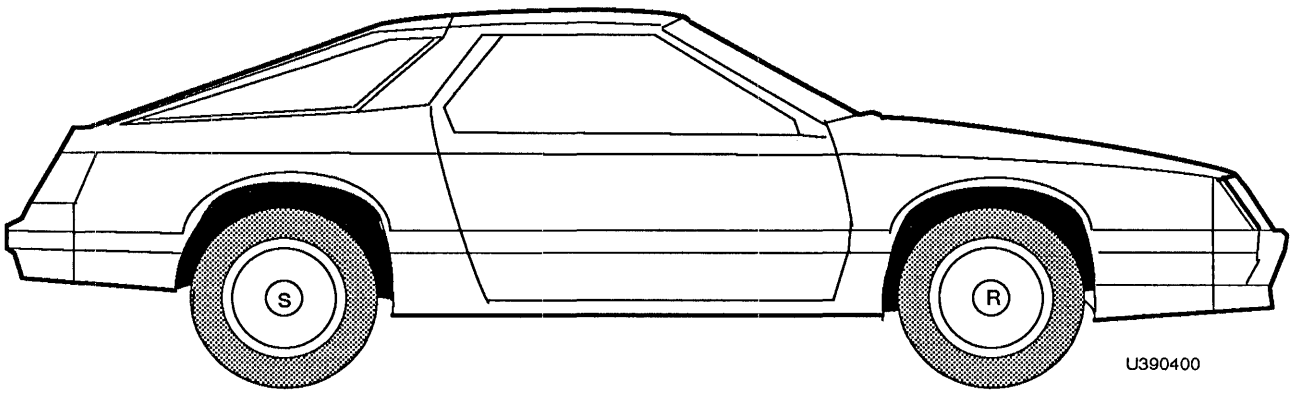
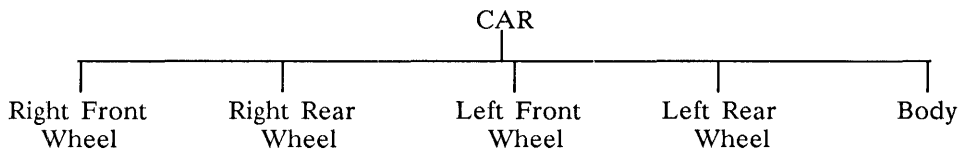


Figure 4-15. Sports Car

Include the capacity for movement in the four wheels (rotation) and for movement of the car as a whole (rotation, translation).

First design an informal hierarchy. Only five parts are needed for this car: the four wheels and the body. Because the body has no moving parts, the whole thing can be thought of as one part. The hierarchy is:



Next, model the primitives and create the display tree concurrently. There are two sets of tires: snow tires on the back and radials on the front. This means three primitives: a vector list for the body of the car, one for the snow tire, and one for the radial tire. These will be represented in the display tree by three data nodes, as shown in Figures 4-16, 4-17, and 4-18.

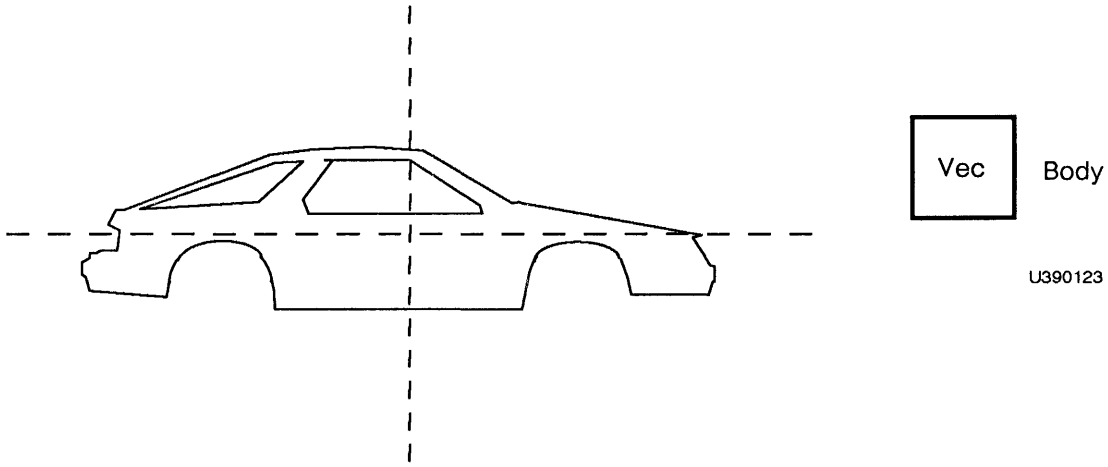


Figure 4-16. Car Primitive—Body

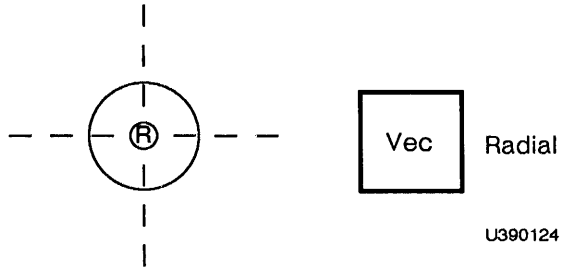


Figure 4-17. Car Primitive—Radial Tire

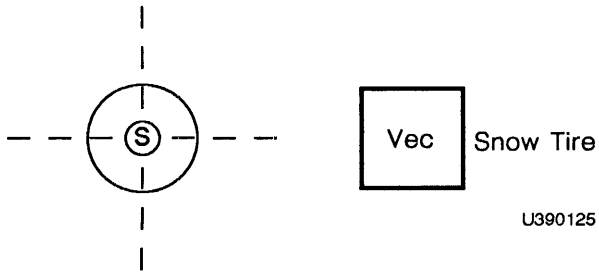


Figure 4-18. Car Primitive—Snow Tire

The wheels are scaled to fit into the wheelwells of the car. This means the data node for each type of tire has a scale applied to it.

Each wheel also has a hubcap on one side. Rotate the two tires on the left of the car 180 degrees about Y so that the hubcaps face out (Figure 4-19).

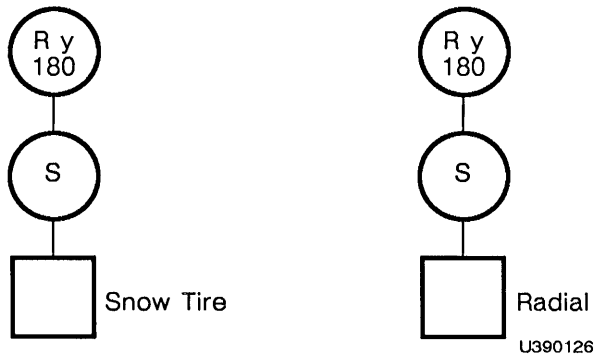


Figure 4-19. Tires Scaled and Rotated 180 Degrees

To allow for rotation of all four tires around the Z axis, insert interaction nodes which can accept values from an input device or host computer via a function network. Since these rotation values will subsequently be changed interactively, they can be 0,0,0 for now (Figure 4-20).

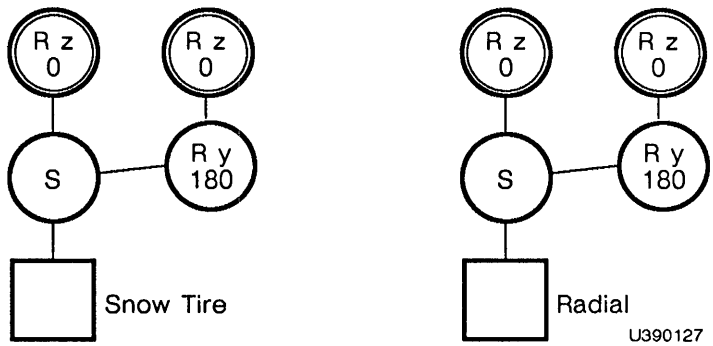


Figure 4-20. Interaction Nodes for Tire

The order of the operations is important here. Moving up the display tree branch, the interaction node applies AFTER the modeling rotate node has been applied to the data (Rot Z is above Rot Y 180). If you build the interaction node first and then turn the left tire out 180 degrees, it rotates in the wrong direction.

After all the rotations are applied, translate each wheel from the origin to its proper position on the car. Then group all parts together as Car.

Two kinds of movement might be desirable for the car as a whole: rotation and translation. These nodes are placed at the top of the structure.

The final display structure is shown in Figure 4-21.

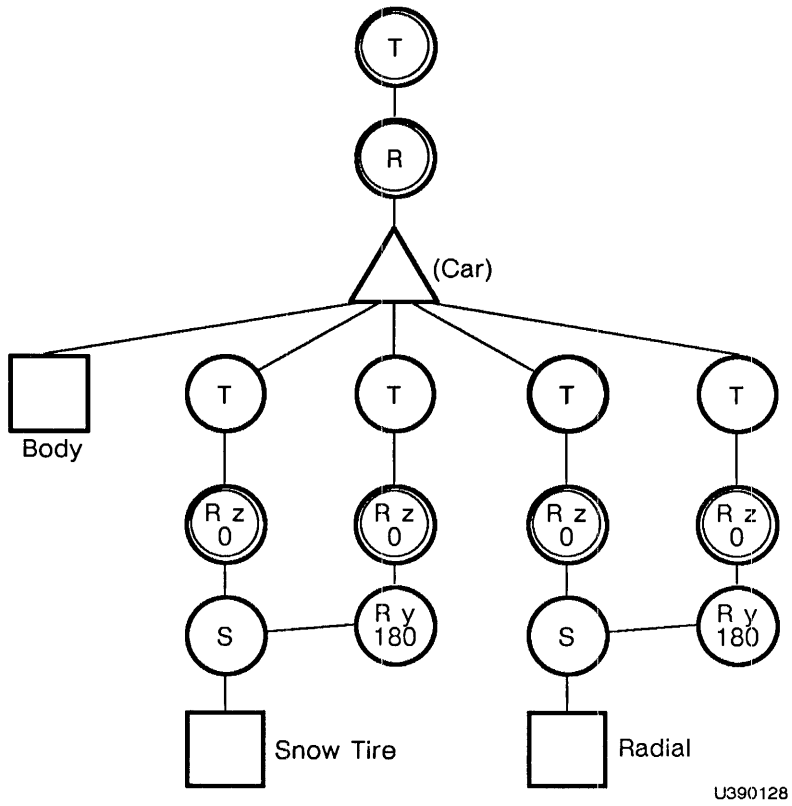


Figure 4-21. Final Display Tree for Car

3. Designing A Complex Model

This section details the steps necessary to design a complex model, an anthropoid robot. The exercise illustrates the importance of interaction nodes, (in this case, for movement) in the design of display trees. It also allows you to deal with specific kinds of modeling problems, giving you practical experience and allowing for some helpful generalizations about good programming techniques.

Design Robot with movement in mind. Robot moves at the joints: waving, swinging his arms, nodding, bowing, kicking, and so on. All of these movements are rotations of one kind or another about the bases of different body parts such as the waist, shoulder, and wrist.

Robot should look like the one shown in Figure 4-22. Notice his initial orientation—what position his limbs are in and where he's located in world space coordinates. To make the design task easier, Robot is placed symmetrically about the Y axis with his center at the origin.

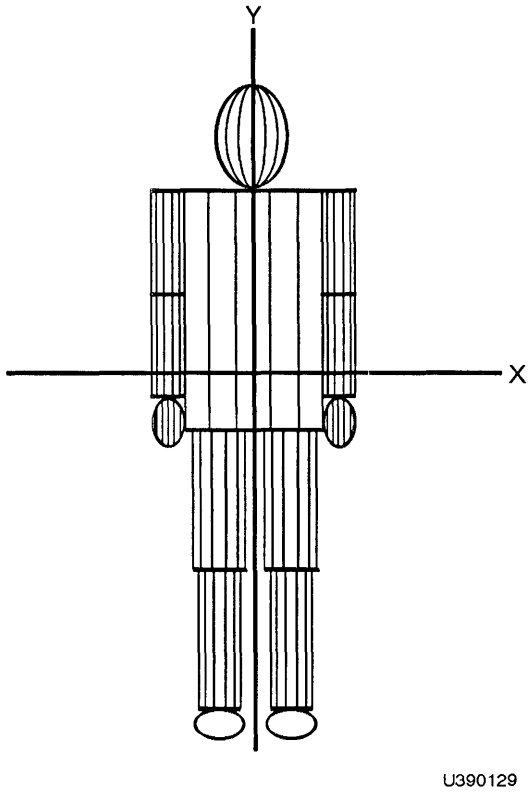


Figure 4-22. Robot—Orientation

Robot's body pieces consist of two primitives: a sphere for the head and hands, and a cylinder for the remaining body pieces. The designer has the option of using a vector list or a polygon list to create the primitives. These two primitives are defined below. Note that they are three-dimensional objects requiring (X,Y,Z) coordinate values.

1. A unit sphere centered at the origin with a radius of 1 (Figure 4-23).

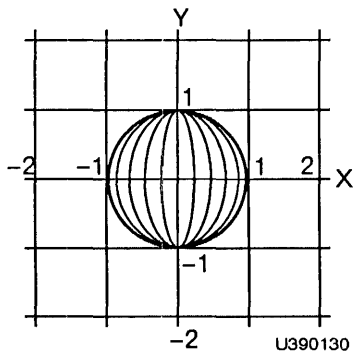


Figure 4-23. Robot Sphere Primitive

   The sphere is centered at the origin because it is easier to calculate the shape in this position. Also, from this central location, the sphere can be translated along axes easily. It will need to be translated up the Y axis when modeling the head and down the same axis when modeling the hands.

2. A unit cylinder with the proportions (2,2,2), hanging on the X,Z plane (its top resting on the X axis), centered on the negative Y axis (Figure 4-24).

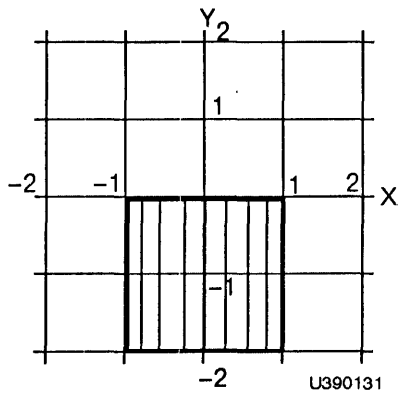


Figure 4-24. Robot Cylinder Primitive

The cylinder could have been centered about the origin as the sphere was. However, it has been created down the Y axis for a reason. Almost all the body pieces that depend on the cylinder rotate from "above". For example, the lower arm rotates at the elbow and the upper arm at the shoulder. If the cylinder were placed at the origin, each time a body piece was created the cylinder would have to be translated down the Y axis for this rotation to be applied "above" the piece.

Placing the primitive below the origin initially, then, saves separately coding a translate node for each piece you create. This is a good example of creating your primitive to suit your design goals.

Once the proportions for primitives have been established, use these to determine the exact size of Robot's body pieces in the world coordinate system. For example, as shown in Figure 4-25, Robot's head is twice as tall as it is wide. This means the sphere primitive will have to be scaled (1,2,1) to make the head.

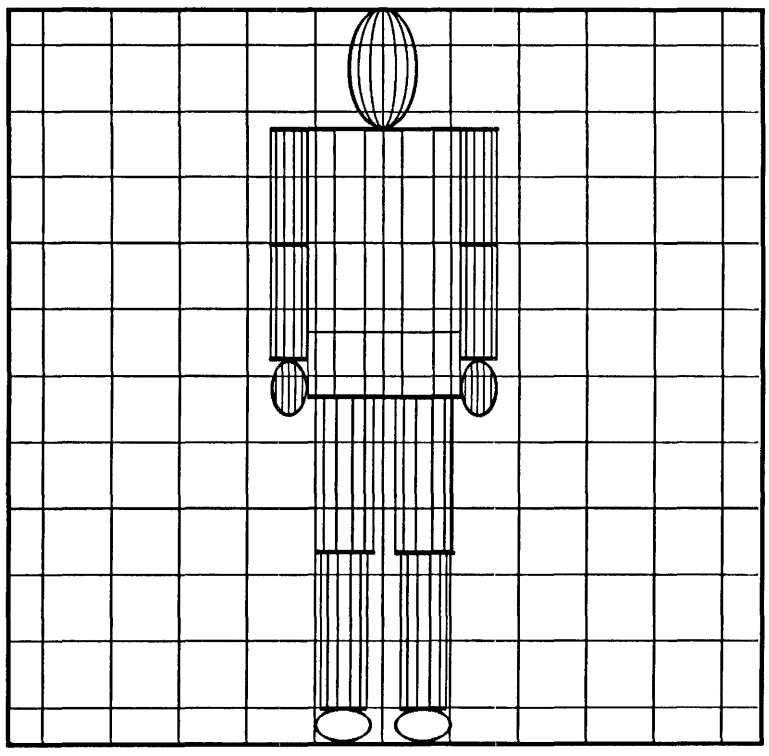


Figure 4-25. Robot—Proportions

3.1 Exercise

Design a hierarchy for Robot. Joints will be at the wrists, elbows, shoulders, ankles, knees, hips, waist, and neck.

Robot is composed of the fifteen individual body pieces shown in Figure 4-26.

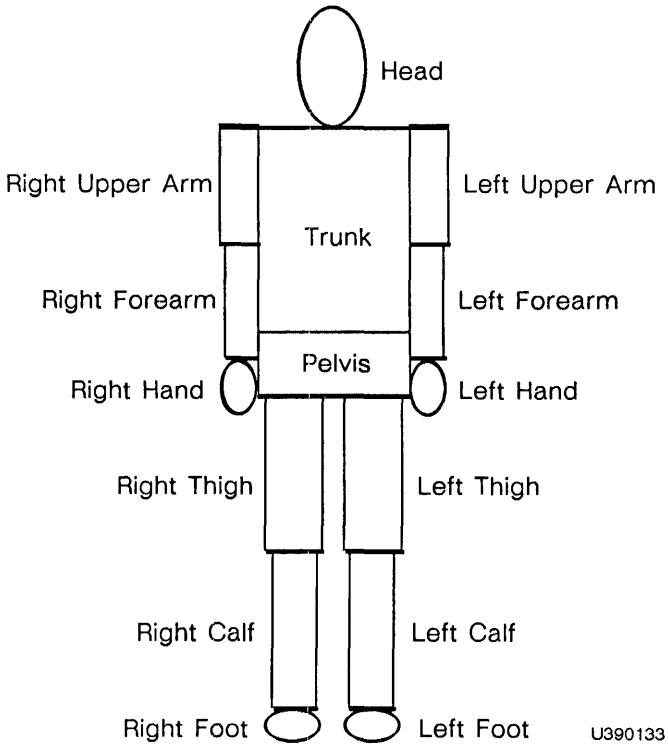


Figure 4-26. Robot—Body Pieces

The pieces should be organized so that rotating a joint causes all appendages affected by that joint to rotate. For example, rotating "upper body" to make Robot bow should cause the trunk, head, and arms to rotate. Though naming may differ somewhat, the hierarchy of named parts should basically look like the one in Figure 4-27.

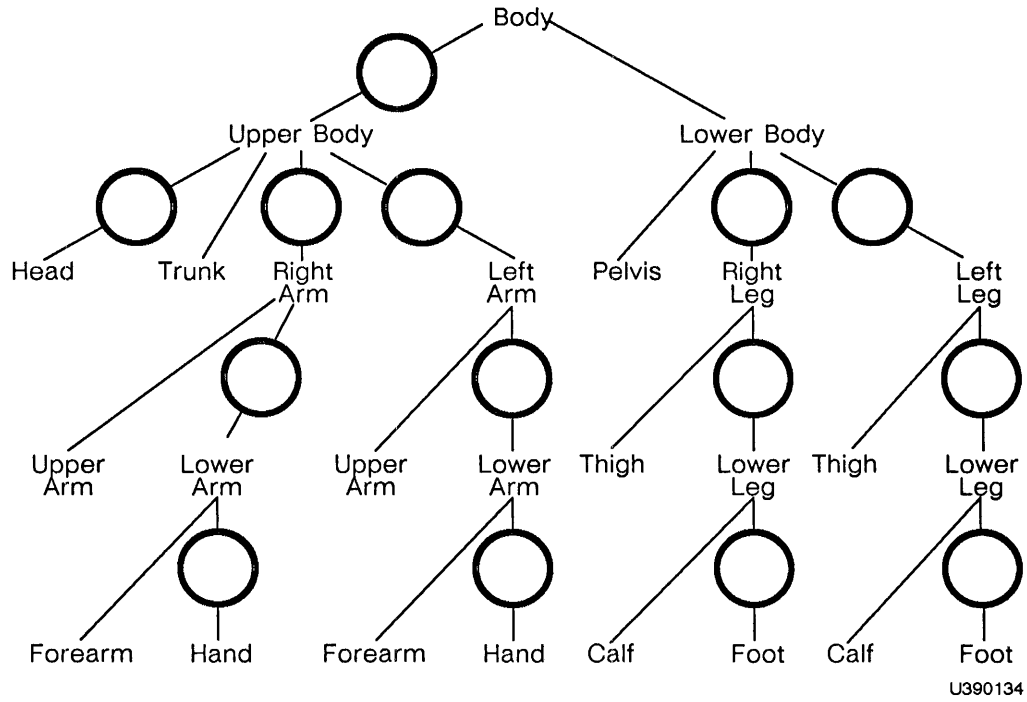


Figure 4-27. Robot—Informal Hierarchy

Notice the hierarchy includes additional "grouping names" (lower leg, right arm, upper body). As with previous examples, interactive points have been added to the hierarchy where the joints will rotate.

3.2 Exercise

Use the informal hierarchy as a guide for the display tree. "Grouping" names can be represented by instance nodes. Data nodes will be terminal nodes at the end of the hierarchical branches. Placement of interactive nodes has already been established. Placement of modeling operation nodes should be carefully worked out as you model each piece in the world coordinate system.

As you design the display tree, make note of where the body pieces for Robot's limbs can be shared by the left and right body pieces. Consider the feet, calves, thighs, forearms, upper arms, and hands. Right and left pieces can share nodes up to the point where the nodes serve to distinguish the two (separate rotate and translate nodes).

Sharing must be done carefully, in a way that allows parts of the model that require individual movement to remain independent. In any given display

structure, there are many different ways to share nodes. The following details the modeling steps and corresponding display tree for Robot.

Creating the Right Hand

Scale the sphere to create the elongated shape of the hand (.5,1,.5). Translate the hand down the Y axis (0,–1) so a rotation can be applied at the origin. Insert the rotate interaction node to simulate the wrist so the hand can "wave". For all interactive nodes, specify a zero value initially because values can be supplied later from interactive devices or a host.

Notice that although you have placed only one rotate node for articulation here, the wrist rotates around three axes (X, Y, and Z axes). Section *GT6 Function Networks I* describes how to allow for rotation in three dimensions with one 3x3 matrix node (rotation node).

Since the hand must be grouped with the forearm piece, translate the hand down the Y axis the length of the forearm piece (0,–3) rather than translating it into its final position in the model. Then when you apply a rotation to the lower arm, both the hand and forearm will rotate properly "from the elbow," rather than "orbiting" the axis.

Figure 4-28 illustrates the series of transformations that create the hand from the sphere primitive.

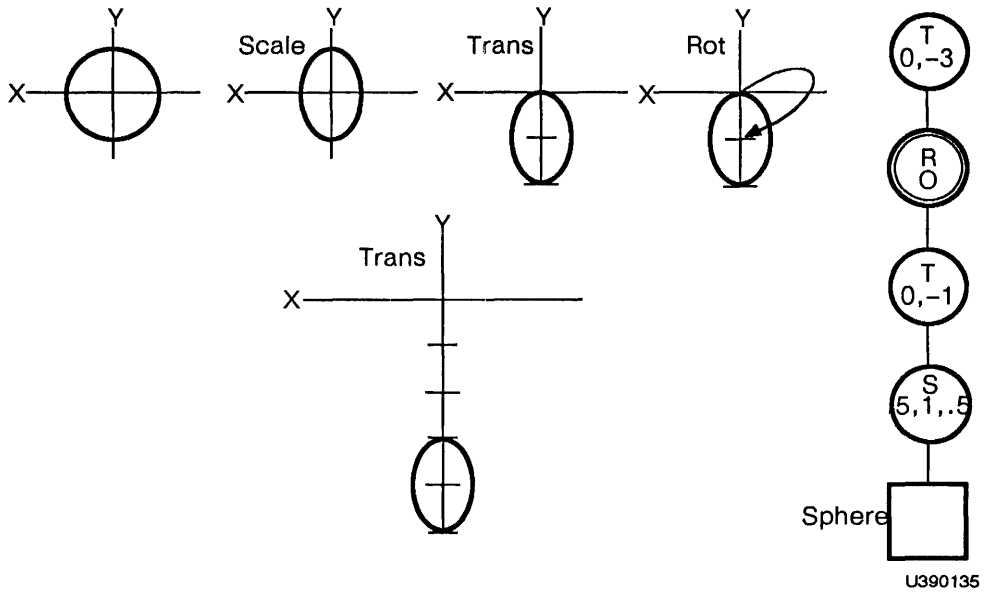


Figure 4-28. Robot—Right Hand Display Tree

Creating the Right Forearm

The forearm piece is created by scaling the cylinder to the proper size (.5,1.5,.5). Scaling the forearm places it in the proper position to meet the hand; there is no need to translate it.

When you rotate the right forearm from the elbow, you want the entire lower arm (the forearm piece and hand) to rotate. To do that, define the right forearm to be an instance of the forearm and hand. Insert a rotate node above the lower arm instance to move the lower arm at the elbow. Then translate the lower arm down the Y axis—this time the length of the upper arm piece (0,–4).

Figure 4-29 shows the series of transformations that create the lower arm.

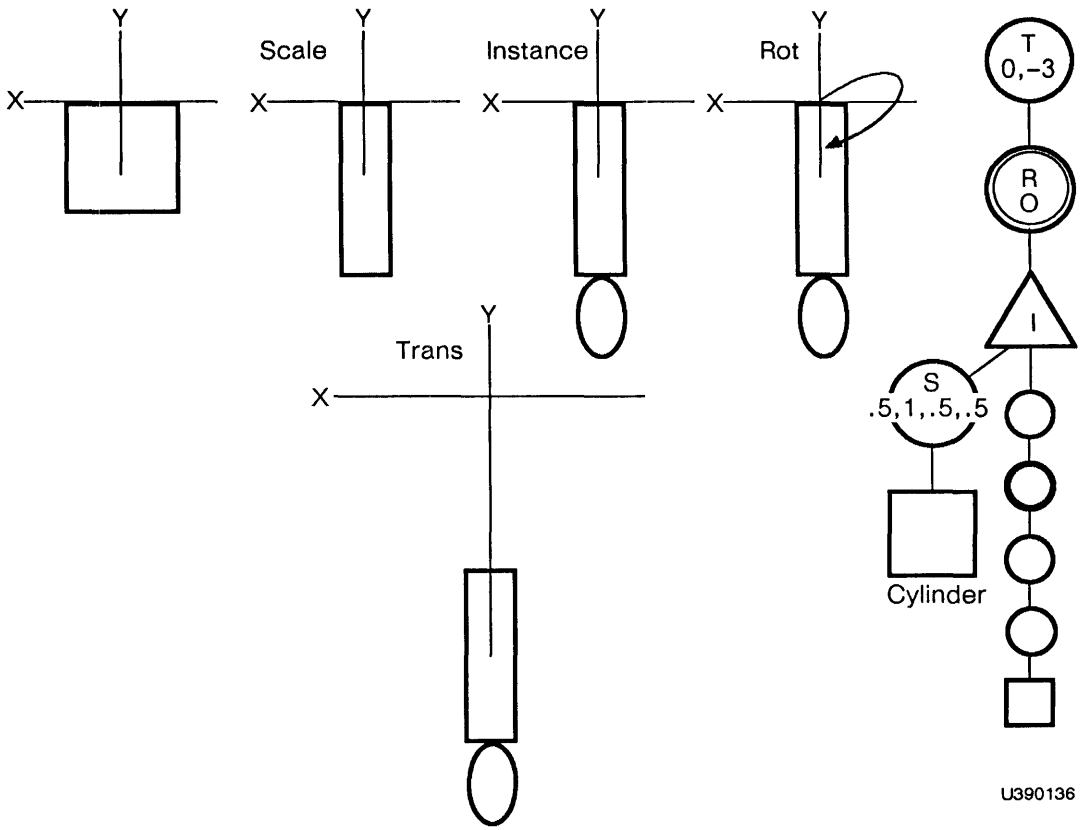


Figure 4-29. Robot—Right Forearm Display Tree

Completing the Right Arm

Build the upper arm piece so you can link it with the lower arm to make the entire arm. First scale the cylinder primitive (.5,2,.5), then link the upper arm piece and forearm together using an instance node. Allow for manipulation by including a rotate node above that. Then translate the arm out to its final place in Robot (-2.5,6). This translation value is the exact X,Y coordinate location of the shoulder (the rest of the arm "hangs" below that point).

Figure 4-30 shows the series of transformations that create the right arm.

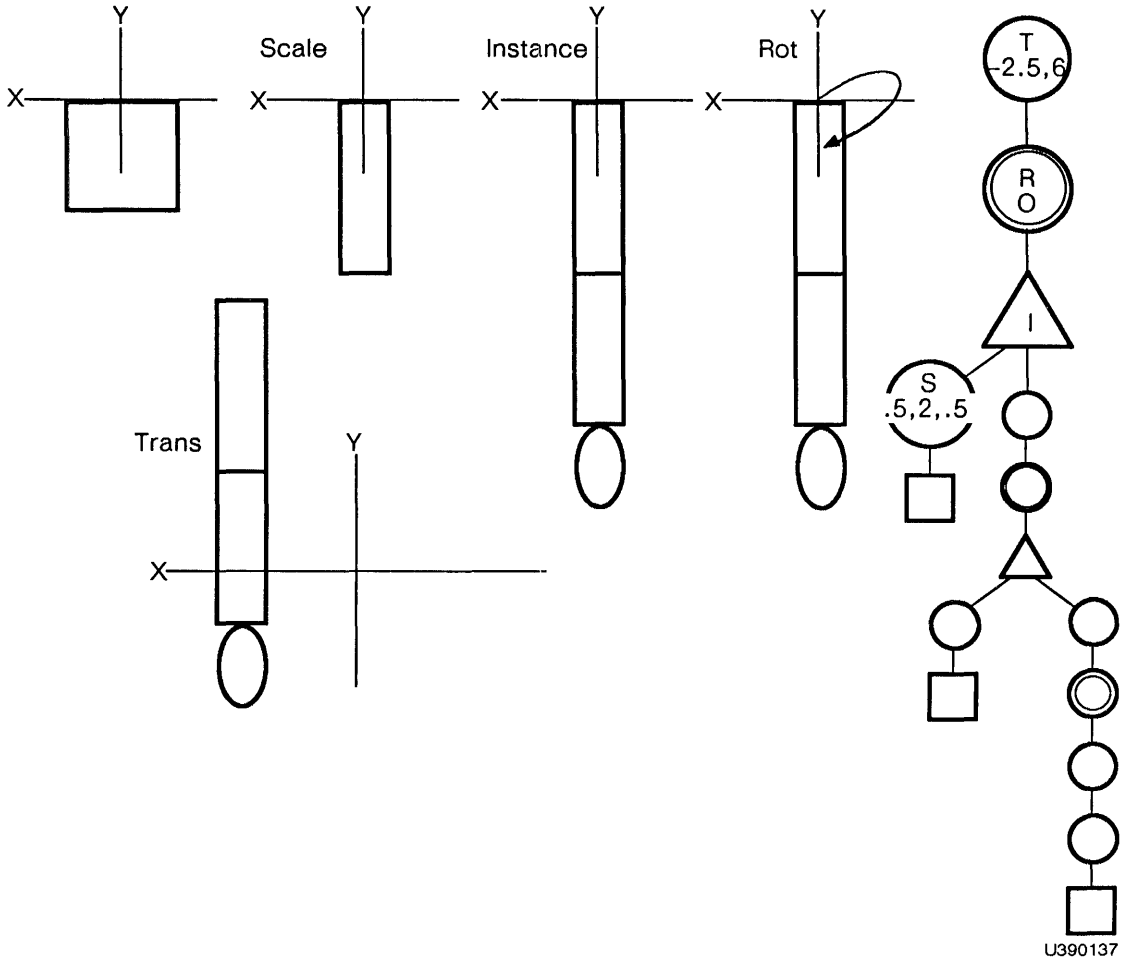


Figure 4-30. Robot—Right Arm Display Tree

Creating the Left Arm

Many of the modeling steps used to create the right arm are used to create the left arm. Rather than repeat these nodes in a second branch of the display tree, you can "share" nodes whenever possible, reducing the total number of nodes in the display tree.

For example, since a hand has already been modeled by scaling and translating a sphere, these nodes can be referenced in the other arm. However, the second hand requires a separate rotate node so the left hand can "wave" independently (Figure 4-31).

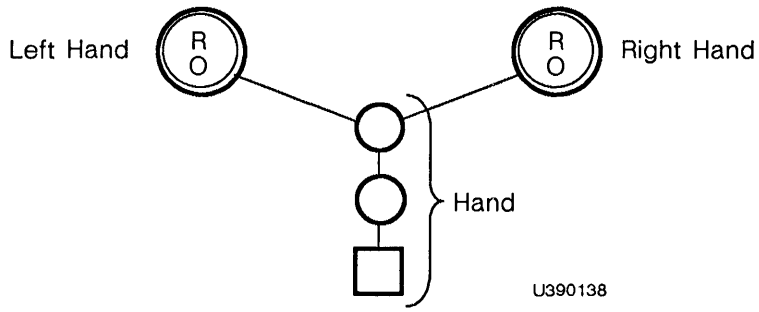


Figure 4-31. Robot—Shared Nodes for Hand

The left hand also requires its own translate node to move the hand from the origin down the Y axis the length of the forearm piece (0,–3) because one transformation cannot point directly to two descendent nodes.

The forearm piece was already created in doing the right arm, so next create left forearm as an instance of the forearm piece and the hand (Figure 4-32).

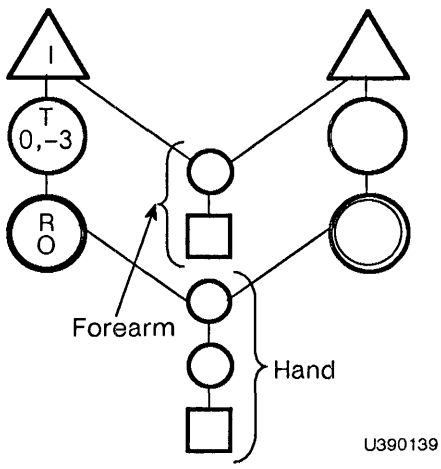


Figure 4-32. Robot—Left Forearm Display Tree

Then insert a rotate node so the lower arm moves at the elbow and translate this piece of the arm down the Y axis the length of the upper arm piece (0,–4).

The upper arm piece is already built, so it can be joined to the rest of left lower arm with an instance node. A rotate node comes next to allow for left shoulder manipulation. Then the left arm can be translated out to its final place in Robot (2.5,6).

Figure 4-33 shows the display tree for the right and left arms.

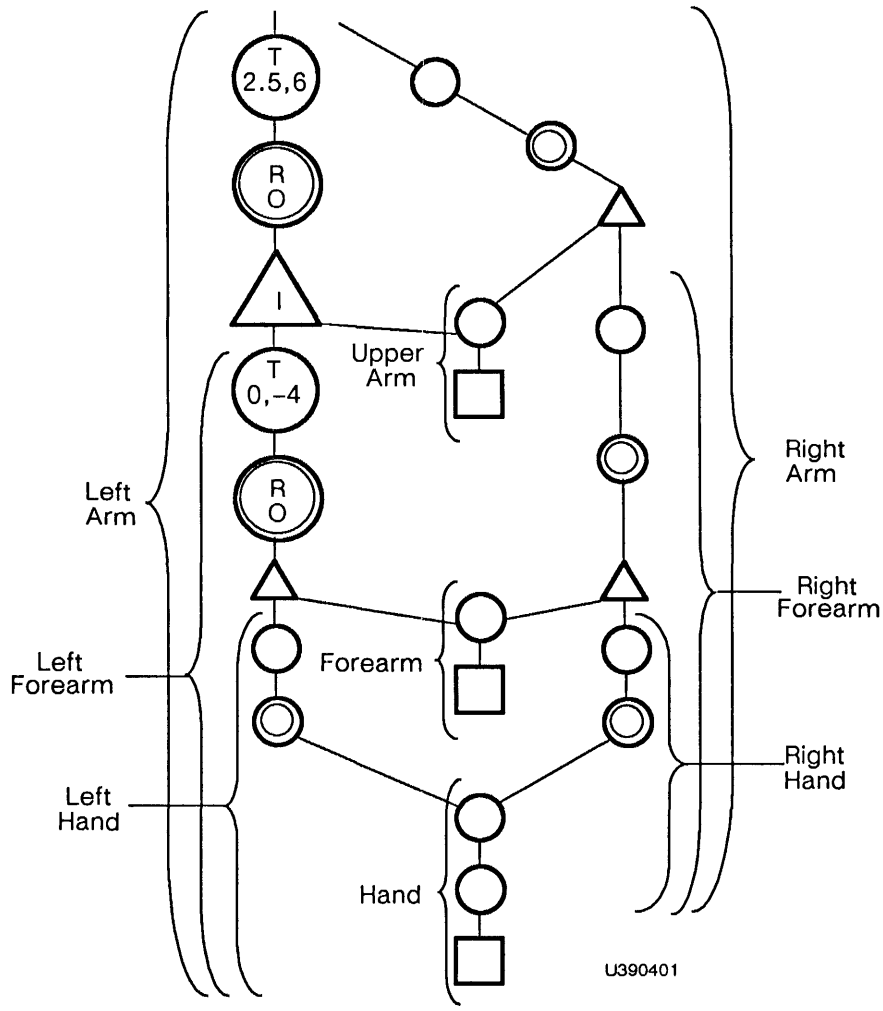


Figure 4-33. Robot—Display Tree for Two Arms

Besides the two arms, the upper body includes the head and trunk.

Creating the Head

Scale (1,2,1) the sphere primitive to create Robot's head. Then translate the head (0,1) so rotations (0,0) such as nodding and shaking the head, take place at the neck. Notice that, in this case, translating before scaling would produce the same result.

The head can then be translated to its final position (0,6). See Figure 4-34.

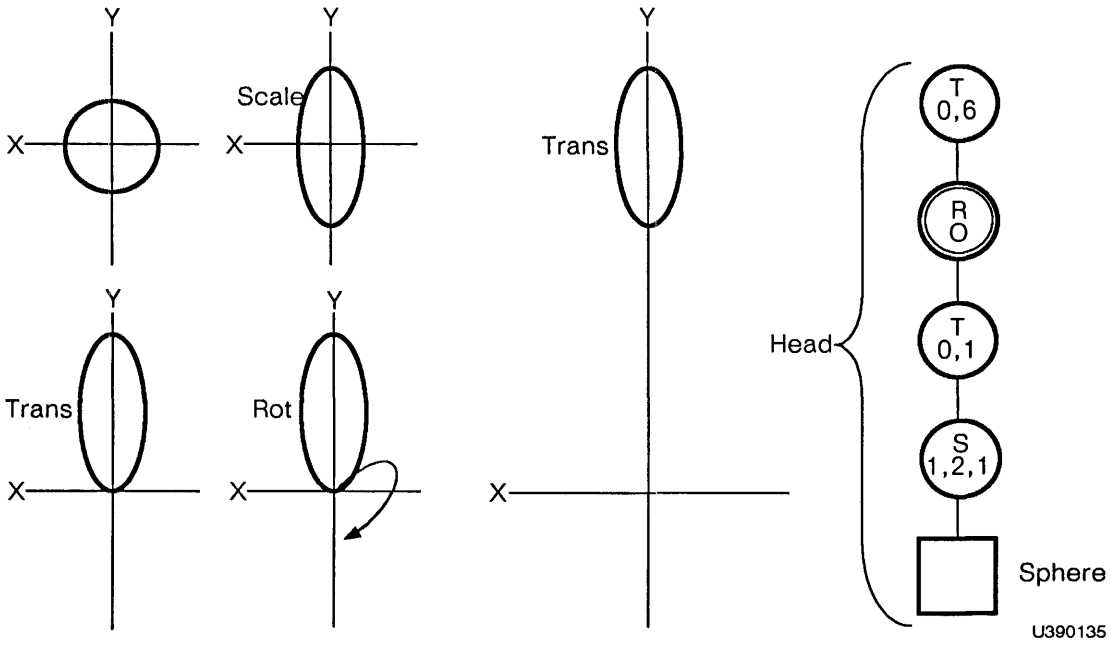


Figure 4-34. Robot—Head Display Tree

Creating the Trunk

With the arms and head built, you need only complete the trunk before linking all four together as the upper body. Scale the cylinder for the trunk (2,3,1). Then translate the cylinder up the Y axis (0,6) to its final position. This is the one time in the Robot model when it would have been better to have a cylinder primitive that rested "on top of" the X axis instead of "hanging down" from it.

Then join the arms, head, and trunk to form the upper body with an instance node. Finally, insert a rotate node above the upper body to allow Robot to bow at the waist and turn from side to side.

Figure 4-35 shows the display tree for transformations that define the trunk and also shows the display tree for the upper body of the robot.

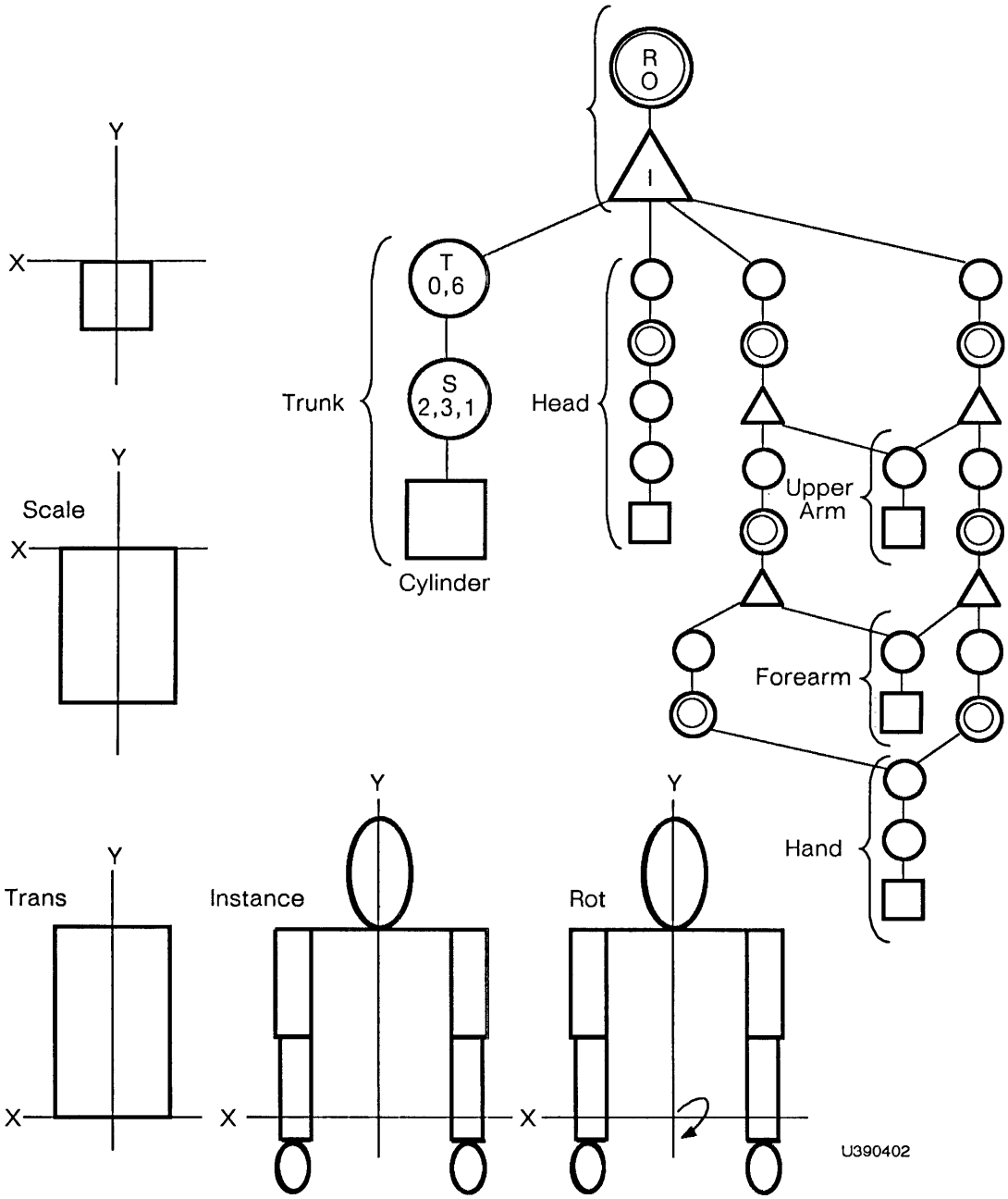


Figure 4-35. Robot—Upper Body Display Tree

No constraints have been placed on how much Robot can turn. He can rotate his head 360 degrees if desirable. If you are trying to model a human realistically, you must set limits. These are put in place using function net-

works. Refer to Section *GT7 Function Networks II* for more information on this.

The rotate node that allows Robot to bow cannot be put above the trunk alone. It must be above the instance node for the upper body in the display structure to affect all the parts of the upper body.

Now that the upper body is finished, the lower body needs to be built before they can be linked together as the entire body. Begin at the bottom of the hierarchy with the foot and build up the display tree. In building the legs, proceed as you did with the arms, sharing nodes whenever possible.

Creating the Right Foot

Because the foot is positioned perpendicular to the leg, the primitive cylinder must first be rotated 90 degrees in X. Then the cylinder can be scaled to its proper size (.75,.5,1). Finally, the scaled foot must be translated back in Z so the foot will be correctly placed on the leg (0,0,1). These transformations are shown in Figure 4-36.

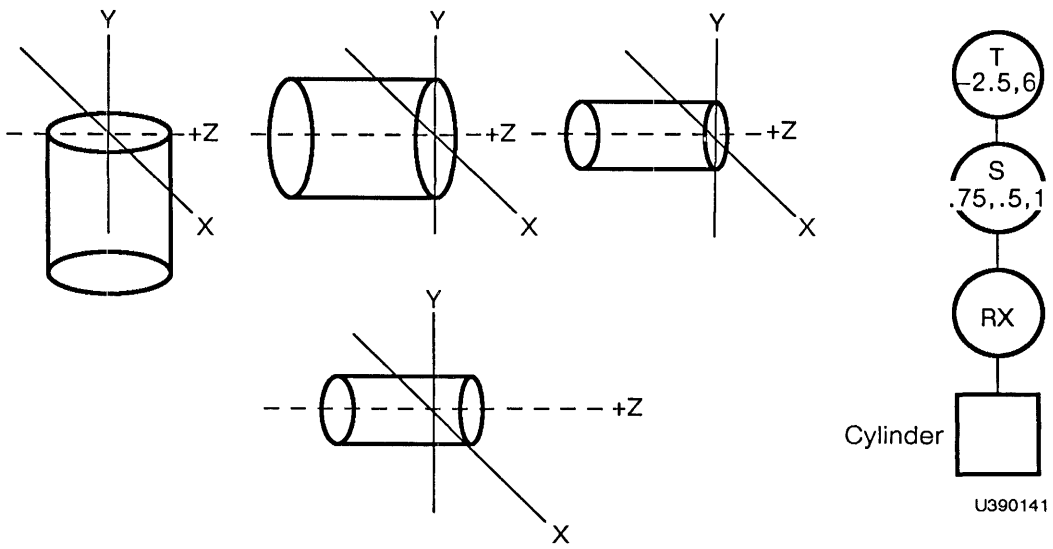


Figure 4-36. Robot—Foot Display Tree

Above the foot, place a rotate node to allow independent movement at the ankle. Then translate the foot down the Y axis so you can build the calf (0,-5.5) (Figure 4-37).

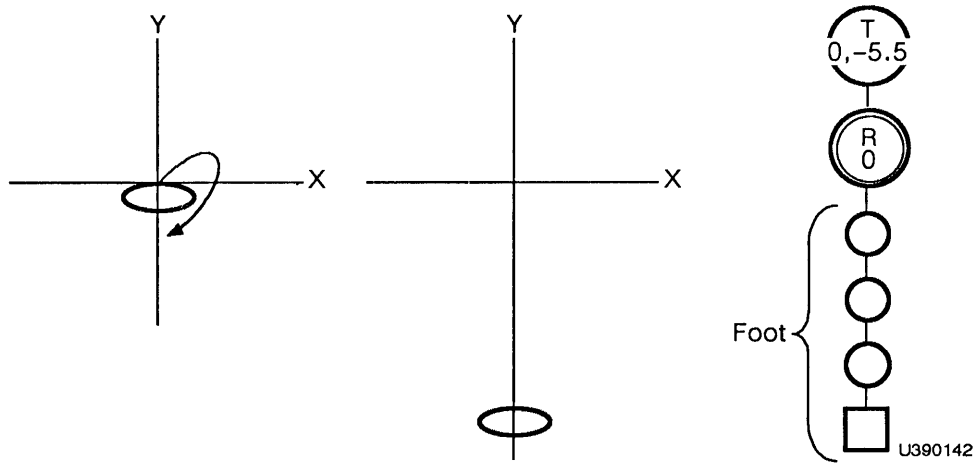


Figure 4-37. Robot—Rotate and Translate for Foot

Creating the Right Calf

Build the calf by scaling the cylinder (.65,2.5,.65). Link the calf and the foot together as the lower leg. Place a rotate node above that to allow the knee to bend, and then translate the right lower leg down the Y axis so you can build the thigh (0,–5). Figure 4-38 shows these transformations.

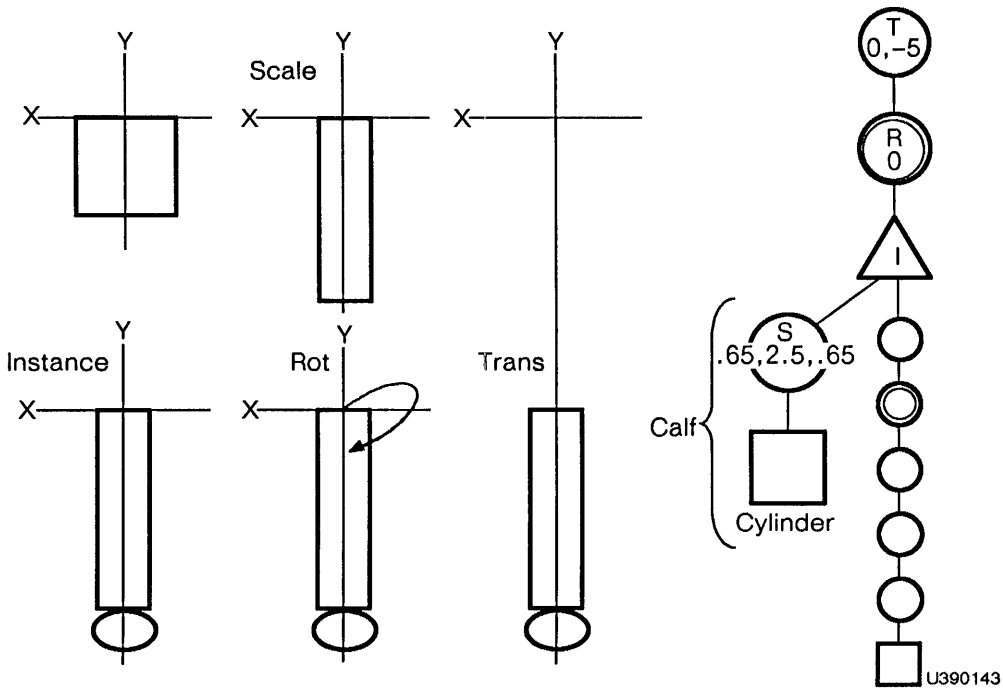


Figure 4-38. Robot—Right Calf Display Tree

Creating the Right Thigh

To create the thigh, scale the cylinder (.75,2.5,.75). Link the thigh and the lower leg together as the right leg, and put a rotate node above that to allow the leg to kick. Then translate the right leg into its final position (–1,–2).

Figure 4-39 shows the transformations that create the right thigh and the display tree for the right leg.

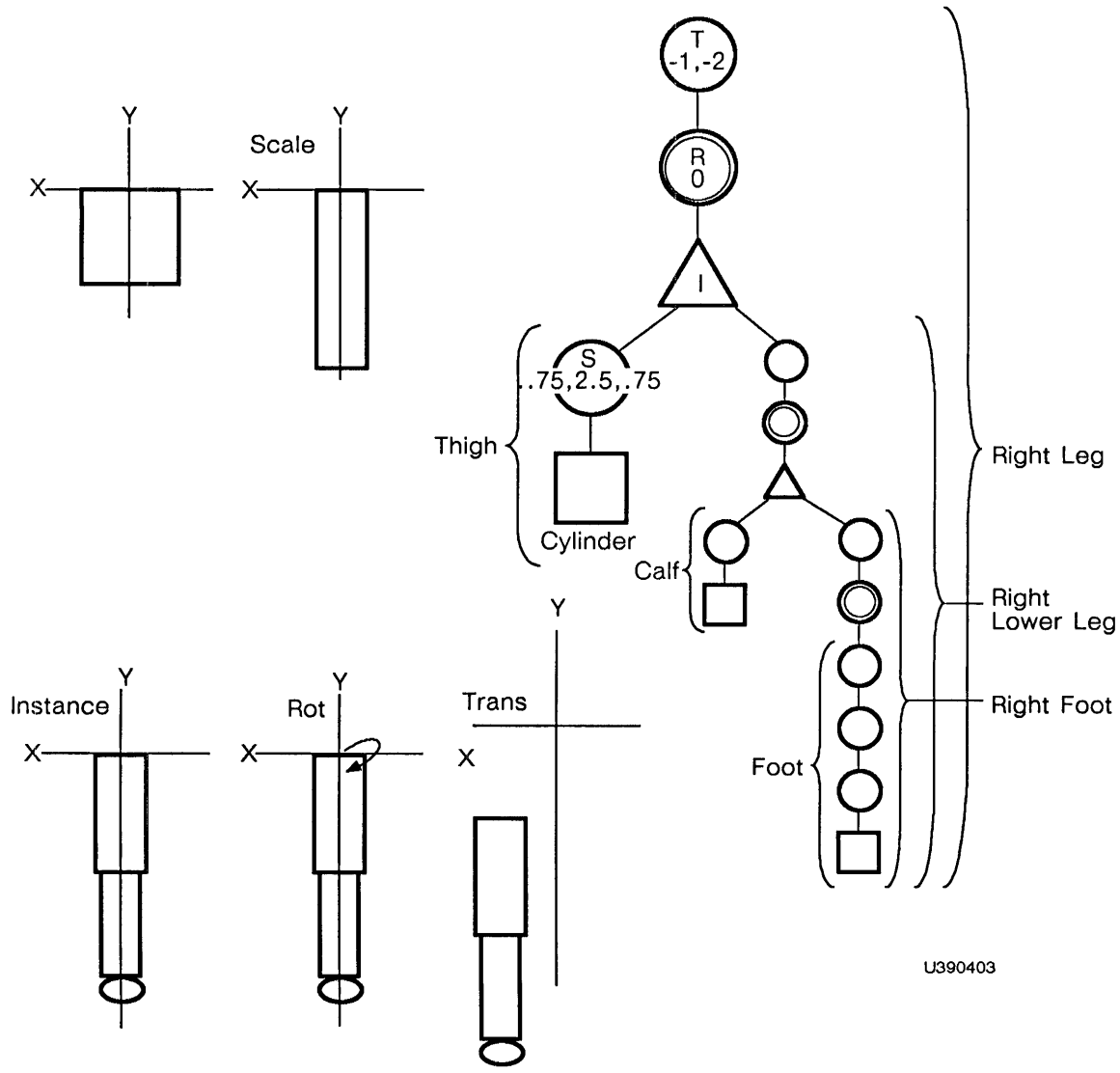


Figure 4-39. Robot—Right Thigh Display Tree

Creating the Left Leg

Many of the modeling steps used to create the right leg are used to create the left leg. Rather than repeat these nodes in a second branch of the display tree, share nodes whenever possible.

For example, since the scaled cylinders for the foot, calf, and thigh pieces are used in both legs, a single scaled primitive for each can be used by both legs.

Since the nodes to create a foot piece are already in place, the first new node needed to build the left leg will be a rotate node so the left ankle can move independently (Figure 4-40).

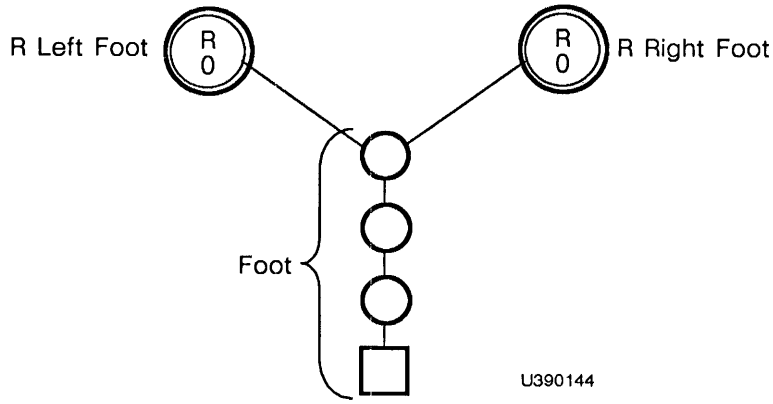


Figure 4-40. Robot—Shared Nodes for Foot

The left foot also requires its own translate node to move the foot from the origin down the Y axis the length of the calf piece (0,–5.5). (Though these translate values are the same as for the right foot, this node cannot be shared because a translate node can have only one direct descendent node.)

The calf piece was already created in doing the right leg, so create the left lower leg as an instance of the calf piece and the left foot as shown in Figure 4-41.

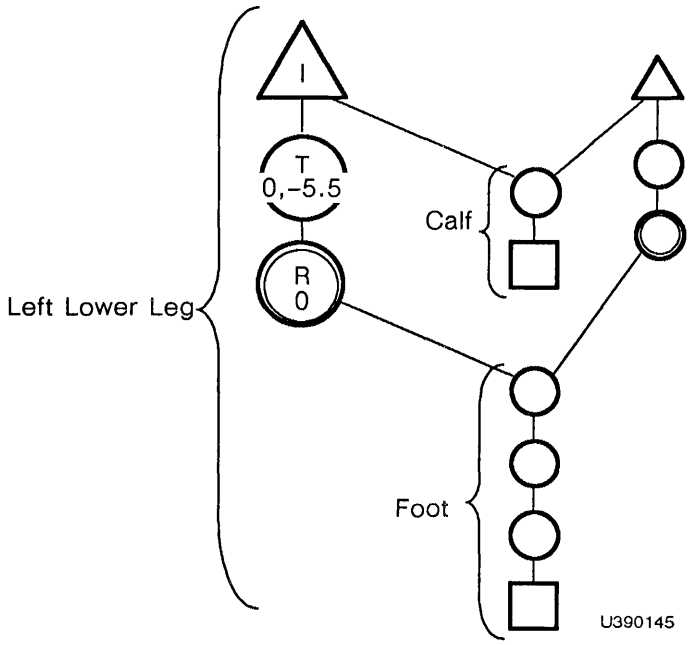


Figure 4-41. Robot—Left Lower Leg Display Tree

Then insert a rotate node so the lower leg moves at the knee and translate this part of the leg down the Y axis to make room for the thigh piece (0,–5).

The thigh piece is already built, so it can be joined to the left lower leg with an instance node. Then a rotate node can be added to allow for manipulation. Finally, the left leg can be translated out to its final place in Robot (1,–2).

Figure 4-42 shows the display tree for the left and right legs.

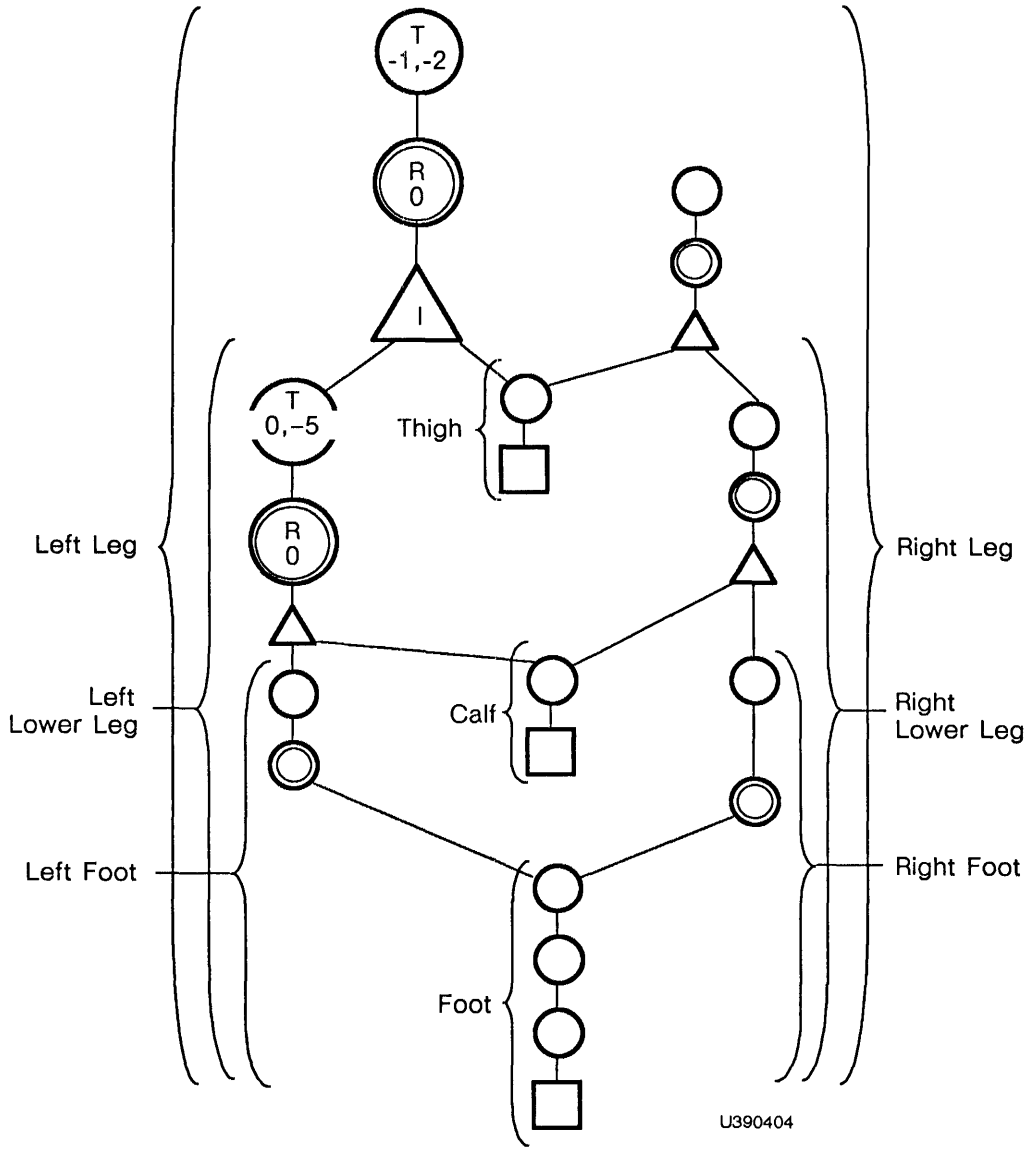


Figure 4-42. Robot—Left and Right Leg Display Tree

Creating Lowerbody

Now build the last piece of the lower body, the pelvis, and then link that with the two legs.

Scale the cylinder (2,1,1). There is no need to translate this into position, since it is already in place below the X axis and the legs have been translated down to fit under the pelvis. Link the pelvis and legs together as an instance of the lower body.

The transformations that create the pelvis, as well as the complete display tree for the lower body, are shown in Figure 4-43.

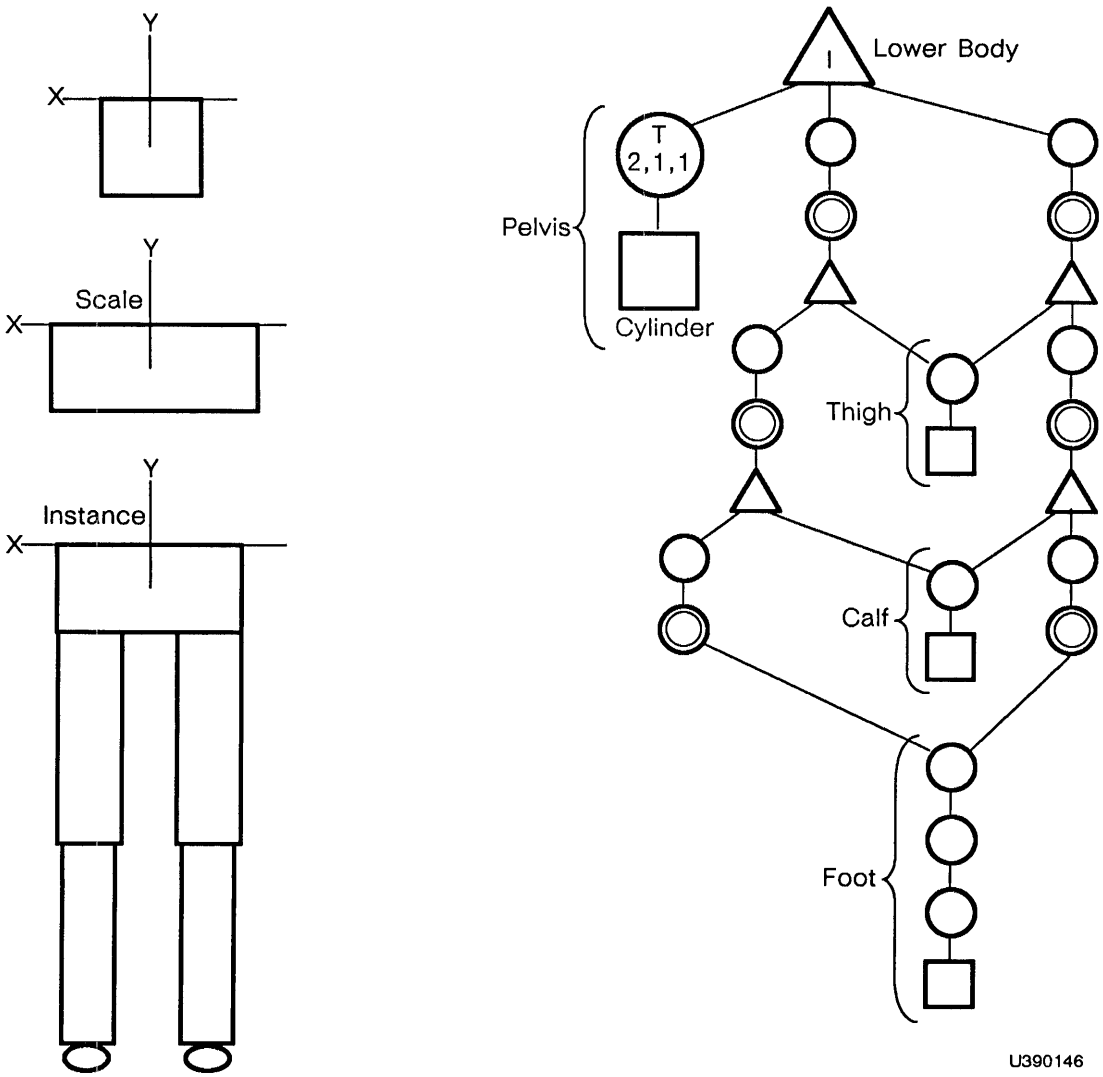


Figure 4-43. Robot—Lower Body Display Tree

Both major subparts of Robot (the upper body and the lower body) are complete. To move Robot as a whole, link the two subparts together with an instance node called Body. Then scale Robot (.075) to proportions visible on the screen (the screen coordinates are positive 1 to negative 1 on the X and Y planes). Finally, allow for rotation and translation of the whole robot with the top two nodes.

The completed display tree for Robot is shown in Figure 4-44.

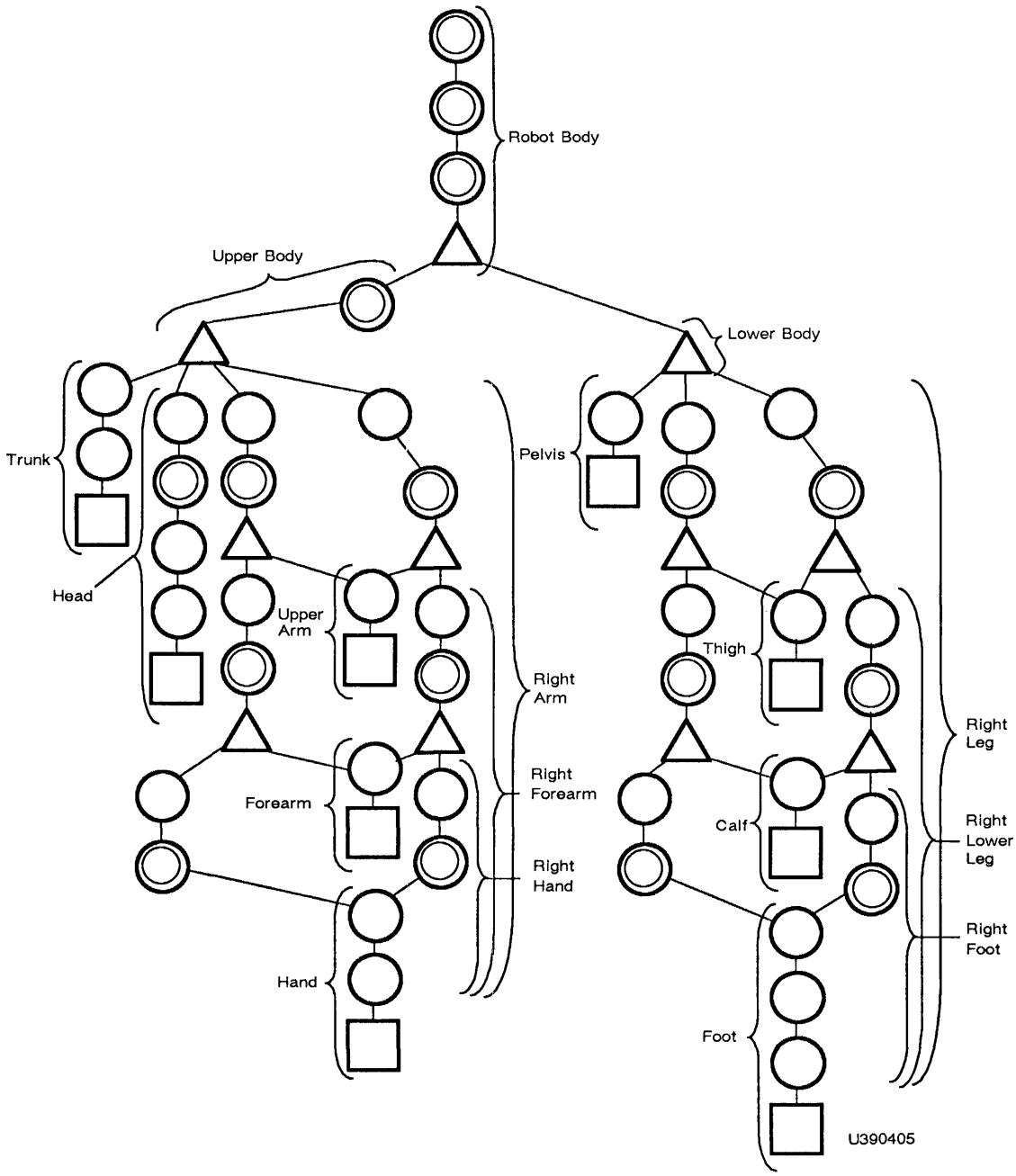


Figure 4-44. Robot—Completed Display Tree

4. Summary

This section details the major steps in designing a conceptual data base:

- Designing a hierarchy
- Designing a display tree

In designing a display tree, you must first be aware of what the model looks like, what attributes you want associated with particular parts, where it is to be placed in the world coordinate system, what primitives it is made of, and how you want to interact with it.

You can then divide your model into pieces and group those pieces into a hierarchy which shows how they relate to each other.

Finally, you should design the display tree from the bottom up, using the hierarchy as your basis of organization. The design process is as much an art as it is a science, requiring attention to detail, synthesis of information, and a good knowledge of the rules governing display trees.

There are certain rules governing display trees which you should be aware of. For your convenience, these rules have been summarized in Table 4-1. A more lengthy summary on data, operation and instance nodes follows Table 4-1.

Section *GT5 Command Language* explains how to code a display tree into the PS 390 using PS 390 commands. It is highly recommended that you read that section next.

Table 4-1. Rules for Display Trees

NODE TYPE	FUNCTION	POINTERS TO OTHER NODES	COMMENTS
DATA	Vector lists, characters, curves, polygons.	0	Data nodes are always terminal nodes in a data structure.
OPERATION	Operation to be performed on data further down the hierarchy. Examples include—translate, rotate, character font, set level-of-detail, etc.	0 or 1	0 pointers makes this node and the path to it useless. All terminal nodes in a data structure should be data nodes.
INSTANCE	Point to other nodes. Save and restore the state of the machine between descendent branches. The state of the machine includes: A. The current transformation matrix (CTM) B. Current level-of-detail C. Current conditional bits values D. Pick IDs active	0,1,2,...	Except for some debugging uses, 0 or 1 pointers from an instance node is an inefficient data structure.

The remaining part of this section details important rules to follow when designing display trees.

Data Nodes

Data nodes represent the primitive shapes that compose a model. Data nodes are always the terminal (bottom) nodes in any display structure; they never "point to" other nodes.

The data base that defines primitives may originate from several sources. You may have been given the geometry already from another source. For example, if you are an architect, you may already have access to primitive shapes to define windows, doors, roofs, and buildings.

You can specify all the vectors in a primitive, or you might use commands to specify characters, curves, and polygonal primitives.

- Vector lists define an object in terms of its coordinate points and how to connect them. Points and line endpoints are expressed as world coordinate locations. The VECTOR_LIST command allows you to specify all the vectors that make up an object.
- You can use line patterns (dashes, center lines, etc.) to draw a vector list with the WITH_PATTERN command.
- The PS 390 allows you to generate vector lists that specify curves using POLYNOMIAL and BSPLINE commands.
- Characters are ASCII character codes that are displayed using a predefined character font. Both the CHARACTERS and LABELS commands define an object as a character string. Refer to Section *GT10 Text Modeling and String Handling* for details on characters.
- Polygons can be created to define surfaces for advanced 3D visualization operations. Refer to Section *GT13 Polygonal Rendering* for more information on this.
- Interactive devices are commonly connected to operation nodes in a display structure, but they can also be connected to other nodes. For example, you can use a dial or data tablet to generate points for a vector list.

Though a data node never points to another node, it can have multiple parents (more than one operation or instance node pointing to it). For example, to display a windmill with four identical blades, the display structure might reuse a single data node translated to distinct locations (Figure 4-45).

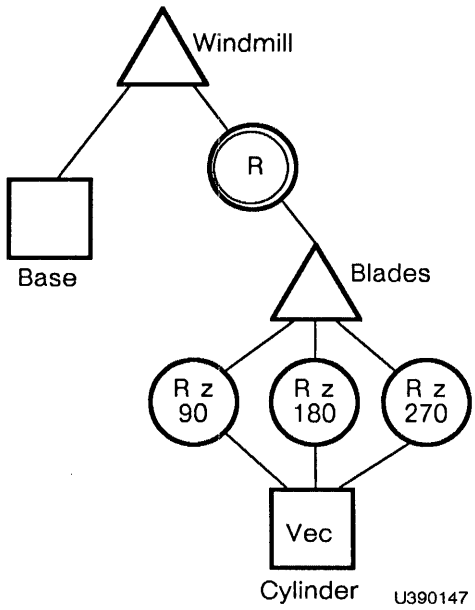


Figure 4-45. Windmill Display Tree #1

Another way to create a display tree for the same windmill is to define all four blades in a single vector list, as in Figure 4-46. Creating this display tree might be more programming work (specifying the points and lines which form each blade) but eliminates four nodes: three operate nodes and one instance node.

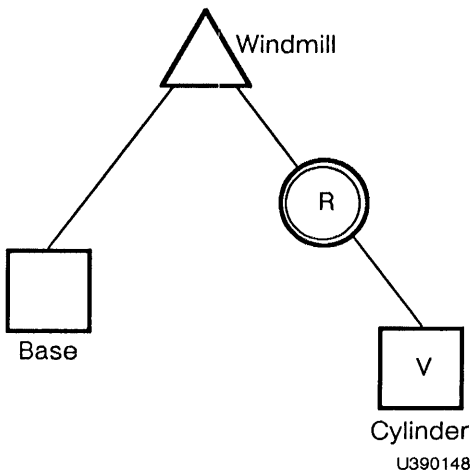


Figure 4-46. Windmill Display Tree #2

This model is simple. Four nodes is not a significant savings unless the blades are to be instanced many times. But in a complex model, you may

save nodes by carefully analyzing the pieces of the model that are better defined with a single vector list.

The tradeoffs are that models made of numerous transformed primitives may be easier and quicker to code than a single vector list of plotted lines and points. However, it often takes a longer time for the display processor to traverse the extra transformation nodes than it does to traverse the single vector list. A longer vector list uses more available memory, and may take longer to program, but it reduces the time required for picture refresh.

To save you the trouble of plotting all the points and lines initially, the PS 390 has a group of commands and functions that convert a data base consisting of transformed data into a single vector list for you. Refer to Section *GT12 Transformed Data and Writeback* for more information on this.

Operation Nodes

An operation node represents an operation to be performed on data below it in the display tree. Operation nodes are used to represent all types of operations, including translations, rotations, and attributes such as set level-of-detail and color.

As part of a display tree, an operation node affects only what is below it on a hierarchical branch. Although an operation node can have multiple nodes pointing to it, it can point to no more than one node below it (Figure 4-47).

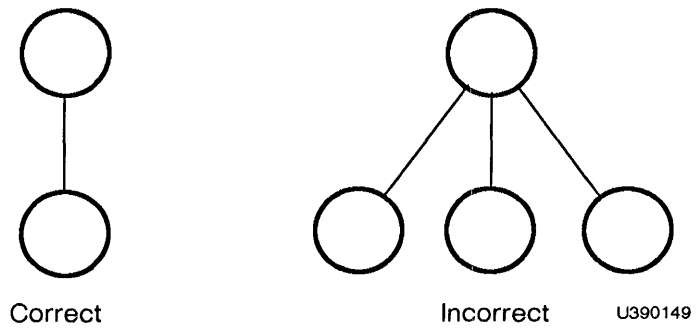


Figure 4-47. Correct and Incorrect Usage of Operate Nodes

Operation nodes can point to a data node, an instance node, or another operation node. However, if a display tree contains a series of operation nodes, the order of the operations is significant. Put the node for the first operation to be performed on the data closest to the data node. Place the second operation node above that, and so on.

Operation nodes are used in two ways: for modeling and for interaction. Modeling operations are done strictly to shape the "building blocks" of a model and move them into place. Interaction operations allow you to interact with a model. Any operation node can be one or the other, depending on how it is used.

On the display tree diagrams, an interaction node is differentiated from other operation nodes by a double circle.

Interaction nodes allow you to interactively translate an object in X, Y, or Z; rotate that object around any one axis; or scale the object. In addition, you can alter the typeface of displayed text by changing the character font, apply viewing transformations (to create a limitless number of different views of an object), or specify viewports (different areas on the screen where the object is displayed).

Interaction nodes receive their values either from interactive devices or from a host computer via a function network. For more information on function networks, refer to Section *GT6 Function Networks I.*

Instance Nodes

Instance nodes serve two purposes:

First, they group other nodes and branches in a display tree. Instance nodes are the only nodes that can point to more than one descendant node in the display tree. Consequently, they are found wherever a hierarchical display tree breaks into more than one descending branch.

Second, instance nodes save and restore the state of the machine between descendant branches. The state of the machine includes the current transformation matrix, the current level of detail, current color, and status of pick identifiers. For more information on this, refer to Section *GT2 Graphics Principles* and to specific tutorial sections.

Instance nodes save you from having to save and store data explicitly before a path is traversed, thus preserving the integrity of the state of the machine down any path. As a quick review, look at the way in which the display processor saves and restores the state of the machine in the display tree shown in Figure 4-48. It is an illustration of the principle of sphere of influence.

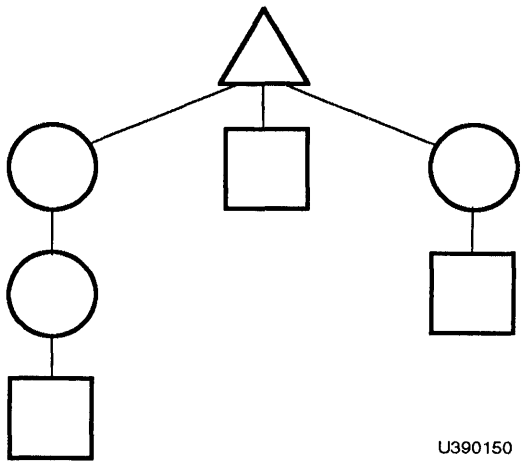


Figure 4-48. Sphere of Influence

When the display processor traverses this display tree, it saves the machine state when it reaches the instance node. It then continues down the leftmost branch until it reaches the data node. The data there are sent through the current transformation matrix and out to be displayed.

The display processor still has to travel down the other branches under the instance node. But the state of the machine is altered by the two operations in the first branch, so it must be restored to what it was when the display processor first traversed the instance node. Since the machine state is saved when it first reaches the instance node, it can be restored to that state.

The display processor returns to the instance node, restores the state that is saved there, and continues down the next branch to the right (the data node). The display processor sends that data through the matrix and out for display, returns to the instance node, restores the state, and travels down the last branch in the structure.

Saving the state of the machine ensures that operations in one branch can accumulate and affect everything below them in the display structure, and still not affect anything in other branches.

If an instance node points directly to data nodes, the state is not saved and restored because data nodes do not "operate" on or alter the state of the display processor (Figure 4-49).

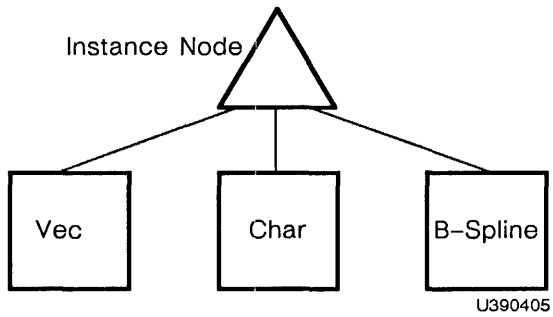


Figure 4-49. Instance Node Pointing to Three Data Nodes

GT5. COMMAND LANGUAGE

COMMUNICATING WITH THE PS 390

CONTENTS

ILLUSTRATIONS

Section GT5
Command Language
Communicating With The PS 390

Introduction

Once you have designed the display tree of the model, you can code the display tree into the PS 390 using PS 390 commands. PS 390 commands:

- Create display trees.
- Modify display trees by sending new information to nodes.
- Create and modify function networks (refer to Section *GT6 Function Networks I*).
- Instruct the display processor to display items or remove them from the display list.
- Query or reset the command interpreter (such as COMMAND STATUS or !RESET).

PS 390 commands are not stored in memory. They are interpreted and either execute immediately (e.g., DISPLAY OBJECT;) or create a data entity in mass memory.

Two kinds of PS 390 commands are detailed in this section: data structuring commands and immediate action commands.

Data structuring commands are the only commands that can be named, either directly or indirectly. Data structuring commands create the data structures in mass memory which correspond to the display tree of a model or to a function network. (Data structuring commands that create function networks are dealt with in Section *GT6 Function Networks I.*) The PS 390 associates the user-assigned name of the command with the mass memory location of the data structure the command creates.

Naming can be done explicitly by giving a unique name to a single node in a display tree, such as naming a rotation node. It can also be done via BEGIN_STRUCTURE ... END_STRUCTURE, where a single name is assigned to a group of nodes.

Data structuring commands can be created in a file or an application program on the host system and then downloaded to the PS 390, or an application program can send these commands either directly in ASCII, or via the Graphics Support Routines (GSRs) in PS 390 binary format (preparsed).

The other type of command, the immediate action command, performs immediate operations, such as displaying an object on the screen. Because it does not create any autonomous structures in mass memory, an immediate action command cannot be named.

PS 390 commands are designed to be easy to use. Once you are familiar with how commands are used, you can refer to Section *RM1 Command Summary* for quick explanations of all existing commands.

You will also want to become familiar with the Graphics Support Routines (GSRs). These are a collection of routines or procedures which allow faster, more efficient communication between the PS 390 and the host computer. Using a Graphics Support Routine (GSR) causes a corresponding command to be sent directly to the PS 390 without requiring further parsing. The GSRs are contained in Section *RM4.*

All commands follow these conventions:

- Commands end with a semicolon.
- The name of each command is indicative of what the command does (for example, INITIALIZE, DISPLAY, and ROTATE).
- Commands have both a long and a short form. The short form is the shortest form of the word that uniquely identifies the command. For example, DELETE can be referenced by DEL; APPLIED TO can be referenced by APPL. In this section, a PS 390 command will be written out fully in capital letters. For the short form of any command, consult Section *RM1 Command Summary.*
- Commands may be entered in uppercase or lowercase letters or any combination of these. The PS 390 does not distinguish between upper and lower case.

- The PS 390 command language is free formatted. Comments go wherever you can put a space and are enclosed in curly braces.

  {This is a comment}

- Comments, carriage returns, line feeds, spaces, and tabs are all treated as delimiters (white space). If a command extends beyond a single line, the PS 390 reads each line as part of the command until it reads a semicolon. For example, the PS 390 interprets all of the following commands in the same way:

```
ROTATE IN X 0 {comment} APPLIED TO Object;
ROTATE IN X 0                THEN Object;
ROTATE IN X 0   <TAB>APPLIED TO Object;
ROTATE IN X 0 <RETURN>
THEN Object;
```

Objectives

In this section, you will use PS 390 commands to create a model in PS 390 mass memory and to display that model on the screen. To do this you will learn to:

- Use explicit naming.
- Use BEGIN_STRUCTURE ... END_STRUCTURE commands.
- Use immediate action commands.
- Enter code into the PS 390.

Prerequisites

Before reading this section, you should be able to design a display tree (refer to Section *GT4 Modeling*). You should also be able to perform the operations detailed in Section *IS3 Operation and Communication*. This includes how to switch to terminal emulator mode, how to use the text editor on your host, and how to download a file from the host.

1. Using Explicit Naming

Once you have the display tree of the model designed on paper, you can code the structure into mass memory by entering data structuring commands into a file on the host. Data structuring commands create each node in the display tree of the model. Each command must be named either directly or indirectly. The name provides the "address" in mass memory for locating the corresponding data structure. Which commands to use are determined by the display tree of the model, like using a flowchart to determine code in conventional programming. One way to code is to have one named command correspond to each node in the display tree. This is called "explicit naming." Another way is to group numerous nodes together in one named command. This is done using the BEGIN_STRUCTURE ... END_STRUCTURE command. Most often, a combination of the two methods is used. With either method, use the following naming conventions:

- Names can be up to 240 characters long. The name can be any alphanumeric combination but it must begin with a letter. The PS 390 does not distinguish between uppercase and lowercase letters, so use these for clarification, such as in the example: RightLowerArm.

- Names can include the underscore character (_), a dollar sign ($), or a period (.). However, it is strongly recommended that you do not use periods when explicitly naming something. The PS 390 automatically inserts periods in the name of nodes contained in a BEGIN_STRUCTURE ... END_STRUCTURE. For example, a node named *Rot* within a BEGIN_STRUCTURE ... END_STRUCTURE that you named *Hand* will automatically be named *Hand.Rot* by the PS 390.

- Names cannot contain a space or other "white space" (return, tab, etc.). These signal the end of a name. It may be convenient to run words together in a name (RightArm) or to use underscores (Right_Arm).

- Names must be unique.

The following PS 390 commands can be used in conjunction with the naming of data structures:

- Use the command (:=) for naming display data structures:

```
Name := display_structure_command;
```

- A null data structure can be named using:

```
Name := NIL;
```

  The command can also be used to redefine a name. The command saves the name but redefines the associated structure.

- The FORGET command deletes the name assigned to a command but saves the associated structure.

- The DELETE command removes both the name and the associated structure.

Primitives (data nodes) are created by specifying a series of points and the lines or planes that connect them. Several PS 390 commands create primitive shapes:

```
VECTOR_LIST
POLYGON
BSPLINE and RATIONAL BSPLINE
POLYNOMIAL and RATIONAL POLYNOMIAL
CHARACTERS
LABELS
```

Text is also a graphical primitive. The CHARACTERS command and the LABELS command create data nodes for displaying text.

This section will not cover how to create data nodes. Rather than listing all the points and lines required to build any data primitive in this section, a VECTOR_LIST command will be represented by the following abbreviated notation:

```
Name := VECTOR_LIST ... ;
```

Do not enter this abbreviated notation into the PS 390. Any data nodes you will need for exercises on the PS 390 have already been provided for you on

the tutorial tape. For more information on creating data nodes, refer to Section *RM1 Command Summary.*

Using explicit naming, code the right forearm for the Robot that was designed in Section *GT4 Modeling*. The display tree looked like this:

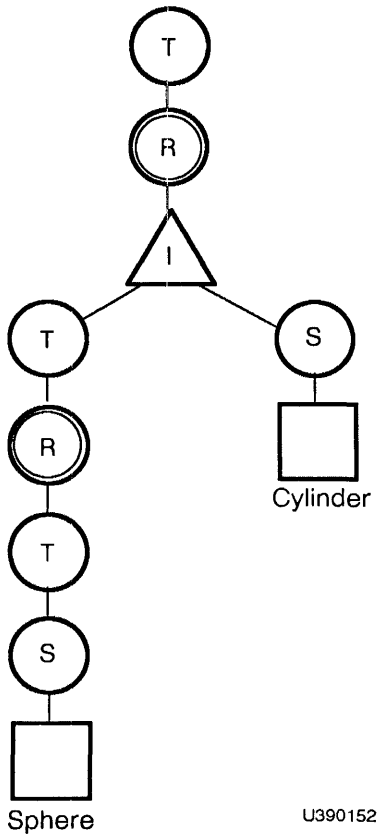


Figure 5-1. Display Tree for Robot's Forearm

Start from the top down.

```
TranRtLowerArm := TRANSLATE BY 0,-4 APPLIED TO RotRtLowerArm;
RotRtLowerArm := ROTATE 0 APPLIED TO RtLowerArm;
RtLowerArm := INSTANCE OF ForearmPiece, TranHand;
ForearmPiece := SCALE BY .5,1.5,.5 APPLIED TO Cylinder;
Cylinder := VECTOR_LIST ... ;
TranHand := TRANSLATE BY 0,-3 APPLIED TO RotHand;
RotHand := ROTATE 0 APPLIED TO TranSphere;
TranSphere := TRANSLATE BY 0,-1 APPLIED TO ScaleSphere;
ScaleSphere := SCALE BY .5,1,.5 APPLIED TO Sphere;
Sphere := VECTOR_LIST ... ;
```

Zeros are given as the values for interactive nodes such as RotRtLowerArm and RotHand because new values will be provided interactively from function networks. With explicit naming, a command can refer, or point, to a name that does not exist yet. The name exists once the PS 390 receives a command defining the data structure associated with that name. Explicit naming has some disadvantages. First, it can be confusing with a complex display tree because you may have hundreds of command names to create and keep track of. Effective comment lines would be essential. The major drawback of explicit naming is that it forces you to name every node in a display tree. This means unnecessary work. The only nodes requiring names are nodes you want to directly reference. There is no need to name nodes that you can safely predict will not receive new values, or be instanced or displayed directly.

1.1 Exercise

In Section *GT4 Modeling,* you designed a display tree for a car. That display tree is shown in Figure 5-2.

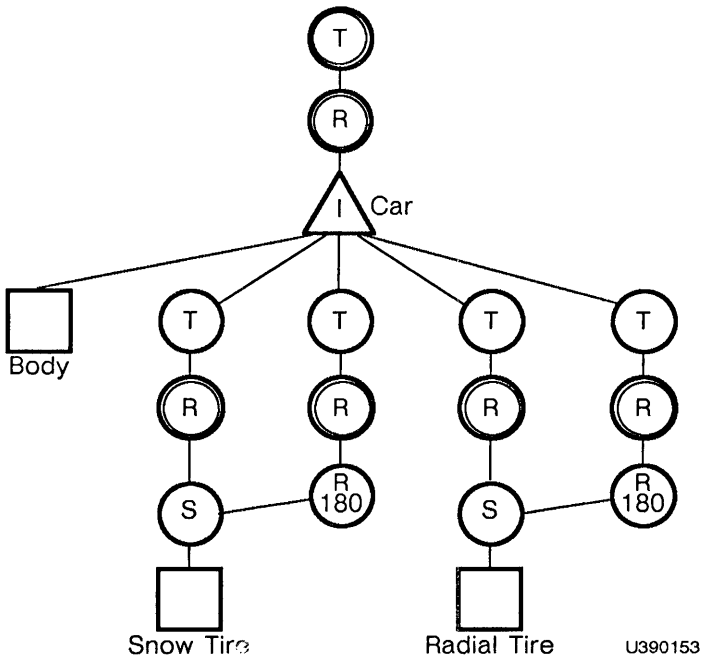


Figure 5-2. Car Display Tree

Code this display tree from the top down using explicit naming. The values provided below have been calculated to produce the desired transformations. The first two nodes are interactive nodes which translate and rotate the whole car:

```
TranCar := TRANSLATE BY 0,0 APPLIED TO RotCar;
RotCar := ROTATE 0 APPLIED TO SportsCar;
```

The car is defined as an instance of the car body and the translations applied to each tire:

```
SportsCar := INSTANCE OF Car_Body, Tran_FR_Tire, Tran_FL_Tire,
             Tran_RR_Tire, Tran_RL_Tire;
```

Define the radial on the rear, right side of the car. A translation node and an interactive rotation node are needed:

```
Tran_RR_Tire := TRANSLATE BY -.5664,-.1598,-.3357 THEN Rot_RR_Tire;
Rot_RR_Tire := ROTATE IN Z 0 THEN Scaled_Radial_Tire;
```

Since both radial tires are scaled, the scaled radial tire can be defined once and then referenced with each tire.

```
Scaled_Radial_Tire := SCALE BY .139 THEN Radial_Tire;
```

The display tree for the radial on the rear, left side of the car also includes a translation and rotation node:

```
Tran_RL_Tire := TRANSLATE BY -.5664,-.1598,.3357 THEN Rot_RL_Tire;
Rot_RL_Tire := ROTATE IN Z 0 THEN Flip_RL_Tire;
```

Then the tire is rotated so the hubcap faces out:

```
Flip_RL_Tire := ROTATE IN Y 180 THEN Scaled_Radial_Tire;
```

The same process is used for the snow tires. Both snow tires consist of a translation and interactive rotation node. Then the snow tire on the front, left side of the car is rotated so the hubcap faces out.

The code for the snow tire on the front, right side of the car would be:

```
Tran_FR_Tire := TRANSLATE BY .5415,-.1598,-.3357 THEN Rot_FR_Tire;
Rot_FR_Tire := ROTATE 0 THEN Scaled_Snow_Tire;
```

Since both snow tires are scaled, the scaled snow tire can be defined once and then referenced twice.

```
Scaled_Snow_Tire := SCALE BY .139 THEN Snow_Tire;
```

The code for the front left snow tire would be:

```
Tran_FL_Tire := TRANSLATE BY .5415,-.1598,.3357 APPLIED TO
                Rot_FL_Tire;
Rot_FL_Tire := ROTATE 0 APPLIED TO Flip_FL_Tire;
Flip_FL_Tire := ROTATE IN Y 180 APPLIED TO Scaled_Snow_Tire;
```

The points and connecting lines for the three primitives must also be defined. In this section, that code is represented by:

```
Snow_Tire := VECTOR_LIST ... ;
Radial_Tire := VECTOR_LIST ... ;
Car_Body := VECTOR_LIST ... ;
```

Since the data primitives for Snow_Tire, Radial_Tire, and Car_Body are already provided for you when you load the PS 390 Tutorial Demonstrations tape, display the car by typing:

```
DISPLAY SportsCar;
```

To prepare for the new definition of SportsCar you will be coding in the next section, enter:

```
INITIALIZE;
```

This removes the present definition of SportsCar you just coded in.

2. Using BEGIN_STRUCTURE ... END_STRUCTURE

An alternative to naming every node is to group nodes inside a BEGIN_STRUCTURE ... END_STRUCTURE. Though each node within a BEGIN_STRUCTURE ... END_STRUCTURE is created in mass memory, you only have to name those nodes which will be accessed again. (The display processor "accesses" the node every time the model is displayed.)

Besides less naming, another advantage of the BEGIN_STRUCTURE... END_STRUCTURE is that it is an effective way to organize the commands in your file. In a complex display tree, nodes that directly affect each other can be grouped together in the same BEGIN_STRUCTURE ... END_STRUCTURE.

BEGIN_STRUCTURE ... END_STRUCTURE is usually used in conjunction with explicit naming. To illustrate this, code SportsCar using a combination of the two. There are many ways to code a model. The following is only one possible way of determining which type of code to use.

Before coding, identify all data nodes and any shared nodes in the display tree of the car. In this case, there are three data nodes: the car body, the radial tire, and the snow tire. The scaled radial tire and scaled snow tire are shared nodes.

Now look at the branches above any shared nodes, data nodes, and instance nodes, for those which have two or more operation nodes. These nodes could be grouped into a BEGIN_STRUCTURE ... END_STRUCTURE.

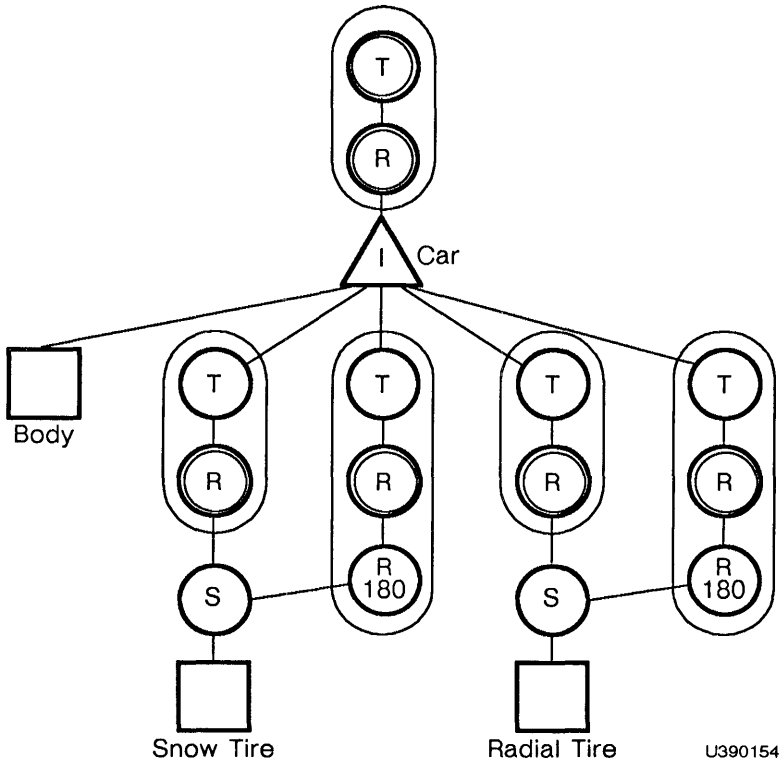


Figure 5-3. Possible BEGIN_STRUCTURE ... END_STRUCTUREs for Car

Begin coding the display tree top down. The first two commands allow you to see the car immediately once it is defined.

```
INITIALIZE DISPLAY;
DISPLAY SportsCar;
```

The display tree begins with a BEGIN_STRUCTURE ... END_STRUCTURE:

```
SportsCar := BEGIN_STRUCTURE
     Tran := TRANSLATE BY 0,0;
      Rot := ROTATE 0;
              INSTANCE OF Car_Body, RL_Tire, RR_Tire, FL_Tire, FR_Tire;
             END_STRUCTURE;
```

The interactive translation and rotation nodes must be explicitly named so they can be accessed to provide values to manipulate the car. Grouping these nodes in a BEGIN_STRUCTURE ... END_STRUCTURE saves you

from having to name the instance node. Naming the whole structure also allows you to reference a "Car" that can be rotated and translated.

Each tire could be defined within a BEGIN_STRUCTURE ... END_STRUCTURE:

```
{Rear left wheel}

   RL_Tire := BEGIN_STRUCTURE
                TRANSLATE BY -.5664,-.1598,.3357;
       Rot :=   ROTATE 0;
                ROTATE IN Y 180 APPLIED TO Scaled_Radial_Tire;
              END_STRUCTURE;

{Rear right wheel}

   RR_Tire := BEGIN_STRUCTURE
                TRANSLATE BY -.5664,-.1598,-.3357;
       Rot :=   ROTATE 0 APPLIED TO Scaled_Radial_Tire;
              END_STRUCTURE;
```

Scaled_Radial_Tire references a scale operation node and a data node. These two nodes can be shared by both the right and the left rear tires. Notice how the operations within the BEGIN_STRUCTURE ... END_STRUCTURE reflect the order indicated in the display tree; i.e., translates precede rotates, which precede scaled data. In much the same way, the last two branches define the snow tire:

```
{Front left wheel}

   FL_Tire := BEGIN_STRUCTURE
                TRANSLATE BY .5415,-.1598,.3357;
       Rot :=   ROTATE 0;
                ROTATE IN Y 180 APPLIED TO Scaled_Snow_Tire;
              END_STRUCTURE;

{Front right wheel}

   FR_Tire := BEGIN_STRUCTURE
                TRANSLATE BY .5415,-.1598,-.3357;
       Rot :=   ROTATE 0 APPLIED TO Scaled_Snow_Tire;
              END_STRUCTURE;
```

The shared nodes for each tire are coded as:

```
Scaled_Radial_Tire := SCALE BY .139 APPLIED TO Radial_Tire;
Scaled_Snow_Tire := SCALE BY .139 APPLIED TO Snow_Tire;
```

The three primitives also need to be defined. The actual vector lists for these have been provided for you in the PS 390 Tutorial Demonstrations tape, so that you may see SportsCar. The following abbreviated code is just to remind you that primitives must always be defined:

```
Snow_Tire := VECTOR_LIST ... ;
Radial_Tire := VECTOR_LIST ... ;
Car_Body := VECTOR_LIST ... ;
```

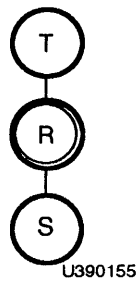
In general, then, a BEGIN_STRUCTURE ... END_STRUCTURE:

- Groups associated nodes together into identifiable parts of a model.
- Reflects the order of operations shown in the display tree.
- Eliminates the unnecessary naming of nodes. Nodes within a structure are only named if they are interactive.

There is one possible disadvantage to using too many BEGIN_STRUCTURE... END_STRUCTURE commands. Each time the PS 390 parses a BEGIN_STRUCTURE ... END_STRUCTURE command, it automatically creates another instance node in the display tree.

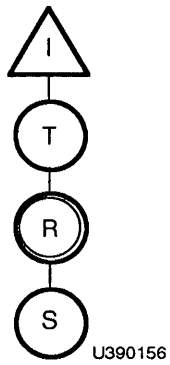
The created instance node is placed above all other nodes within that BEGIN_STRUCTURE ... END_STRUCTURE command. The name of the BEGIN_STRUCTURE ... END_STRUCTURE is actually the name of the created instance node. For example, if you put the following nodes into a BEGIN_STRUCTURE... END_STRUCTURE:

```
TransMolecule := TRANSLATE BY 0,1 APPLIED TO RotMolecule;
RotMolecule := ROTATE 0 APPLIED to ScaleMolecule;
ScaleMolecule := SCALE 2,2 APPLIED TO Molecule;
```



The PS 390 would create a display tree like this:

```
Molecule := BEGIN_STRUCTURE
              TRANSLATE 0,1;
     Rot :=   ROTATE 0;
              SCALE 2,2 APPLIED TO Molecule;
            END_STRUCTURE;
```



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Extraneous instance nodes are only costly if they are used so frequently that they begin to affect the traversal time of the display processor. In evaluating when to use BEGIN_STRUCTURE ... END_STRUCTURE command, then, you must weigh the advantage of grouping nodes together without having to name each node against the disadvantage of creating an extra instance node in the display tree.

Now that you are familiar with BEGIN_STRUCTURE ... END_STRUCTURE commands, examine some rules regarding their use.

1. When using BEGIN_STRUCTURE ... END_STRUCTURE, note that an operation is applied to everything below it in the structure unless the operation is explicitly applied to another structure. If an operation is applied directly to a name, nothing else listed below it in the structure is affected by that operation.

   So in the following example, the cylinder is both translated and scaled, but the piston is only translated:

   ```
   Shaft_Housing := BEGIN_STRUCTURE
                      TRANSLATE BY 0,1,0;
                      SCALE 2,2 APPLIED TO Cylinder;
                      INSTANCE OF Piston;
                    END_STRUCTURE;
   ```

   Look at another example. Each operation applies to everything following it in the BEGIN_STRUCTURE ... END_STRUCTURE. So the

Cube is rotated in X 30 degrees. The sphere is rotated in Y 10 degrees and rotated in X 30 degrees. The pyramid is translated by 0,1,1; rotated in Y 10 degrees; and rotated in X 30 degrees.

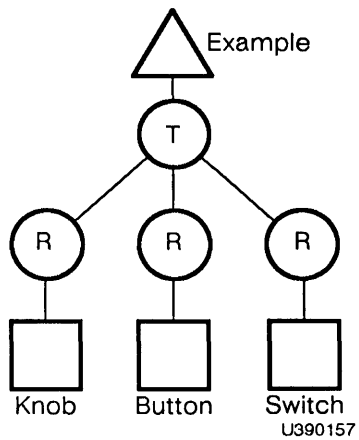
```
Shapes := BEGIN_STRUCTURE
            XRot := ROTATE IN X 30;
            Cube := VECTOR_LIST ...;

            YRot := ROTATE IN Y 10;
            Sphere := VECTOR_LIST ...;

            Tran := TRANSLATE BY 0,1,1;
            Pyramid := VECTOR_LIST ...;
          END_STRUCTURE;
```

2. Remember from Section *GT4 Modeling* that instance nodes can point to any number of descending nodes, operation nodes can point to only one descending node, and data nodes are terminal nodes; that is, they have no descending nodes.

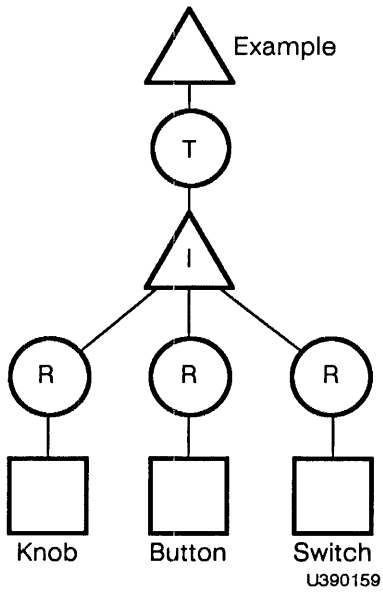
   Inside a BEGIN_STRUCTURE ... END_STRUCTURE, if an operation node points to more than one other node below it, the PS 390 automatically creates an instance node below the operation node. The operation node points to the instance node, which points to the descendant branches.

   For example, the BEGIN_STRUCTURE ... END_STRUCTURE code below is illegal because the translation applies to all three rotations below it.

```
Example := BEGIN_STRUCTURE
             TRANSLATE BY 0,2;
  RotKnob :=   ROTATE IN X
                 APPLIED TO Knob;
Rotbutton :=   ROTATE IN Y
                 APPLIED TO Button;
Rotswitch :=   ROTATE IN Z
                 APPLIED TO Switch;
           END_STRUCTURE;
```



In this case, the PS 390 automatically places an instance node below the translation node:



You could create the instance node explicitly with the following code:

```
 Tran := TRANSLATE BY 0,2 APPLIED TO Parts;
Parts := INSTANCE OF RotKnob, Rotbutton, Rotswitch;
```

3. When located inside a BEGIN_STRUCTURE ... END_STRUCTURE, a user-named node is assigned a name by the system which consists of the BEGIN_STRUCTURE ... END_STRUCTURE name, a period, and the user-assigned name of the node. So in the previous example of the BEGIN_STRUCTURE ... END_STRUCTURE named Shapes, the X Rotate node can be accessed as SHAPES.XROT. The period indicates that the name XROT is in the BEGIN_STRUCTURE ... END_STRUCTURE named "Shapes".

   The PS 390 assigns the name automatically, so you can keep your naming procedures simple, reusing descriptive names like SCALE, ROTATE, and TRANSLATE as long as they are not repeated in the same BEGIN_STRUCTURE ... END_STRUCTURE (so all names remain unique).

   If a node is not named, it is just part of the hierarchical structure and cannot be addressed explicitly. This is indirect "naming" of a node.

4. BEGIN_STRUCTURE ... END_STRUCTUREs can be nested inside each other. No operations within a nested BEGIN_STRUCTURE ... END_STRUCTURE apply to any nodes in the encompassing BEGIN_STRUCTURE... END_STRUCTURE. Think of the nested BEGIN_STRUCTURE... END_STRUCTURE as a terminal node in the display tree.
5. No immediate action commands should be placed in BEGIN_STRUCTURE... END_STRUCTUREs (with two debugging exceptions: COMMAND_STATUS and !RESET). Immediate action commands are discussed in the next section.

2.1 Exercise

In this section you will use the following display tree, which was designed in Section *GT4 Modeling*, to code Robot into mass memory.

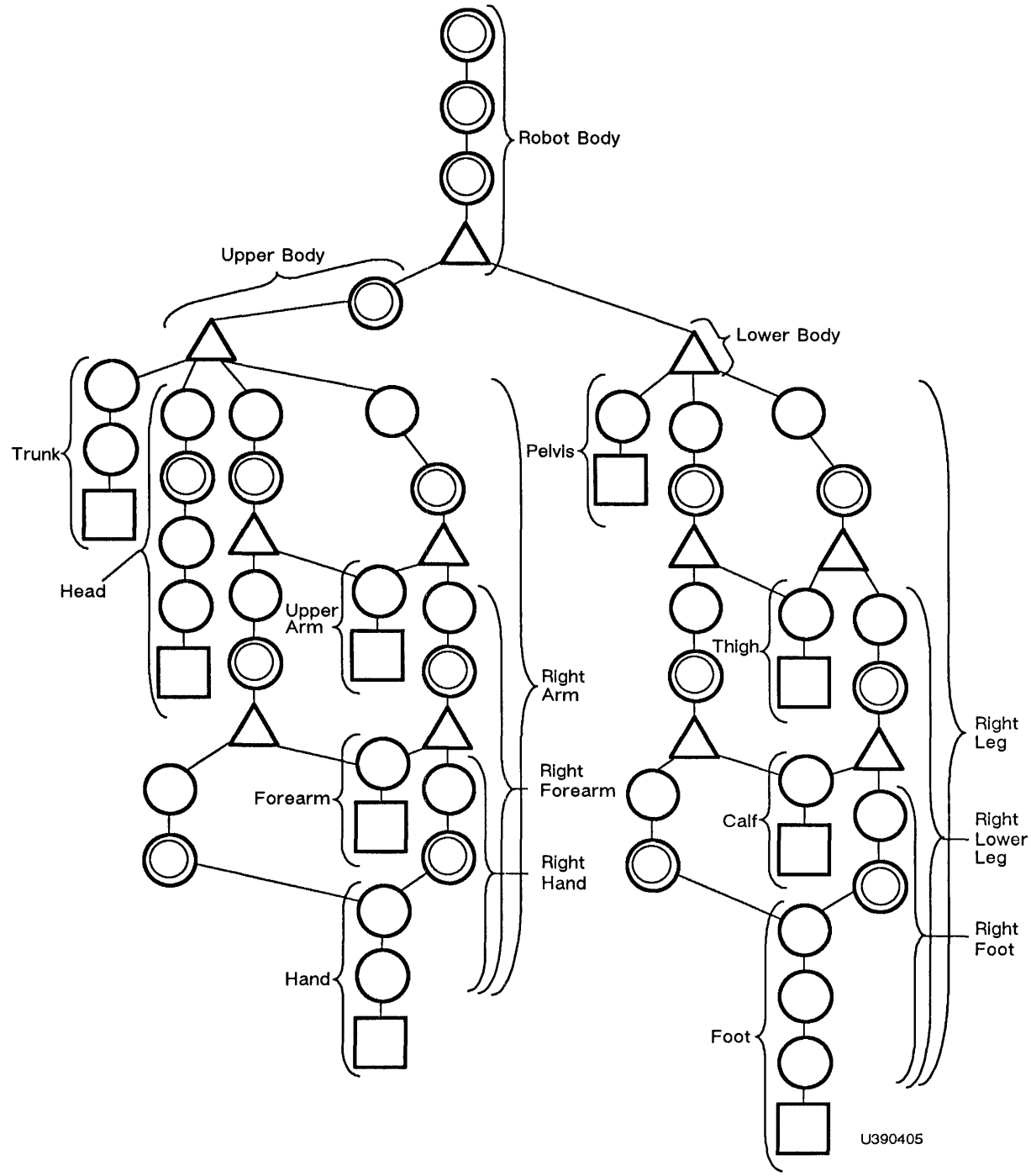


Figure 5-4. Robot Display Tree

Enter the commands in a host file as you proceed (otherwise, they cannot be saved).

Use explicit naming and BEGIN_STRUCTURE ... END_STRUCTURE to the best advantage. Keep in mind that you could use BEGIN_STRUCTURE... END_STRUCTURE any number of ways to help you organize and economize on code. This example develops one possible way.

First, isolate and identify all data nodes and any shared nodes.

Remember that the same data node—Cylinder—has been used for all the body pieces except the hands and head, which are spheres. Shared nodes have already been specified in the design of the display tree. These form the pieces labeled hand, forearm, upper arm, foot, calf, and thigh.

The first step is to code the primitives. The sphere and cylinder are vector lists that have been provided for you in the PS 390 Tutorial Demonstrations tape. The following serves only as a reminder that you must always define primitives.

```
  Sphere := VECTOR_LIST ... ;
Cylinder := VECTOR_LIST ... ;
```

Code the shared body pieces using both explicit naming and using BEGIN_STRUCTURE ... END_STRUCTURE. Calf, Thigh, Forearm, and Upper_Arm each consist of one node above a data node, so each can be coded explicitly:

```
Upper_Arm := SCALE BY .5,2,.5 APPLIED TO Cylinder;
  Forearm := SCALE BY .5,1.5,.5 APPLIED TO Cylinder;
    Thigh := SCALE BY .75,2.5,.75 APPLIED TO Cylinder;
     Calf := SCALE BY .65,2.5,.65 APPLIED TO Cylinder;
```

The Hand and Foot have two or more operation nodes above data nodes and so code them using BEGIN_STRUCTURE ... END_STRUCTURE:

```
Hand := BEGIN_STRUCTURE
           TRANSLATE BY 0,-1;
           SCALE BY .5,1,.5 APPLIED TO Sphere;
        END_STRUCTURE;
```

```
Foot := BEGIN_STRUCTURE
           TRANSLATE BY 0,0,1;
           SCALE BY .75, .5, 1;
        ROTATE IN X 90 APPLIED TO Cylinder;
        END_STRUCTURE;
```

Figure 5-5 illustrates what nodes in the display tree remain to be coded. The nodes already accounted for are represented by name. The branches containing two or more operation nodes above a name, a data node, or an instance node have been circled. These could be coded using BEGIN_STRUCTURE ... END_STRUCTURE. Explicit naming could be used elsewhere.

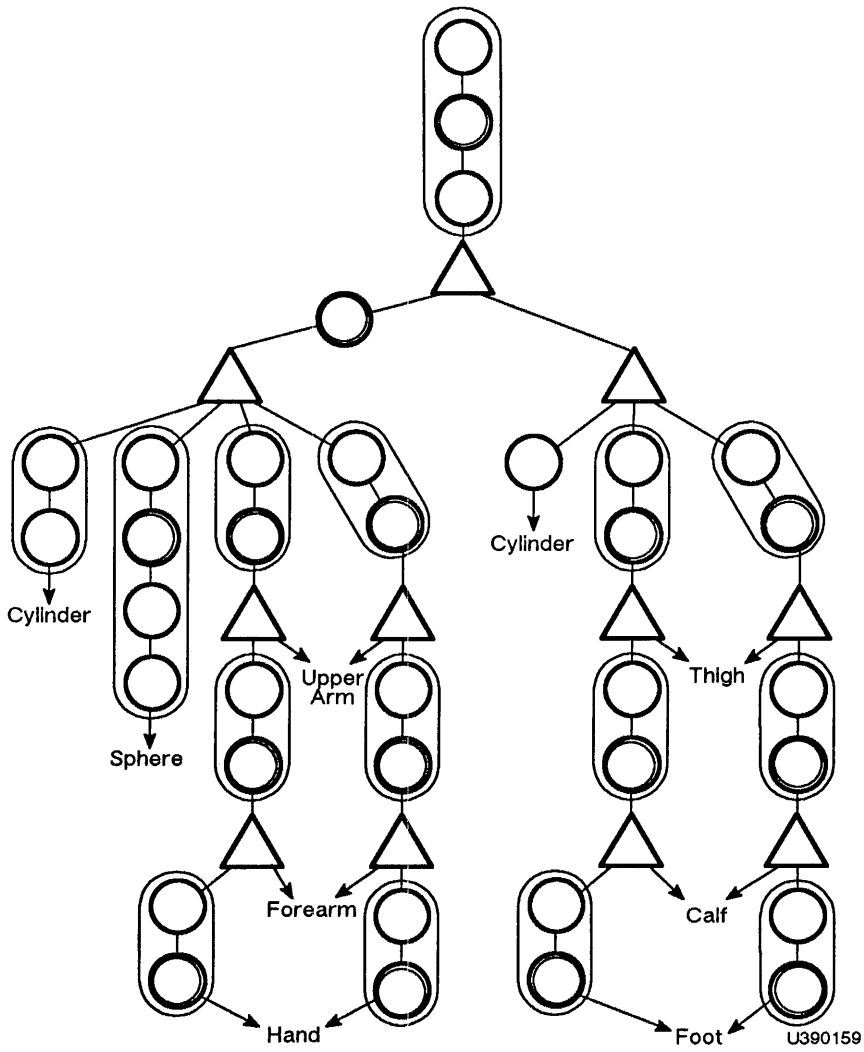


Figure 5-5. Possible BEGIN_STRUCTURE ... END_STRUCTUREs for Robot

With this in mind, begin at the top branches of the display tree and code down.

The top of the display tree can be coded in one BEGIN_STRUCTURE... END_STRUCTURE:

```
Robot := BEGIN_STRUCTURE
 Tran :=   TRANSLATE BY 0,0;
  Rot :=   ROTATE 0;
Scale :=   SCALE BY .075;
           INSTANCE OF Upper_Body, Lower_Body;
         END_STRUCTURE;
```

Remember that PS 390 screen coordinates are +1 to –1 units, so the screen is 2 units across. Because of the dimensions of the Robot, it is scaled so it is viewable on the display screen.

Each of these top nodes could have been coded explicitly since three of the four nodes are interactive and must be named regardless:

```
TranRobot := TRANSLATE BY 0,0 APPLIED TO RotRobot;
RotRobot := ROTATE 0 APPLIED TO ScaleRobot;
ScaleRobot := SCALE BY .075 APPLIED TO Robot;
Robot := INSTANCE OF Upper_Body, Lower_Body;
```

However, BEGIN_STRUCTURE ... END_STRUCTURE saves naming one node, the instance node, within the structure and groups all the interactive nodes under a single name: Robot. The tradeoff, an additional instance node, is not prohibitive in this case.

Next, Upper_Body groups all the upper body parts into one entity which can be rotated interactively.

```
Upper_Body := BEGIN_STRUCTURE
       Rot :=   ROTATE 0;
                INSTANCE OF Head, Right_Arm, Left_Arm, Trunk;
              END_STRUCTURE;
```

The above could be coded explicitly:

```
Rot_Upper_Body := ROTATE 0 APPLIED TO Upper_Body;
Upper_Body := INSTANCE OF Head, Right_Arm, Left_Arm, Trunk;
```

However, it may be more convenient to group them into a BEGIN_STRUCTURE... END_STRUCTURE under a single name. This way, Robot could subsequently be coded as an instance of Upper_Body and Lower_Body instead of an instance of Rot_Upper_Body and Lower_Body.

You could choose to code explicitly for efficiency. However, in this example, the convenience is worth the extra instance node. Both the trunk and head could be defined in a BEGIN_STRUCTURE... END_STRUCTURE.

```
Trunk := BEGIN_STRUCTURE
           TRANSLATE BY 0,6;
           SCALE BY 2,3,1 APPLIED TO Cylinder;
         END_STRUCTURE;

Head := BEGIN_STRUCTURE
          TRANSLATE BY 0,6;
 Rot :=   ROTATE 0;
          SCALE BY 1,2,1;
          TRANSLATE BY 0,1 APPLIED TO Sphere;
        END_STRUCTURE;
```

Notice that only the rotation node (Head.Rot) is named so values may be sent interactively to move the head.

Now work through the rest of the code. When you are finished, you can compare your code with the following:

Begin with Right_Arm and code top down. The circled display tree indicates the arm may be coded in three BEGIN_STRUCTURE ... END_STRUCTURE groups.

```
Right_Arm := BEGIN_STRUCTURE
               TRANSLATE BY -2.5,6;
      Rot :=   ROTATE 0;
               INSTANCE OF Upper_Arm, Right_Forearm;
             END_STRUCTURE;

Right_Forearm := BEGIN_STRUCTURE
                   TRANSLATE BY 0,-4;
          Rot :=   ROTATE 0;
                   INSTANCE OF Forearm, Right_Hand;
                 END_STRUCTURE;
```

Since Hand has already been coded, Right_Hand is defined as:

```
Right_Hand := BEGIN_STRUCTURE
                TRANSLATE BY 0,-3;
       Rot :=   ROTATE 0 APPLIED TO HAND;
              END_STRUCTURE;
```

Left_Arm is coded like Right_Arm but with different transformation values and name changes:

```
Left_Arm := BEGIN_STRUCTURE
              TRANSLATE BY 2.5,6;
     Rot :=   ROTATE 0;
              INSTANCE OF Upper_Arm, Left_Forearm;
            END_STRUCTURE;
```

The pattern is similar for Left_Forearm. Note that it references Forearm and Left_Hand, which have both been defined:

```
Left_Forearm := BEGIN_STRUCTURE
                  TRANSLATE BY 0,-4;
         Rot :=   ROTATE 0;
                  INSTANCE OF Forearm, Left_Hand;
                END_STRUCTURE;
```

Notice in these two structures, the instance nodes are defined on a separate line from the rotation node because there is more than one instance node being referenced.

Since Hand has already been coded, Left_Hand is defined as:

```
Left_Hand := BEGIN_STRUCTURE
               TRANSLATE BY 0,-3;
      Rot :=   ROTATE 0 APPLIED TO HAND;
             END_STRUCTURE;
```

Now the lower half of Robot can be coded. First, group the pieces of the lower body of the Robot together in one line of code:

```
Lower_Body := INSTANCE OF Pelvis, Right_Leg, Left_Leg;
```

Then define each piece. Pelvis can be coded explicitly:

```
Pelvis := SCALE BY 2,1,1 APPLIED TO Cylinder;
```

The legs, like the arms, consist of BEGIN_STRUCTURE ... END_STRUCTURE groups:

```
Right_Leg := BEGIN_STRUCTURE
               TRANSLATE BY -1,-2;
      Rot :=   ROTATE 0;
               INSTANCE OF Thigh, Right_Lower_Leg;
             END_STRUCTURE;

Right_Lower_Leg := BEGIN_STRUCTURE
                     TRANSLATE BY 0,-5;
            Rot :=   ROTATE 0;
                     INSTANCE OF Calf, Right_Foot;
                   END_STRUCTURE;

Right_Foot := BEGIN_STRUCTURE
                TRANSLATE BY 0,-5.5;
       Rot :=   ROTATE 0;
                TRANSLATE BY 0,0,-.5 APPLIED TO Foot;
              END_STRUCTURE;

Left_Leg := BEGIN_STRUCTURE
              TRANSLATE BY 1,-2;
     Rot :=   ROTATE 0;
              INSTANCE of Thigh, Left_Lower_Leg;
            END_STRUCTURE;

Left_Lower_Leg := BEGIN_STRUCTURE
                    TRANSLATE BY 0,-5;
           Rot :=   ROTATE 0;
                    INSTANCE OF Calf, Left_Foot;
                  END_STRUCTURE;

Left_Foot := BEGIN_STRUCTURE
               TRANSLATE BY 0,-5.5;
      Rot :=   ROTATE 0;
               TRANSLATE BY 0,0,-.5 APPLIED TO Foot;
             END_STRUCTURE;
```

3. Using Immediate Action Commands

Immediate action commands are executed immediately when they are received by the system. This kind of command cannot be named. For example:

```
DISPLAY Smallstar;
```

is a command that causes the model (data structure) named Smallstar to be displayed. The data structure Smallstar already exists in mass memory; the DISPLAY command creates no additional data structure. Naming the display command:

```
Name := DISPLAY Smallstar;
```

would cause an error message to appear. Immediate action commands can be divided into three types:

1. Those used with function networks. (For more information on these, refer to Section *GT6 Function Networks I.*)

   CONNECT
   DISCONNECT
   SEND
   STORE

2. General commands

   BEGIN...END

   Defines a batch of commands so they appear to execute simultaneously.

   COMMAND STATUS

   Reports current level to which BEGIN...END and BEGIN_STRUCTURE...END_STRUCTURE commands are nested.

   DISPLAY
   REMOVE

   Cause objects either to appear on or disappear from the screen.

FORGET (data structures)

Removes a name from use while leaving the data structure associated with the name in place.

DELETE

Removes a name and its associated data structure from use.

INITIALIZE

Clears all user-defined structures from mass memory.

OPTIMIZE STRUCTURE ... END OPTIMIZE

Places the PS 390 in, and removes it from, "optimization mode," which minimizes display processor traversal time for structures created in this mode.

!RESET

Equivalent to entering enough "END_STRUCTURE;" commands to terminate any unended BEGIN_STRUCTURE ... END_STRUCTUREs (i.e., more BEGIN_STRUCTURE statements than END_STRUCTURE statements, creating an "unended" structure).

3. Structuring commands

These "hybrid" commands have characteristics of both immediate action commands and data structuring commands. Like data structuring commands, they create data tree nodes in mass memory by inserting nodes into an already named display tree. (Note that the SEND command sends new values to existing display tree nodes).

Unlike data structuring commands, these commands cannot be named (the nodes they create derive their names or traversal paths from existing nodes), so they are considered immediate action commands.

FOLLOW WITH
REMOVE FOLLOWER

The first command follows a named operation node with another operation node. The second command removes this added operation node.

INCLUDE
REMOVE FROM

The first command modifies an existing INSTANCE display tree node by including one named display tree in a named INSTANCE display tree. The second command removes this added structure.

PREFIX WITH
REMOVE PREFIX

The first command prefixes a named display tree with an operation node. The second command removes the prefixed node.

SEND

This command sends a value to a display tree node, as well as to a function instance or variable.

Immediate action commands are not only used for interactions such as displaying or deleting an object on the screen. They are also useful for making experimental or temporary changes to the display structure of a model in mass memory. For example, if you wanted to change the view of a given model, you could add operation nodes to the the display structure of a model (in command mode) by using the FOLLOW WITH command. Should the view prove undesirable, you could remove these nodes with the REMOVE FOLLOWER command.

If you liked the effect and wanted the nodes permanently, you could edit the display tree of the model file (in terminal emulator mode) adding data structuring commands.

4. Entering Code In The PS 390

When you have determined the commands needed to create the display tree, enter them into the PS 390. You could enter them directly, as you did in Section *GT1 Hands-On Experience,* but this means they will not be saved.

To retain a copy of the code for further use, enter the commands into a text file on your host computer. The procedure for this varies according to the host. Refer to your host documentation for details.

The file can then be downloaded to the PS 390. For details on how to do this, refer to Section *IS3 Operation and Communication.*

When the transfer is completed, you can display the model using the DISPLAY command.

For example, transfer the Robot file to the PS 390 and display the Robot model by pressing CTRL/LINE_LOCAL and entering:

```
DISPLAY Robot;
```

4.1 Command Summary

Now that you are familiar with how the commands work, the *Command Summary* in Section *RM1* should be the only reference you need. The Command Summary serves as a quick, complete reference on all available commands. Commands are listed alphabetically. Acceptable abbreviations, formal command syntax, and information on data types for parameters are supplied.

4.2 Graphics Support Routines

The Graphics Support Routines (GSRs) in Section *RM4* are a collection of procedures which are used to improve speed and efficiency in communications between the host computer and the PS 390. They reside in the host computer.

Most of the PS 390 commands have a corresponding Graphics Support Routine. When you call one of these routines, the corresponding PS 390 command is sent in binary directly to the PS 390 to be executed.

This improves efficiency in that data is received in the format required by the PS 390, ready for direct interpretation. Because the data requires no further parsing, less time is required by the PS 390 to interpret commands.

Keep in mind that the GSR software does not replace the PS 390 command language. It is an alternative way to invoke it. For details on the Graphics Support Routines, refer to Section *RM4*.

5. Summary

All PS 390 commands:

- End with a semicolon.
- Are free-formatted.
- Have a long and short form.
- Can consist of uppercase and/or lowercase letters.

Two kinds of PS 390 commands are needed to create a model in PS 390 mass memory and display it on the screen: data structuring commands and immediate action commands.

Immediate action commands are executed immediately, and cannot be named by the user. These are used in function networks, for general system operations such as displaying or removing an object from the PS 390 screen, and for temporary modifications to existing display trees in mass memory.

Display trees are initially created in mass memory using data structuring commands. All data structuring commands must be named, either explicitly or using BEGIN_STRUCTURE ... END_STRUCTURE.

Whichever method you use, the following naming conventions must be followed.

- A name can be up to 240 characters and consist of any alphanumeric combination as long as it begins with a letter.
- A name can include underscore characters (_), a dollar sign ($), or a period (.). However, using periods may be confusing because the PS 390 automatically inserts periods in the name of nodes contained in a BEGIN_STRUCTURE... END_STRUCTURE.
- A name cannot contain a space or other delimiter (return, tab, etc.).
- A name is followed by a colon, an equal sign, and the command to be associated with the name.
- Other PS 390 commands can be used in conjunction with the naming of data structures:

  The FORGET command
  The DELETE command

Most display trees are coded using a combination of explicit naming and BEGIN_STRUCTURE ... END_STRUCTURE. In general, BEGIN_STRUCTURE... END_STRUCTURE:

- Groups associated nodes together into identifiable parts of a model.
- Reflects the order of operations shown in the display tree.
- Eliminates the unnecessary naming of nodes: nodes within a structure are only named if they are interactive.

The BEGIN_STRUCTURE ... END_STRUCTURE command follows certain conventions:

- BEGIN_STRUCTURE ... END_STRUCTURE always creates an instance node.
- Operation commands inside a BEGIN_STRUCTURE ... END_STRUCTURE apply to everything below in the structure unless they are explicitly applied to other structures.
- If an operation node in a BEGIN_STRUCTURE ... END_STRUCTURE is to be applied to more than one branch of the hierarchy, the PS 390 creates an instance node below the operation node, and the instance node points to the appropriate branches.
- In a BEGIN_STRUCTURE ... END_STRUCTURE, the PS 390 automatically prefixes the name of a user-named node with the name of the BEGIN_STRUCTURE... END_STRUCTURE. The prefixed (hierarchical) name is first, followed by a period (.) and the user given name.
- END_STRUCTURE does not create a data node, but merely indicates to the PS 390 that the BEGIN_STRUCTURE ... END_STRUCTURE is finished.
- Nested BEGIN_STRUCTURE ... END_STRUCTURE groups can be considered as terminal nodes in the encompassing BEGIN_STRUCTURE... END_STRUCTURE. In other words, nothing in the nested structure is applied to anything in the rest of the encompassing BEGIN_STRUCTURE... END_STRUCTURE.

The display tree of a model is coded in a text file or an application program on the host computer and then downloaded to the PS 390. For quicker communications between host and PS 390, use the PS 390 Graphic Support Routines. Use Section *RM1 Command Summary* as an easy reference manual of all available commands.

For information on how to connect function networks into the display tree of a model, to manipulate the model interactively, refer to Section *GT6 Function Networks I.*

GT6. FUNCTION NETWORKS I

GT6. FUNCTION NETWORKS I

INTERACTION WITH A MODEL

CONTENTS

ILLUSTRATIONS

Section GT6

Function Networks I

Interaction With A Model

Introduction

This section illustrates how to construct simple function networks. Function networks allow you to interact with a model you have created for display.

The first steps to using function networks were detailed in Sections *GT4 Modeling* and *GT5 Command Language*. There, you analyzed a model (the robot) for movement, allowed for that movement by including interaction nodes in the display tree, and named those nodes when you coded the model so they could be accessed.

Interactive nodes can be accessed using function networks. For example, in Section *GT1 Hands-On Experience,* you used a simple function network to rotate a star on the screen Figure 6-1.

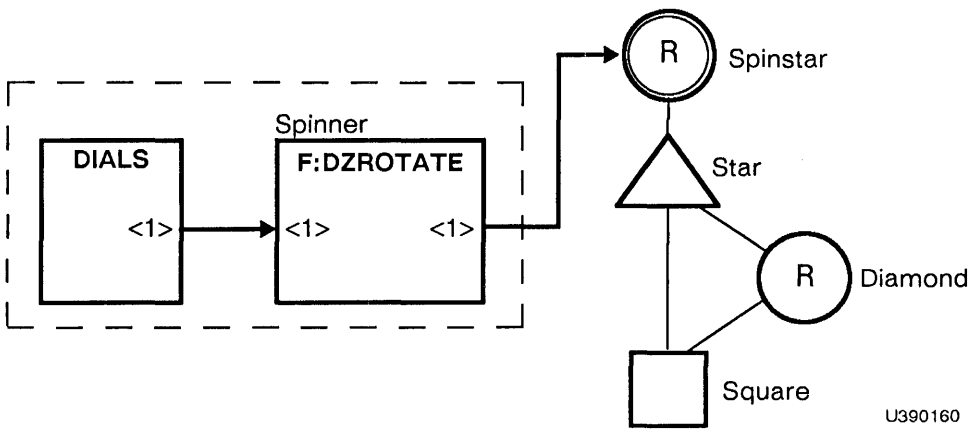


Figure 6-1. Sample Function Network

This section will illustrate in greater detail how this kind of function network operates.

You will also learn how to use PS 390 interactive devices to move a more complex model, the robot. When the robot display tree was initially coded, zero values were assigned to the interaction nodes. In the case of rotating the model, this meant the model would rotate zero degrees from initial position when first displayed. To rotate the model, you can create a function network to send a nonzero value to the rotate node. Specifically, this function network takes values from input devices and transforms them into values the interaction nodes can accept.

Part of this process entails selecting the appropriate PS 390 functions and linking them together into a function network. This function network may contain additional functions which perform other kinds of tasks, such as accumulating values which are not large enough.

As you did when you created a display tree for your model, you will first create a diagram of your function network and then code from that. Creating a diagram of the network first allows you to modify it easily and detect errors before they become bugs in the code.

Objectives

In this section you will learn how to:

- Select functions which will convert input device values into values that can update an interaction node.
- Add functions to the network for rotation in all three dimensions.
- Expand the network for other kinds of interaction (scaling and translating).
- Use a clock function as an alternate source of input for the network.

Prerequisites

Before beginning this section, you should be familiar with the concepts presented in Sections *GT4 Modeling* and *GT5 PS 390 Command Language*.

1. Converting Input Device Values To Update An Interaction Node

The first step to selecting the appropriate function to convert input values into values that can update an interaction node is to identify the type of values needed by the node. To understand this, look at the the most common graphics transformations—rotation, scaling, and translation.

Rotations and scales are done with 3x3 matrices; translations are specified with a 2- or 3-dimensional vector. It makes sense, then, that the type of data used by a rotation or scale node is a 3x3 matrix, and the data type for a translation node is a vector.

Your task, if you are trying to rotate part of a model, is to find a way to make an input device, such as a dial, send the correct 3x3 matrices to a rotate node. In this section, this process will be represented by a "black box" (Figure 6-2) that takes one kind of value and changes it into another kind.

Figure 6-2. The "Black Box"

In Section *GT1 Hands-On Experience,* you created Diamond by specifying a 45 degree rotation of Square. You did not need to work out what the 3x3 matrix for 45 degrees was. Whenever you use a command to create a rotate or scale node (such as Diamond), you only have to specify an angle using a real number value and the PS 390 automatically creates the associated 3x3 matrix.

Once the node is created, however, you can only update it with the type of data it accepts—in this case, a 3x3 matrix. For example, look at the robot display tree again (Figure 6-3). The names for the interactive nodes are supplied so you can refer to them.

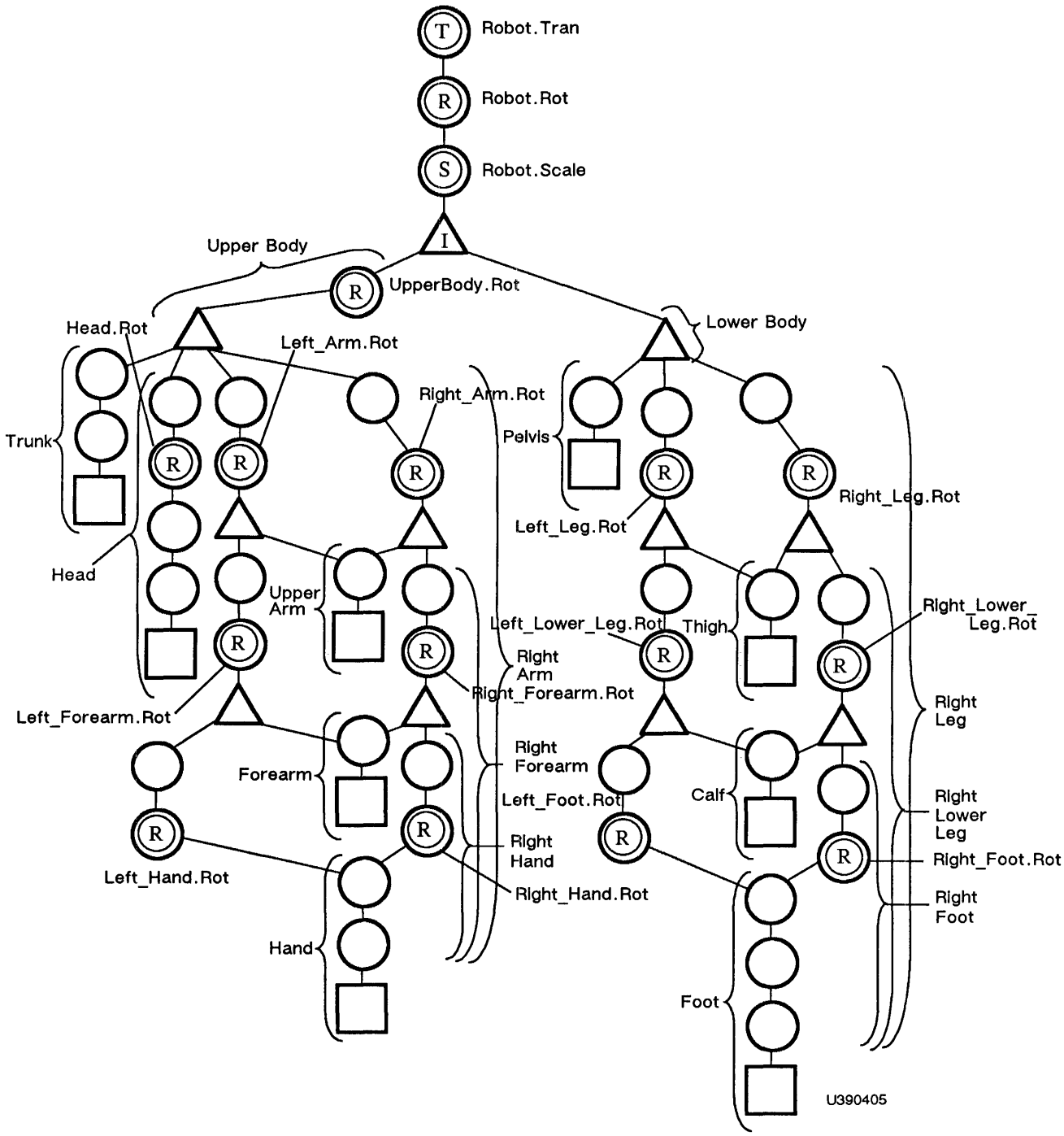


Figure 6-3. Interactive Nodes in Robot Display Tree

To move the left arm, you must send a rotation matrix to the node named Left_Arm.Rot.

Look at the other interaction nodes. Almost all of the them are rotations except for the translate node above robot (Robot.Tran). All of these rotate nodes accept 3x3 rotation matrices, and the translation node, Robot.Tran, requires vectors.

One other node in the robot display tree is interactive: Robot.Scale, the scale node above Robot. Unlike the rotation nodes, it currently contains a non-zero value (.05). Since it has been named, you can reference it and connect functions to it. This will allow you to change the values it contains, interactively making the robot larger or smaller.

You can control whether or not any operation node in the display tree will be processed. Sending a Boolean value FALSE to input <–1> of any operation node will turn off the action specified in that node. Sending a TRUE to input <–1> will turn it back on. The default is ON.

Once you know what values you need to produce for interaction nodes (output from the black box), you should identify the type of values produced from the input device (input to the black box).

The twelve function keys across the top of the PS 300-style keyboard produce discrete integer values from 1 to 36. Consequently, they are a useful source of input for discrete tasks such as changing states or modes.

The data tablet is commonly used for digitizing (sketching or tracing from a drawing), making menu selections, and picking. The values it produces are XY vectors with fractional values between plus and minus 1.

This section focuses on the dials. Dials produce a stream of small, incremental real numbers. This means the dials are well-suited for producing smooth motion, so they are often used in controlling the three common transformations: translations, rotations, and scaling. When you turn a dial clockwise, it sends out a stream of fractional values (called delta values) that sum to 1 after a complete rotation of the dial. If you turn it a full turn counterclockwise, the values sum to –1.

If the delta value is .1, every time you turn the dial one-tenth of the way around, it produces a .1. If you turned the dial one-twentieth of a turn, it will not produce a value. By default, a dial is set to produce a delta of about .001. This makes the dial extremely responsive. Only a slight movement of the dial will generate a value.

The delta values produced by the dials do not accumulate. In other words, the dial does not send out .001 the first click, .002 the next, and so on, ending with 1.0 after one complete turn. After one complete turn, the dial still sends out the same delta value it did when it was turned enough to produce a value. This fact is extremely important to remember when you are designing function networks.

Once you have identified the input source and the type of values it generates, you can use Section *RM1 Command Summary* to identify the appropriate function(s) to convert incoming values from an input device into appropriate output. For rotations, the function(s) must convert real numbers sent out by the dials into 3x3 matrices needed for the interaction nodes.

Section *RM1 Command Summary* contains a description of each command associated with a node (INSTANCE OF, ROTATE, VECTOR LIST, and so on). In each description is a list of associated functions that produce values the node can accept. For example, if you look up ROTATE, you will find these associated functions:

F:MATRIX3, F:XROTATE, F:YROTATE, F:ZROTATE, F:DXROTATE, F:DYROTATE, F:DZROTATE, F:SCALE, F:DSCALE

All of these functions produce 3x3 matrices, so, in theory, all of them can be connected to a rotate node. However, those most closely associated with rotate nodes are the ones with ROTATE in their names. These are the candidate functions for the black box.

Section *RM1 Command Summary* lists the following associated functions in its description of the SCALE and TRANSLATE operation nodes:

SCALE: F:MATRIX3, F:XROTATE, F:YROTATE, F:ZROTATE, F:DXROTATE, F:DYROTATE, F:DZROTATE, F:SCALE, F:DSCALE

TRANSLATE: F:XVECTOR, F:YVECTOR, F:ZVECTOR

As with the ROTATE command, where a number of associated functions produce the type of output needed, the name indicates the most likely functions to use. So if you wanted to send values to a scale node, you should use F:SCALE and F:DSCALE (for the differences between F:SCALE and F:DSCALE, refer to Section *RM2 Intrinsic Functions*).

Note that the associated functions for TRANSLATE do not have "TRAN" in their names. Since TRANSLATE nodes accept 3D vectors as input, the associated functions are ones that generate 3D vectors—F:XVECTOR, F:YVECTOR, and F:ZVECTOR.

To evaluate the functions themselves, look them up in Section *RM2 Intrinsic Functions*. The following example illustrates how functions work, and how *RM2 Intrinsic Functions* presents the information.

Assume you want to rotate Robot in Y, that is, to make it spin around around its vertical axis. The node to interact with is the rotate node named Robot.Rot in the display tree. Y rotations are associated with the functions F:YROTATE and F:DYROTATE. Under F:YROTATE in the Section *RM2 Intrinsic Functions* you will find a diagram like the one in Figure 6-4.

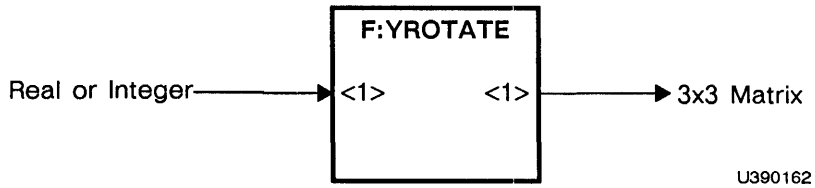


Figure 6-4. F:YROTATE

The diagram indicates that this function has one input on the left and one output on the right. It can accept real values which represent degrees of rotation on its input and send out 3x3 rotation matrices as output values.

Like all PS 390 functions, it waits until an input value has arrived, performs computations, and outputs the value. It is capable of consuming a steady stream of input values and producing a steady stream of outputs.

F:YROTATE seems to be the likely candidate for the black box. It accepts real numbers so it can be connected to the dials, and it produces 3x3 matrices to send to the rotation node. Look at example shown in Figure 6-5.

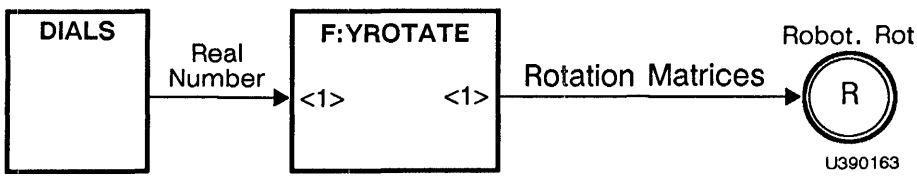


Figure 6-5. Possible Y Rotation Network

If you were to test this function with a stream of values from the dials, you would discover several facts. The first is that the values from the dial are very tiny. Each one supplies only a fraction of a degree of rotation to F:YROTATE, so the corresponding matrices that F:YROTATE sends out specify almost insignificant amounts of rotation in the model on the screen. You need a way to multiply the effect the dial values have. Adding a new function can do that (see Figure 6-6).

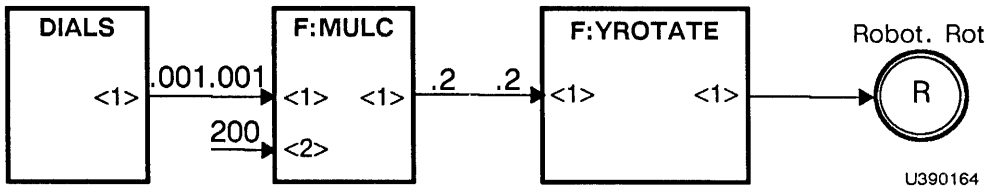


Figure 6-6. Y-Rotation Network With Multiplier

F:MULC is a multiplying function that takes any value it receives on input <1> and multiplies it by the constant value on input <2>. Many PS 390 functions have constant inputs. Unlike regular inputs, called active inputs, constant inputs never consume the values on them. If you place a large number on input <2> (200 is the value shown in the diagram), then each incoming dial value will be converted to a value 200 times greater. That will specify noticeable amounts of rotation for F:YROTATE. F:MULC converts a .001 from the dials to 0.2.

Continue to trace successive values through this modified network. When F:YROTATE receives the 0.2 from F:MULC, it will immediately send out a matrix to Robot.Rot that will rotate Robot 0.2 degrees.

The dial produces only a stream of incremental delta values; each one is about 0.2. As F:YROTATE receives these, it produces a stream of matrices, each corresponding to about .2 degrees of rotation. But nothing greater than about a fifth of a degree of rotation ever occurs. The effect of this is that the robot rotates only a small amount and stays there. It may even look like the robot is not responding to the dials at all.

What is needed is a way to accumulate values, so the first delta value causes .02 degree of rotation, the second value .04 degrees, and so on. This calls for another modification of the network. Figure 6-7 shows one method of adding an accumulator.

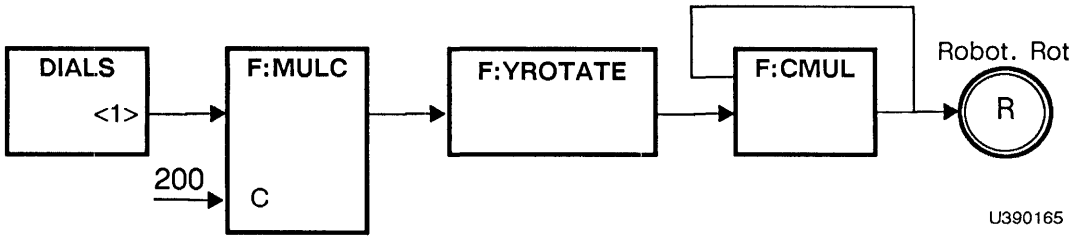


Figure 6-7. Adding an Accumulator

Values from F:YROTATE can accumulate using a multiply function (F:CMUL) as the accumulator. F:CMUL is the same as F:MULC, except its first input is constant. To fire, this function needs to be "primed" the same way F:MULC did. Place an identity matrix on input <1>. This ensures that F:YROTATE will produce a product. When the first incoming value from F:YROTATE arrives of at input <2> of F:CMUL, it will be multiplied by the matrix waiting on input <1>.

The product of these two matrices goes to update the rotation node. It also goes back to F:CMUL input <1> to replace the identity matrix that was there. So the next rotation matrix to arrive on F:CMUL input <2> gets multiplied by the accumulated matrix, not by the identity matrix first placed there.

This whole process repeats each time F:CMUL fires. A new matrix, containing the accumulated rotations is continually being sent back to input <1> as each new matrix is output from the function.

Figure 6-8, Figure 6-9 and Figure 6-10 trace a stream of three or four values from the dial through the network to see if the modifications that are added produce the desired matrices.

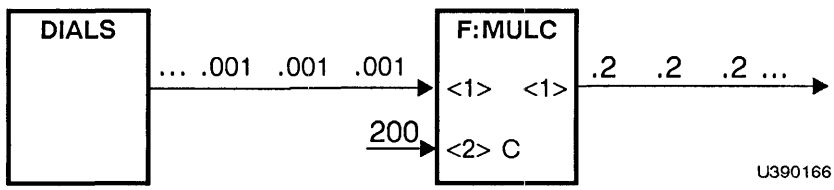


Figure 6-8. Tracing Dial Values (Part 1)

As shown in NO TAG, F:MULC multiplies the first dial value by 200 to produce a 0.2. This value triggers F:YROTATE to produce a rotation matrix

for one-fifth of a degree of rotation. That travels to F:CMUL, where it will be multiplied by an identity matrix (I) on input <1> (see Figure 6-9).

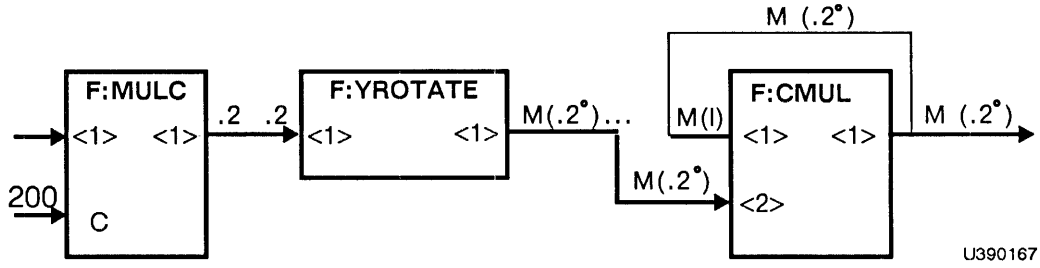


Figure 6-9. Tracing Dial Values (Part 2)

Multiplying a matrix by an identity matrix has the same effect that multiplying by 1 has on numbers. The matrix that first arrives on F:CMUL input <2> from F:YROTATE is multiplied by the identity matrix on input <1> and output unchanged from the function to the rotate node. This matrix also travels back to F:CMUL constant input <1> and replaces the identity matrix that was there.

The second dial value goes through the exact same process, causing F:MULC to send out a 0.2, which causes F:YROTATE to send out another matrix for 0.2 degree of rotation. But this second matrix gets multiplied, not by the identity matrix as the first matrix did, but by the most recent value sitting on input <1>. In this case, that value is a matrix for .2 degrees of rotation (Figure 6-10).

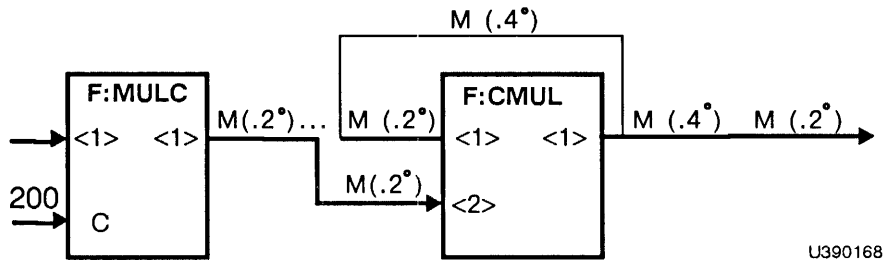


Figure 6-10. Tracing Dial Values (Part 3)

The second product from F:CMUL is a new accumulated matrix for .4 degrees of rotation that updates the rotate node and goes back to replace the .2-degree matrix on the F:CMUL constant input. Each time a new 0.2-degree rotation matrix comes from F:YROTATE, this process repeats,

and a new cumulative rotation matrix goes around to the F:CMUL constant input. So each time F:CMUL fires, the matrix sent to Robot.Rot will specify a little more rotation than the one before it.

Once this network is implemented, it handles input values from the dials so quickly that the model will appear to rotate in real time. It also provides the expected results when the dial is turned the other way: it generates small, negative values which cause F:YROTATE to output rotation matrices for negative rotation. The result is that the model rotates in the opposite direction.

Examine the diagram you have so far. It illustrates several important facts about functions. One of the functions, F:YROTATE, is a data conversion function. It takes one type of input and produces a different type. Other functions do not do this. For example, F:ADD is an arithmetic operation function. It adds two incoming values and produces the same type of data it receives as input. F:MULC and F:CMUL, used in this network, are also examples of functions that do arithmetic operations. Other functions perform logical operations or select and route data. The classes of functions are outlined below:

- Data Conversion

  Data conversion functions combine vectors into matrices, extract vectors from matrices; form vectors from real numbers, round or truncate real numbers to integers, float integers to equivalent real numbers, make printable characters and convert character strings to a string of integers.

- Arithmetic and Logical

  These functions perform all arithmetic operations (add, divide, subtract, multiply, square root, sine, and cosine) and logical operations (and, or, exclusive-or, and complement).

- Comparison

  Comparison functions test whether values are greater than, less than, equal to, not equal to, greater than or equal to, and less than or equal to other values.

- Data Selection and Manipulation

  These functions are used to selectively switch functions, choose outputs, and route data.

- Viewing Transformation

  Viewing transformation functions connect to viewing operation nodes in display trees to interactively change line-of-sight, window size, and viewing angle.

- Object Transformation

  Object transformation functions connect to modeling operation nodes in display trees to interactively rotate, translate, and scale objects.

- Character Transformation

  These functions are used to interactively position, rotate, and scale text.

- Data Input and Output

  These functions set up and control the interactive devices (dials, function keys, function buttons, data tablet, and keyboard) and output values to the optional LED labels that several of the devices have.

- Miscellaneous

  Other functions set up and control picking, clocking, timing, and synchronizing operations.

Notice from the function network diagrams that values flow from left to right, with the input device usually situated "upstream" at the extreme left and the destination for the values (the nodes) "downstream" on the extreme right.

Despite this general direction of flow, values can be routed virtually anywhere in the network. A function output can be connected to the input of any other function, including itself, as F:CMUL demonstrates.

In addition, an output can be connected to more than one destination. Again, F:CMUL illustrates this. Its output goes to a rotate node and also

back to its own input. Similarly, an input can be fed by more than one source.

As mentioned, functions have two kinds of inputs: active and constant. Values coming in on an active input are consumed as the function executes, clearing the input for the arrival of a new value. If the function cannot execute yet because values for other inputs have not arrived, active input values will queue up, waiting their turn to be consumed.

Values on constant inputs stay on the input; they are not consumed when the function executes. If another value arrives, it does not queue up; it replaces the value that was there. In effect, then, there can only be one value at a time on a constant input. Constant inputs are useful in a situation like the previous network, where F:MULC is used to multiply a stream of values coming in on one input by the same constant factor.

Contrast this with the multiplying function F:MUL, which has two active inputs (Figure 6-11).

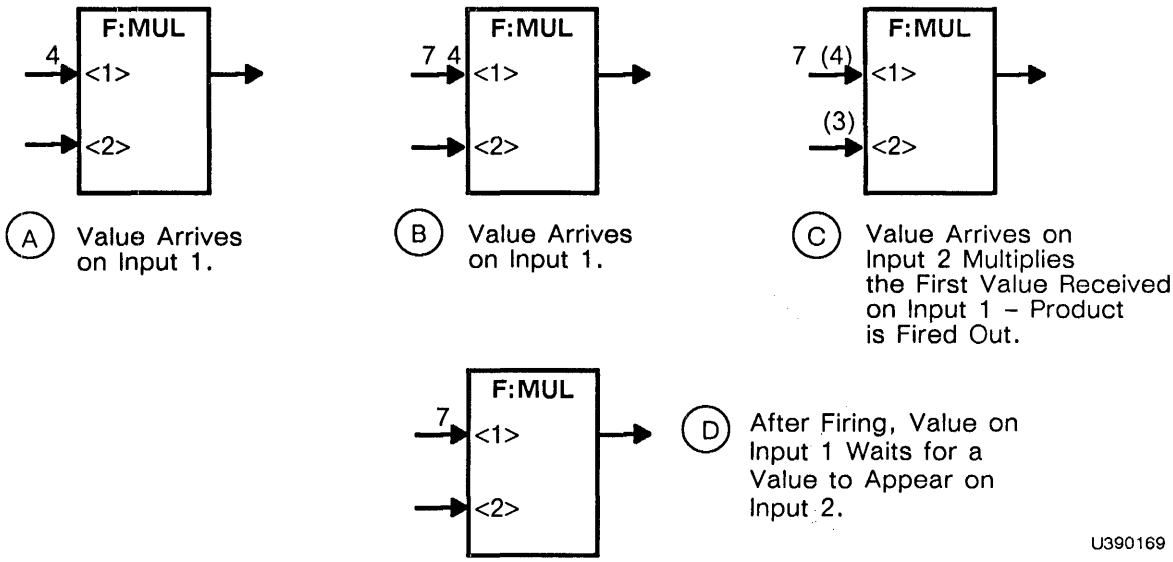


Figure 6-11. F:MUL

If you sent 200 to input <2> of F:MUL, it would remain there until the first value from the dial arrived on input <1>. Then the function would send out the product and the two input values would disappear. A second value from the dial would arrive on input <1> and wait, because there would be no value on input <2> to multiply it by. The third, fourth, and all succeeding

values from the dial would queue up behind it on input <1>, all waiting for their turn to be multiplied. To keep F:MUL working, you would need to supply it with a steady stream of fresh 200s for input <2>. Obviously, it is easier to use a constant input for this, as with F:MULC.

This section employs PS 390 functions with fixed constant or active inputs. At times, however, it will be useful to specify whether an input to a function is active or constant. Refer to Section *RM1 Command Summary* for information on the SETUP CNESS command, which allows you to determine whether or not an input is constant or active.

As a rule, PS 390 functions execute only when all the inputs have values. Some functions like F:ZVECTOR have only one input, so they fire whenever the correct value arrives on it. Others, such as F:MUL, require a value on each of two inputs. F:MULC and F:CMUL are this way, except that you can place a single value on the constant input and then control the firing of the function by sending or not sending values to the active input.

Many PS 390 functions have two or more inputs which must be accounted for. Some function inputs have default values that do not need to be primed before using the function. The descriptions in Section *RM2 Intrinsic Functions* detail which inputs are constant and which have default values provided for them.

So far you have a function network to serve as the black box for rotating the robot. There is still one other function to evaluate, F:DYROTATE. F:DYROTATE is shown in Figure 6-12.

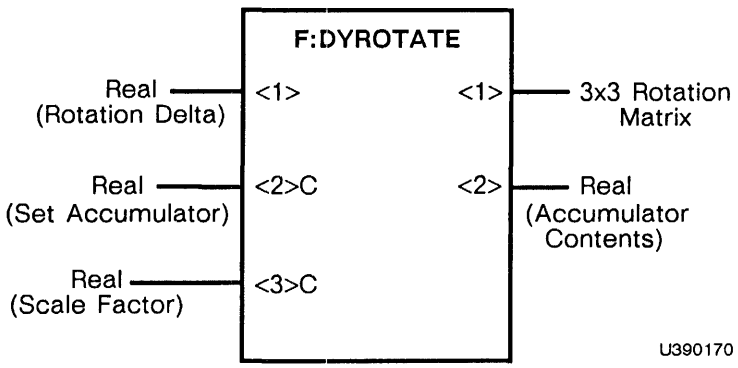


Figure 6-12. F:DYROTATE

This function has three inputs. Input <1> takes values directly from the dials. Input <3>, a constant input, holds a magnifying value and does the

same thing F:MULC does in the F:YROTATE network; the values coming in on input <1> get multiplied by the value on F:DYROTATE's input <3>.

Input <2> is an accumulator value. It performs the same function F:CMUL does in the other network. This input requires an initial or reset value (in this case 0) the same way F:CMUL needs an identity matrix at input <1>. (You can send a zero to input <2> and reset the accumulator whenever desired.) Output <2> is not used here but consists of the constant accumulator content on input <2>.

In short, F:DYROTATE does everything the F:YROTATE network does with one function instead of three. Since there is no reason to use three functions where one will do, the next task is to use PS 390 commands to implement a function network using F:DYROTATE (Figure 6-13).

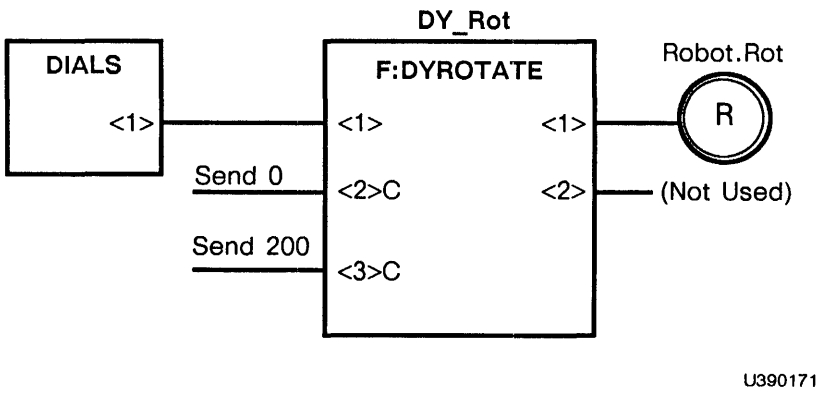


Figure 6-13. F:DYROTATE Function Network

This network consists of two functions and a named node. The first function, DIALS, is an initial function instance. It has eight outputs, one for each dial. You do not have to instance it; the PS 390 does that automatically when you turn it on.

The second function in the network, F:DYROTATE, must be instanced and assigned a name.

This network is almost identical to the one used in Section *GT1 Hands-On Experience*. There you rotated the star-shaped object named Spinstar by connecting it to a F:DZROTATE function (Figure 6-14).

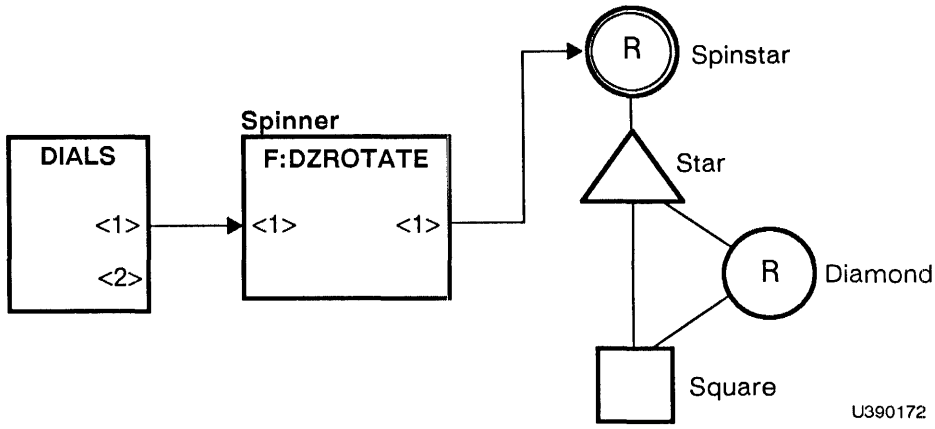


Figure 6-14. "Spinner" Function Diagram

To use that function, you had to instance it, i.e., assign it a unique name (Spinner). Then, using the CONNECT command, you connected DIALS<1> to the input of Spinner and its output to the interaction node named Spinstar. Spinner was primed by sending initial values to its two constant inputs. Then it was ready to use. Turning the dial activated the network, causing the star to spin on the screen. Do the same thing in the following exercise.

1.1 Exercise

Define DY_Rot to be an instance of F:DYROTATE using this command

```
DY_Rot := F:DYROTATE;
```

Now connect outputs to inputs as shown in the diagram. Connect DIALS<1> (the output of the top left dial) to the input of DY_Rot and the output of DY_Rot to Robot.Rot with the CONNECT command:

```
CONNECT DIALS<1>:<1>DY_Rot;
CONNECT DY_Rot<1>:<1>Robot.Rot;
```

In the CONNECT command, the input number of a function always precedes its name and the output number always follows it.

Send initial values where they are indicated. There are only two in this network: the two constant inputs of DY_Rot.

```
SEND 0 to <2>DY_Rot;
SEND 100 to <3>DY_Rot;
```

Everything in the function network diagram you drew is now accounted for and implemented in the PS 390. Turn dial 1 and the model should rotate on the screen.

Then try to enlarge the network so dials 2 and 3 control the other two rotations in X and Z, using F:DXROTATE and F:DZROTATE in exactly the same way. When the network is coded, move the dials and watch what happens to the model on the screen.

Whenever you construct a function network, use the following good programming practices:

- Always design your network before you try to code it. If you work from a diagram, you will not forget to instance a needed function or to make a required connection.
- Instance all required functions, and check them off in the diagram as you instance them. If you try to connect a function that has not first been instanced, you will create an error.
- Next, make connections from left to right in the diagram, and check them off as you make them. Starting with the functions most upstream, make all connections until you reach the outputs of the network.
- Last, prime the network with initial values. Make sure that you send a number to a constant input whenever you need to.

Figure 6-15 is a diagram of a larger network that includes the other two rotations.

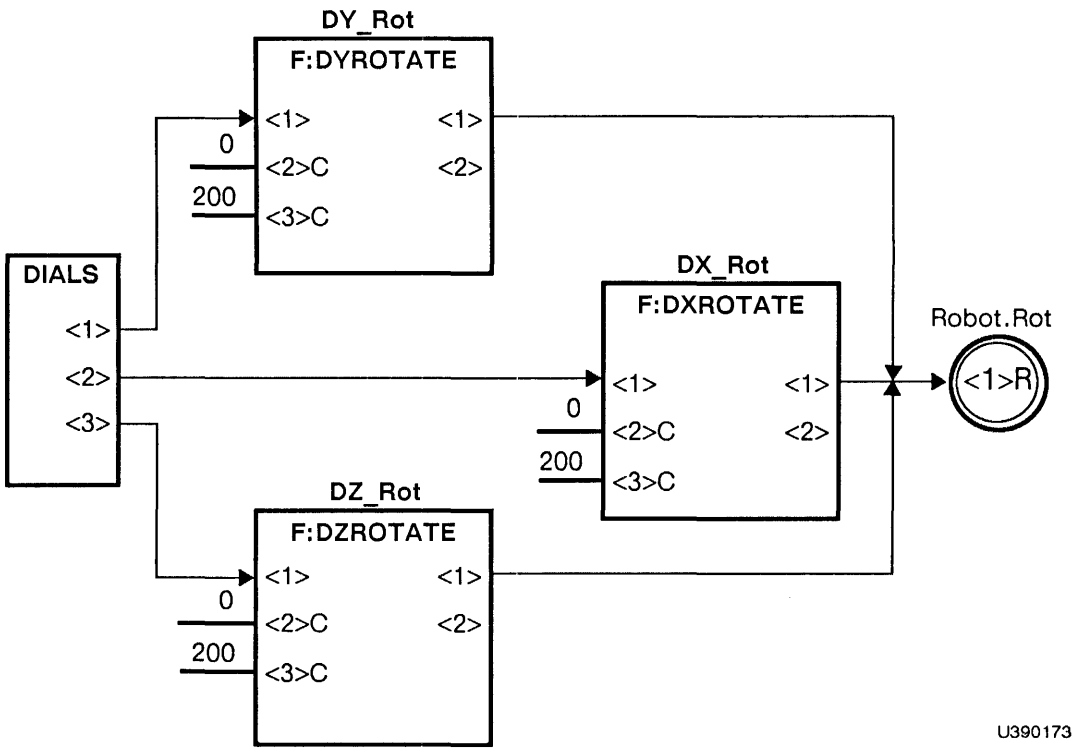


Figure 6-15. Completed Function Network for X, Y and Z Rotation

Probably the only differences between your network and this one will be the names used to instance functions. If you diagrammed your network and entered the commands correctly, you should see some unexpected jerking around in the model if you turn one dial after turning another. The next section explains why.

2. Adding Further Interaction: Rotation In Other Dimensions

The first attempt to expand the number of rotations for Robot using F:DXROTATE and F:DZROTATE produced some jerkiness. The jerkiness occurs because each rotation function in this network has its own built-in accumulator (input <2>). If you rotate the robot in Y 90 degrees, you have an accumulated 90-degree rotation value in DYROTATE. Turning the X dial generates a matrix that specifies X rotations from the initial position in X, Y, and Z. In other words, the matrix that DXROTATE produces overrides the accumulations already in DYROTATE. The X rotation applies as if no other rotation has occurred. So the model appears to jump back to its initial position before it starts rotating in X.

It was not wrong to pick F:DYROTATE instead of the F:YROTATE network if you only want to rotate a model around one axis. In that case, a D_ROTATE function is simpler to use. But to add rotations in other dimensions, you need to account for all the rotations. You could add two more rotate nodes to the display tree for X and Z rotations as shown in Figure 6-16.

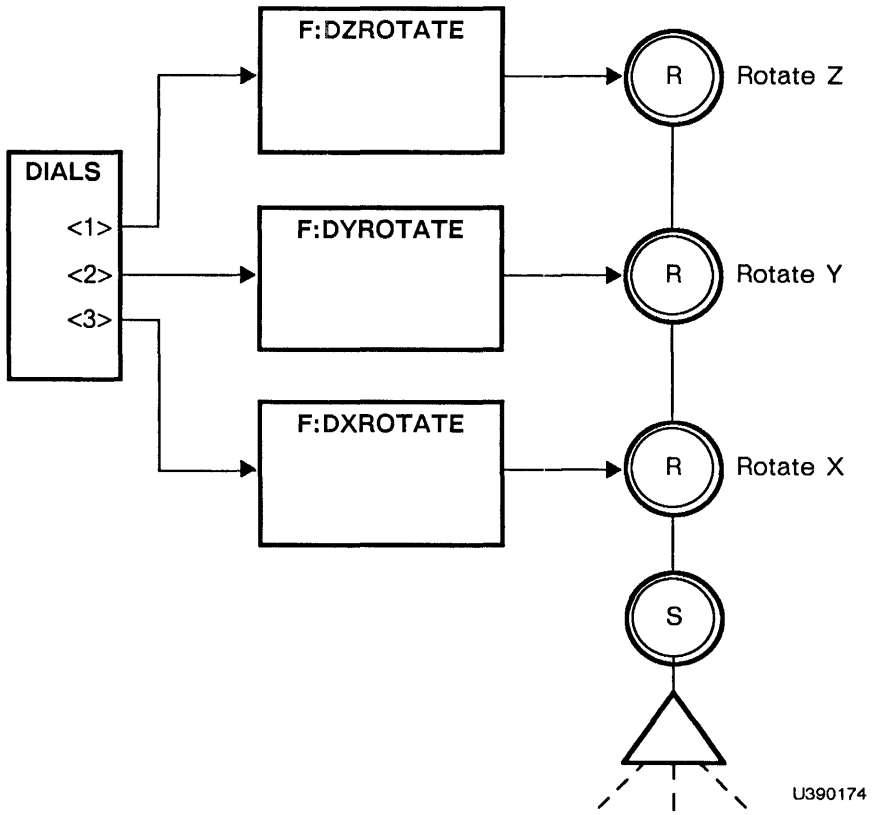


Figure 6-16. Modified Display Tree With Three Rotate Nodes

Another method is to provide a common accumulator for the whole group. Look at the network with F:YROTATE (Figure 6-17).

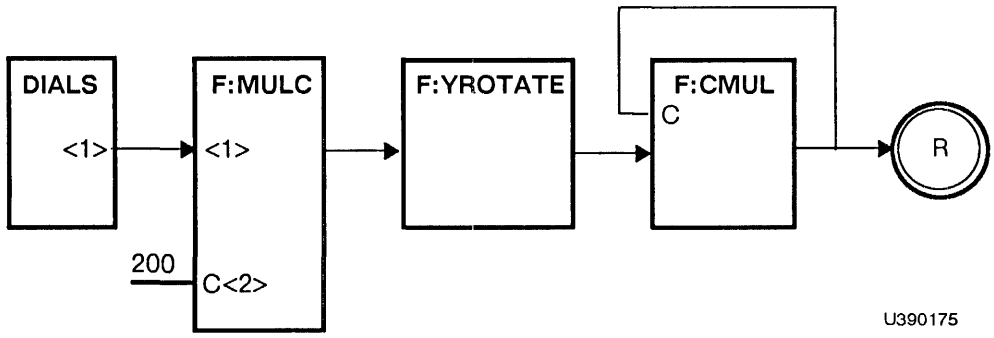


Figure 6-17. F:YROTATE Network

This network has a separate accumulator, an instance of F:CMUL. It can serve as the sole accumulator for all of the rotations of Robot.Rot, if all three ROTATE functions are connected to it.

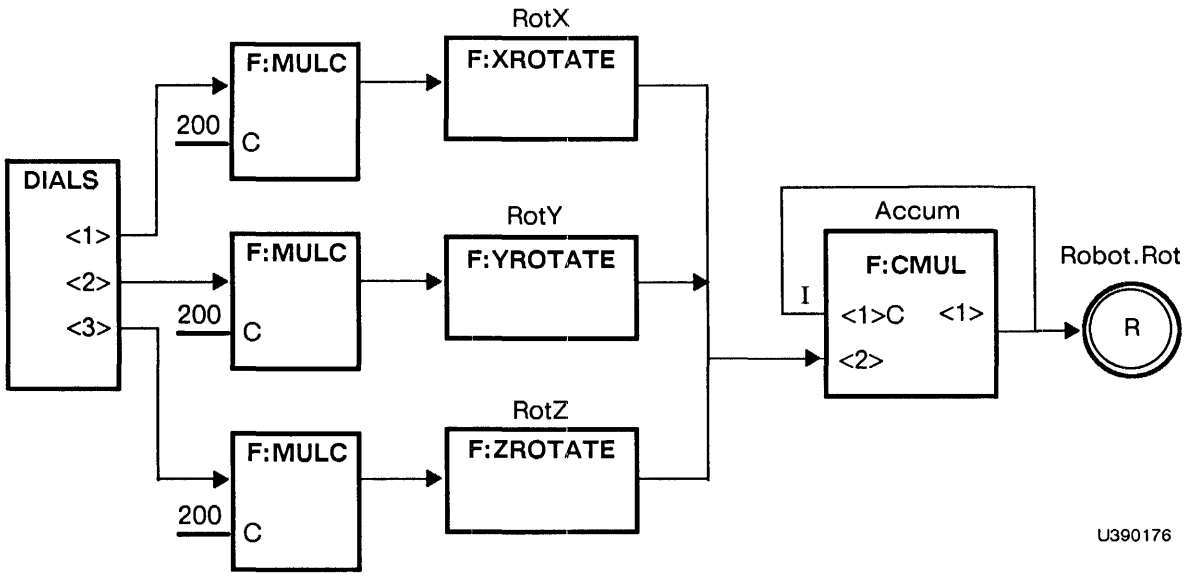


Figure 6-18. Common Accumulator for Rotate Functions

This example (Figure 6-18) shows how a single input of a function (<2>F:CMUL) can receive values from more than one source (F:XROTATE<1>, F:YROTATE<1>, F:ZROTATE<1>).

2.1 Exercise

Use the DISCONNECT command to break the connections for the network you have programmed into the PS 390. Enter:

```
DISCONNECT DIALS<1>:<1>DY_Rot;
DISCONNECT DIALS<2>:<1>DX_Rot;
DISCONNECT DIALS<3>:<1>DZ_Rot;
```

Now program the network shown in Figure 6-18. Then turn all three dials and pay close attention to how the model moves in Y after you have moved it in Z.

First, the functions must be instanced:

```
Xmul := F:MULC;
Ymul := F:MULC;
Zmul := F:MULC;
RotX := F:XROTATE;
RotY := F:YROTATE;
RotZ := F:ZROTATE;
Accum := F:CMUL;
```

Second, connections must be made between the functions:

```
CONNECT DIALS<1>:<1>Xmul;
CONNECT DIALS<2>:<1>Ymul;
CONNECT DIALS<3>:<1>Zmul;

CONNECT Xmul<1>:<1>RotX;
CONNECT Ymul<1>:<1>RotY;
CONNECT Zmul<1>:<1>RotZ;

CONNECT RotX<1>:<2>Accum;
CONNECT RotY<1>:<2>Accum;
CONNECT RotZ<1>:<2>Accum;

CONNECT Accum<1>:<1>Accum;
CONNECT Accum<1>:<1>Robot.Rot;
```

Finally, the functions must be primed by sending initial values to their constant inputs. This includes sending an identity matrix to initialize input <1> of the accumulator.

```
SEND 200 to <2>Xmul;
SEND 200 to <2>Ymul;
SEND 200 to <2>Zmul;
SEND M3D(1,0,0   0,1,0   0,0,1) to <1>Accum;
```

These rotations are called world-space rotations; they take place around the world axes and not the model axes. Once you rotate Robot in Z, if you rotate him in Y he will spin around an axis running through him that is parallel to the Y axis of the coordinate system. When a model rotates around its own axes, that is called object-space rotation. For a further discussion of object-space and world-space rotations, refer to Section *TT7 Application Notes.*

3. Expanding The Network For Other Kinds Of Interaction: Scaling and Translating

Two other transformations are possible for Robot: scaling and translations. You have already laid the groundwork by including a scaling node and a translation node at the top of the robot display tree.

Dials 1, 2 and 3 now control the model's rotations. Determine which of the remaining dials will control scaling and translation. Figure 6-19 shows a sample configuration for using the dials to control rotations, translation, and scaling for an object. One dial controls scaling, and three each are assigned for rotation and translation. One dial is unassigned.

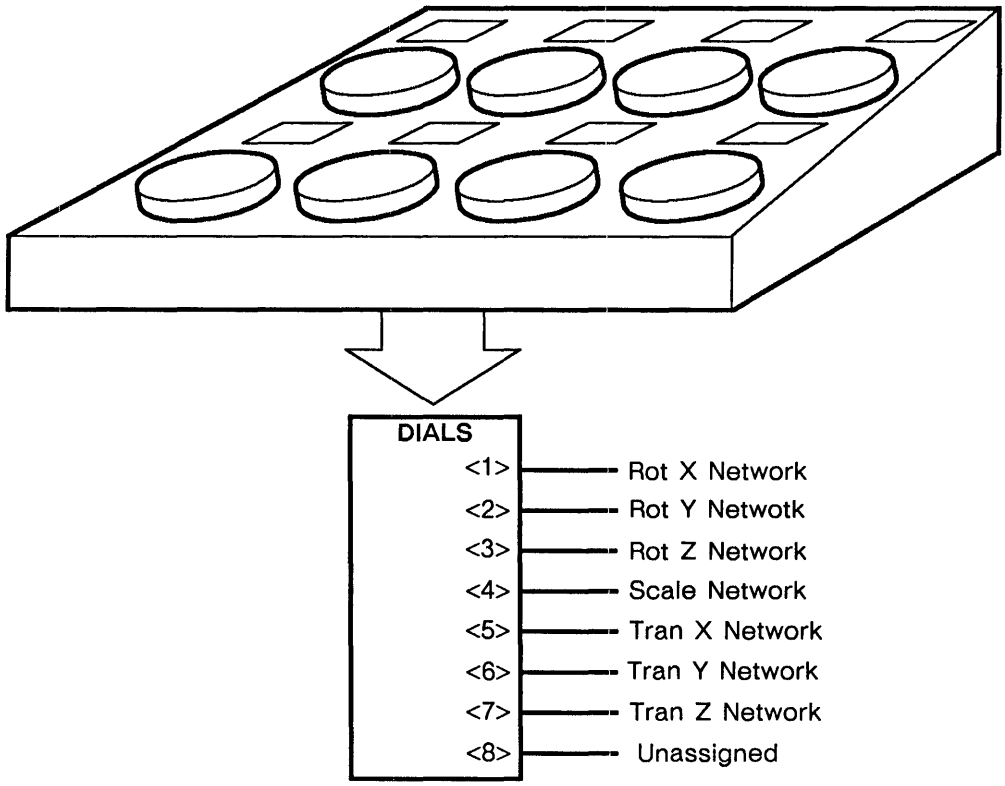


Figure 6-19. Sample Configuration for Dials

Translations take place in X, Y, and Z and need three dials: 5, 6, and 7. The type of scaling here is uniform scaling, so one value will scale in all dimensions equally. Only one dial needs to be used: dial 4.

Often, all the rotations you will need to make a model fully interactive will require more than eight dials. In the proposed network you have so far, for instance, only three nodes from the display tree of the model use up seven dials. The remaining interaction nodes in the display tree require up to three dials each. This means about fifty dials are necessary to handle all those rotations. A way to reuse a single set of eight dials to solve this problem is discussed in Section *GT7 Function Networks II.*

Now enlarge the network to translate the robot. This network will closely resemble the one just finished for rotations. First, determine what data type the node requires.

Translate nodes accept vectors. The associated functions of the TRANSLATE command in Section *RM1 Command Summary* are F:XVECTOR, F:YVECTOR, and F:ZVECTOR. These all take real numbers as their input and produce 3D vectors. The input value is in the X (or Y or Z) position in the vector. F:XVECTOR, for example, would take the real number 4.5 and send out the vector (4.5, 0, 0). F:YVECTOR would take the same input and send out (0, 4.5, 0).

Figure 6-20 shows a network with VECTOR functions for translating in three dimensions.

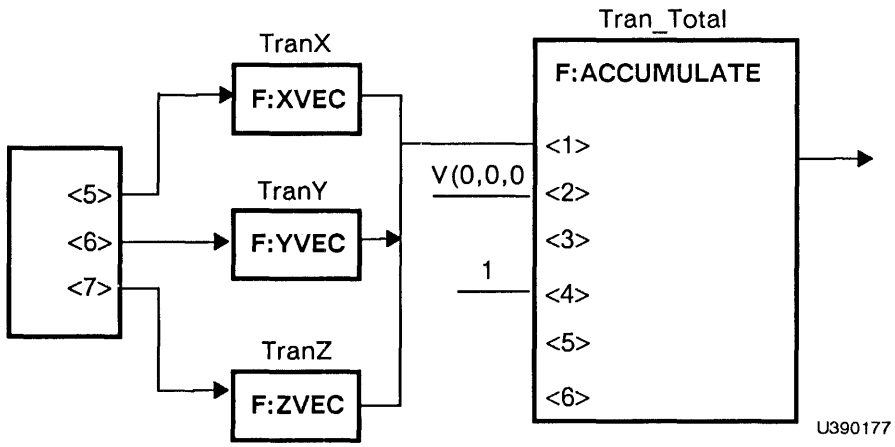


Figure 6-20. Translate Network

The accumulator in this network is not the multiplying function F:CMUL but a new one, F:ACCUMULATE. F:ACCUMULATE does the job of several functions. There is no need, for example, to put a multiplying function like F:MULC in this network. To enlarge dial values, send a multiplying factor to F:ACCUMULATE input <4>. In the case of this translate network, a suggested factor is 10 (that corresponds to the 200 multiplying factor for rotations). The reset value for the accumulator goes on input <2>.

Three inputs are not used in this application. Input <3> lets you control the smoothness of translation by setting the minimum change in position per output. And the last two inputs control limits. If you do not want an object to move more than a specified amount (to keep it within the limits of the screen, for example), you can set limits on its movement with inputs <5> and <6>.

The accumulator is shared by all three VECTOR functions just as the three ROTATE functions share a common accumulator.

3.1 Exercise

Instance the functions in the translate network using the names suggested in NO TAG, connect them to dials 6, and 7, and prime constant queues <2> and <4> of F:ACCUMULATE. Then use what you know about building networks to diagram one for scaling the robot.

To create the translate network, first instance the functions:

```
TranX := F:XVEC;
TranY := F:YVEC;
TranZ := F:ZVEC;
Tran_Total := F:ACCUMULATE;
```

Then connect the functions to the dials:

```
CONNECT Dials<5>:<1>TranX;
CONNECT Dials<6>:<1>TranY;
CONNECT Dials<7>:<1>TranZ;

CONNECT TranX<1>:<1>Tran_Total;
CONNECT TranY<1>:<1>Tran_Total;
CONNECT TranZ<1>:<1>Tran_Total;
CONNECT Tran_Total<1>:<1> Robot.Tran;
```

Prime the functions by sending initial values to all constant inputs.

```
SEND V(0,0,0) TO <2>Tran_Total;
SEND 1 TO <4>Tran_Total;{Note that 1 is the default for input <4>}
```

To construct a network for scaling, first use Section *RM1 Command Summary* to determine what values the scale node of the model uses—3x3 matrices—and what its associated functions are. You will find the same functions that are listed under the ROTATE command, but the applicable ones here are F:SCALE and F:DSCALE. To use F:SCALE, you need a separate multiplying function and a separate accumulator.

F:DSCALE is more of a "3-in-1" function like F:ACCUMULATE and the DROTATE functions. It combines a matrix-producing function, an accumulator, and a multiplier all in one. Since you only have one scaling factor,

F:DSCALE will be safe to use here (you do not have to worry about separate X, Y, and Z scaling factors).

The values from the dial come in on input <1>. Input <3> is the multiplying factor for dial values. Rather than using 100, as you did in the rotation network, use 0.1. This smaller value is used because robot is initially scaled by .075. (See Figure 6-21.)

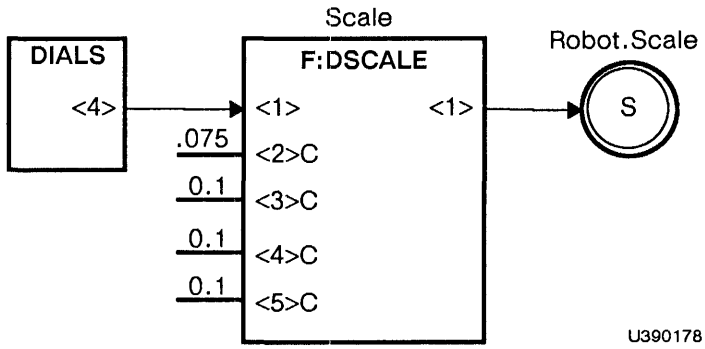


Figure 6-21. Network for Uniform Scaling

F:DSCALE requires an accumulator reset value for input <2>. This should correspond to the initial value the object is scaled to. In most cases, that is 1, but remember the robot is already scaled to .075 so he will be small enough to appear on the screen. Be sure to send this initial scale value (.075) to input <2>.

F:DSCALE, like F:ACCUMULATE in the translation network, also lets you set upper and lower limits so the object being scaled does not become too large or small. If you sent 0.1 to input <4> and .01 to input <5>, for example, the robot would never become more than twice or less than one-fifth his initial size (.075) on the screen. If you do not send limits to these two inputs, no limit is set.

3.2 Exercise

Tracing two or three of the fractional values from the dial shows that F:DSCALE accumulates scaling values as you expect. Now, use the names shown in Figure 6-21 to instance, connect, and prime the functions.

To create the scale network, first instance the function:

```
Scale := F:DSCALE;
```

Then connect the function to the dial and the interactive scale node in the robot display tree:

```
CONNECT Dials<4>:<1>Scale;
CONNECT Scale<1>:<1>Robot.Scale;
```

Finally, prime the function by sending initial values to the constant inputs.

```
SEND .075 TO <2>Scale;
SEND 0.1 TO <3>Scale;
SEND 0.1 TO <4>Scale;
SEND .01 TO <5>Scale;
```

4. A Clock Function As An Alternate Source Of Input For The Network

It is not always necessary to use dials, function keys, or data tablets to provide input for a function network. You may want some action to happen automatically or to cycle through and repeat. This section discusses how to use a clock function to do that for Y rotations. When the network is connected to the robot, it will automatically rotate.

Whenever you SEND an integer to a function, use FIX(i), where (i) is the integer being sent. FIX indicates the value is an integer and not a real number. If you do not use FIX, the function will still operate, but it requires more computation time.

Use F:CLFRAMES, shown in Figure 6-22.

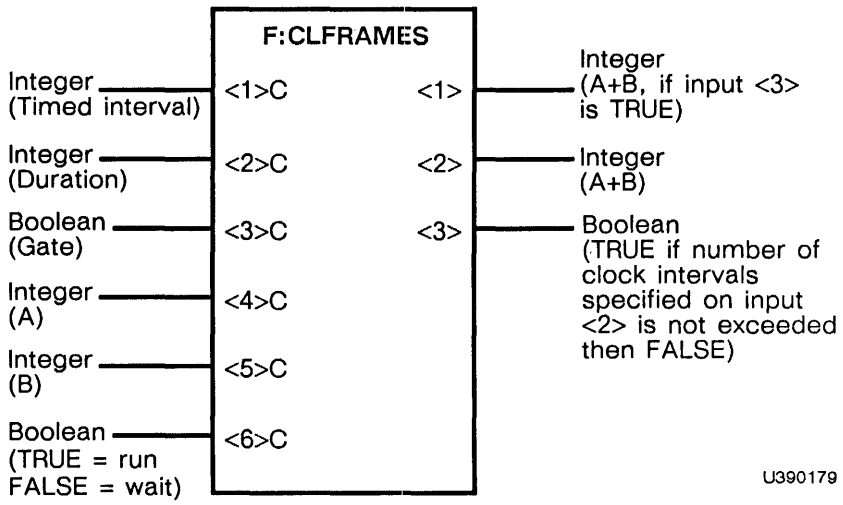


Figure 6-22. F:CLFRAMES

The "CL" in the name indicates it is a clock function; "FRAMES" means that its "ticking" depends on the rate at which display frames are traversed. F:CLFRAMES sends out a value when a certain number of frames have been traversed, independent of time. The integer you place on input <1> specifies how many frames you want to elapse before F:CLFRAMES "ticks."

In all, there are six inputs and three outputs for this function. These allow you to use F:CLFRAMES as more than just a simple counter, which is all it will be used for in this example.

Input <1> is the interval measured in frames. It requires an integer, so SEND it a FIX(2). This will result in about 30 degrees rotation per second.

Input <2> affects output <3> but has no effect on what you are doing right now. It requires an integer, so SEND it a FIX(1).

Input <3> shuts down or opens output <1>. Since you will not use output <1> here, send a FALSE to input <3>.

Inputs <4> and <5> are constant, and contain integer values whose sum is generated when F:CLFRAMES ticks. You can accumulate the sum by connecting output <2> back around to input <5> and then SENDing FIX(1) to input <4> and FIX(0) to input <5>. However, since F:CLFRAMES is to be used in a network that is already set up to accumulate values from the dials (ACCUM), values should not be accumulated in F:CLFRAMES.

F:CLFRAMES output <2> is connected to the rotation network you already have, as shown in Figure 6-23.

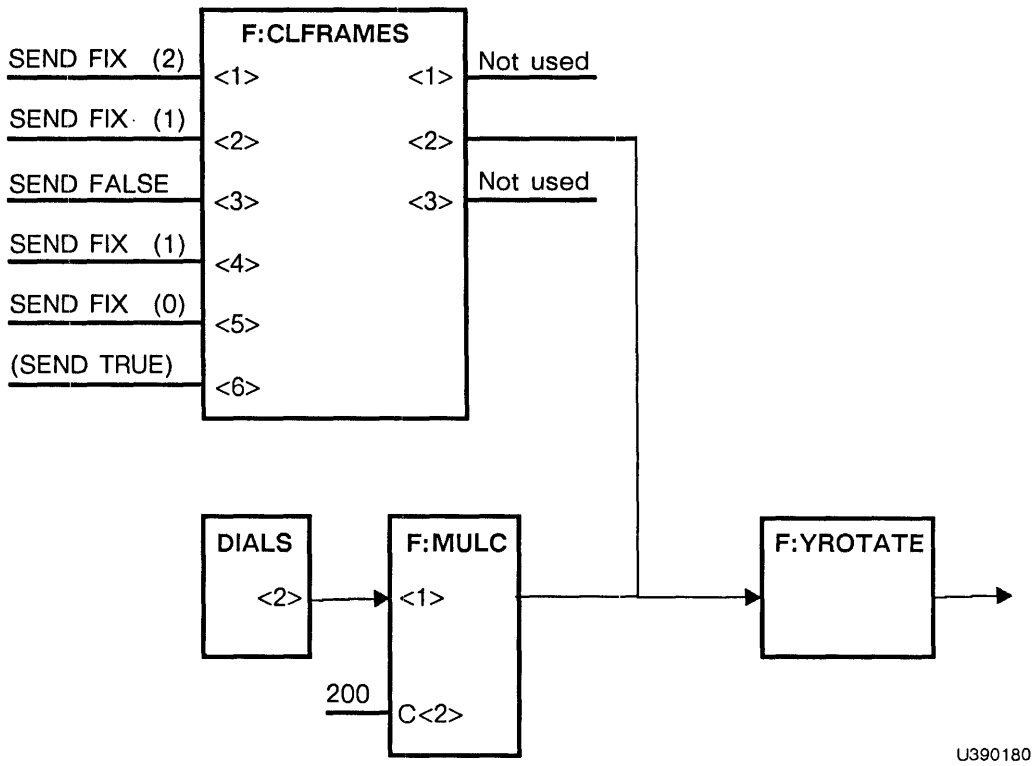


Figure 6-23. F:CLFRAMES as Input Source for Y Rotation

The diagram shows initial values for inputs <2> and <3> of F:CLFRAMES. Though they are not used here, they must be supplied for F:CLFRAMES to function. In the same way that F:ADD will not fire until it has two inputs, F:CLFRAMES requires that some value must be placed on all its inputs in order to run. The diagram reminds you of all the values you need to send to prime the network.

Input <6> provides a switch to operate the clock. It requires a Boolean value, TRUE to run the clock or FALSE to stop it.

4.1 Exercise

Instance F:CLFRAMES as "Timer" and connect the function into the network as shown in Figure 6-23. Be sure to send initial values to all of the first five inputs. Last, send a TRUE to input <6> to make the model begin spinning. Here is a list of the commands needed to implement the network shown in Figure 6-23.

```
Timer := F:CLFRAMES;

CONNECT Timer<2>:<1>RotY;

SEND FIX(2) TO <1>Timer;
SEND FIX(1) TO <2>Timer;
SEND FALSE TO <3>Timer;
SEND FIX(1) TO <4>Timer;
SEND FIX(0) TO <5>Timer;
SEND TRUE TO <6>Timer;
```

To stop the robot from twirling, send a FALSE to input <6>.

Remember that the dials are still connected to the robot. You now have two sources of input for a function (RotY receives from DIALS through the instance of F:MULC and from the clock function). To be sure the two sources of input do not compete, you can shut F:CLFRAMES off when you use the dials by sending FALSE to input <6>.

You can also "unplug" it entirely by using the DISCONNECT command. Use this command exactly as you do CONNECT:

```
DISCONNECT Timer<2>:<1>RotY;
```

Of course, to ensure that the dial does not interfere with the clock, you could break the connections between the dial and the instance of F:MULC that leads to RotY.

When you do turn the clock off by sending FALSE to input <6>, it would be convenient to do so by simply pushing a button instead of typing in SEND commands repetitively.

Since function networks are so flexible, there are dozens of ways to accomplish something, as you have already seen with the two or three ways to control rotations in a model. Designing a switch is just as open-ended. You

could arrange to have F:CLFRAMES start firing when you push function key F1 and stop when you push function key F2, for instance. Or it could start if you sent it any value larger than five, and stop if it received a value less than five. The network shown in Figure 6-24, however, toggles. If you press any function key, it turns F:CLFRAMES on; if you press it again, F:CLFRAMES turns off.

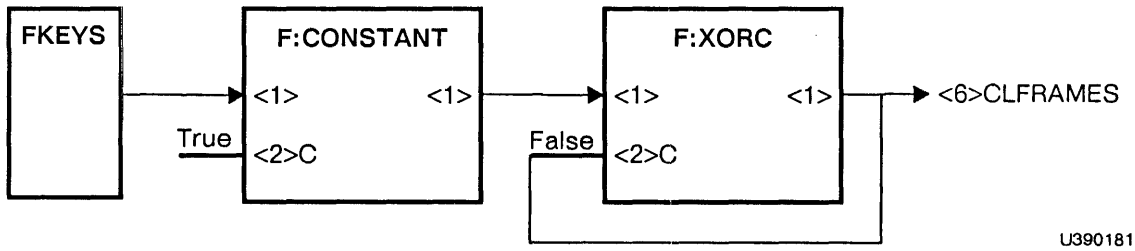


Figure 6-24. A Network That Toggles

In this network, F:CONSTANT can hold any value (a number, a matrix, a Boolean value) on its constant input <2> and will send out that value when any value arrives on input <1>.

Place a TRUE on input <2> and connect the output of F:CONSTANT to another function, F:XORC. This function performs a logical_operation, EXCLUSIVE-OR. It compares the Boolean value it receives on input <1> to the Boolean value on its constant input <2> and produces a TRUE if they are different and a FALSE if they are the same. The output of F:XORC is then sent back to its own constant input and also on to the place you need to toggle (input <6> of F:CLFRAMES).

Trace a couple of values from the function keys function FKEYS through this network to confirm that you get alternating TRUE and FALSE values as output.

To emphasize that there are many ways to do something with function networks, Figure 6-25 shows a more efficient network for a switch.

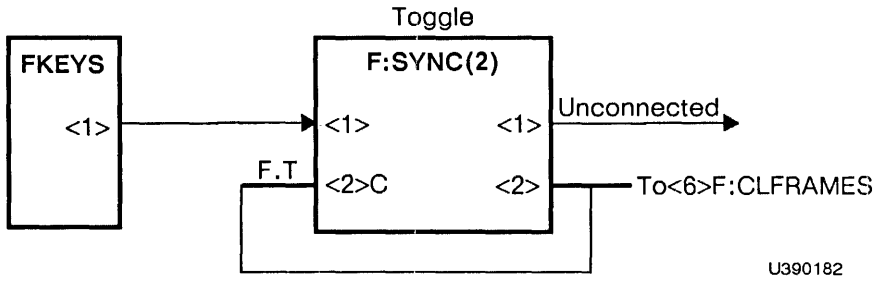


Figure 6-25. A More Efficient Toggle Switch

Here the network is composed of only one function. The stackable nature of active inputs is used to queue a FALSE and a TRUE. Then F:SYNC's output is connected back to its own input 2 so the two Boolean values can alternate as output values.

5. Summary

If you added to your function network throughout this section, the final network diagram should look like the one in Figure 6-26.

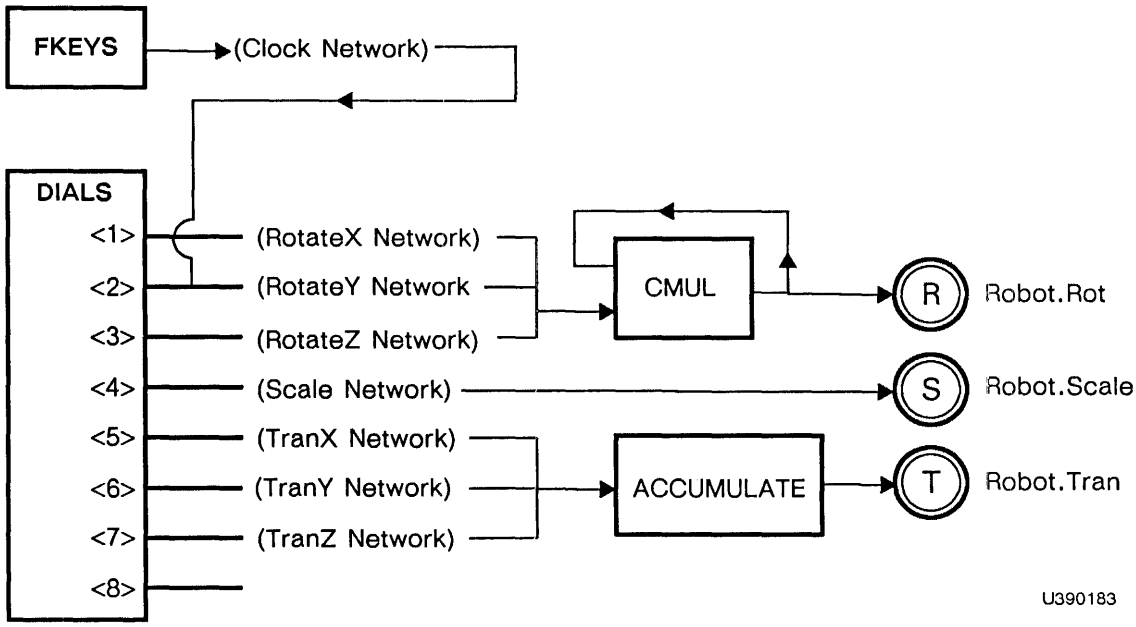


Figure 6-26. The Completed Network

When the diagram contains all function instance names and initial values to be sent, it looks complicated, but its operations are fairly simple. It controls interactions for only three display tree nodes.

5.1 Review of Major Points

To build a function network, you must find candidate functions or function networks (represented as a black box) which convert input device values into values that can update interaction nodes in a display tree. To do this:

- Identify the type of output needed by interaction nodes.
- Identify sources of input and what type of values they generate.
- Use Section *RM1 Command Summary* to find related functions for interaction nodes.
- Use Section *RM2 Intrinsic Functions* to evaluate candidate functions or networks and modify the network as needed with additional functions.
- Implement the network using good programming practices:

  Always diagram the network first
  Instance functions first
  Make connections from left to right in the diagram
  SEND any initial values to prime the network.

Once the basic network is built, you can expand it. In the network of this section, you added:

- Rotations in other dimensions. Some way of accumulating rotations is usually needed.
- Other kinds of interaction—scaling and translating.
- An alternate source of input for the network—a clock function. This can be toggled on and off with a switch network connected to a function key.

5.2 Important Facts About PS 390 Functions

- When a complete set of input values arrives, the function executes and sends out values on its outputs.

- Functions can have constant or active inputs. A value on an active input disappears or is consumed when the function fires. If values arrive on an active input faster than they are consumed, they will queue in the order they arrive. Constant inputs hold only one value at a time—there is no queuing. A value on a constant queue is not consumed when the function fires. It will remain until it is overwritten by another value.

- Functions perform arithmetic, logical, routing, or data conversion operations.

- In a function network, values flow from left (upstream) to right (downstream).

- Functions that are directly associated with an input device, such as DIALS and FKEYS, do not need to be instanced. These are examples of initial_function_instances; they are instanced by the system.

5.3 PS 390 Commands Discussed in This Section

- Immediate action commands: CONNECT, DISCONNECT, SEND.
- Function-instancing commands: name := F:function name.

GT7. FUNCTION NETWORKS II

GT7. FUNCTION NETWORKS II

SWITCHING NETWORKS

CONTENTS

ILLUSTRATIONS

Section GT7
Function Networks II
Switching Networks

Introduction

This section consists of four parts that build on ideas about function networks introduced in Section *GT6 Function Networks I.*

In Section *GT6 Function Networks I* you used the PS 390 dials to manipulate a robot. Each dial was connected to a node in the robot display tree so that moving the dial caused Robot to move in a specific way. One dial was needed for each manipulation.

In this section, you will learn how to use a dial for multiple interactions. This can be done using function networks and PS 390 function keys. Pressing a function key allows you to use the same dial for different kinds of interactions in different modes.

The section also details how to send a label to the LEDs above each dial. These labels remind you of the function of a dial and can change interactively each time a new function key is pressed.

Note

The Soft_labels network redefines the dynamic viewport on the PS 390 to allow the left edge of the display screen to be used as a display area for the function key labels (flabels) and dial labels (dlabels). This network can be useful for PS 390 systems with control dials and function keys that do not have LEDs. For details of the Soft_labels network refer to Section *TT2*.

In addition, you will learn about several useful tasks which function networks can perform. These include limiting the robot movement so that it remains "true to life" and using variables to store values coming from a network.

Because the function networks in this section will differ from those created in Section *GT6 Function Networks I*, it is suggested that you save the code from this section in a separate file on your host. To avoid errors, do not combine these two sets of code.

Objectives

In this section you will learn how to:

- Make a single input device (the dials) control multiple interactions.
- Label the dials so that the label changes when the dial's function changes.
- Set limits on the motion of a model.
- Use variables to store values.

Prerequisites

Before beginning this section, you should be familiar with the concepts presented in Sections GT4 *Modeling*, GT5 *PS 390 Command Language*, and GT6 *Function Networks I*.

1. Making a Single Input Device Control Multiple Interactions

In Section GT6 *Function Networks I*, you constructed a function network for the display tree shown in Figure 7-1.

This function network supplied interactions for the top three nodes of the display tree: Robot.Scale, Robot.Rot, and Robot.Tran. Seven dials were required to manipulate the robot: three to rotate it in the X, Y, and Z planes, three to translate it in X, Y, and Z, and one dial to scale the model. Only one free dial remains, but no other interactive nodes in the robot display tree have yet been connected to functions. To supply X, Y, and/or Z rotations for all the other interactive nodes would require dozens of other dials. This section illustrates how to solve this problem by making one set of eight dials perform like many sets.

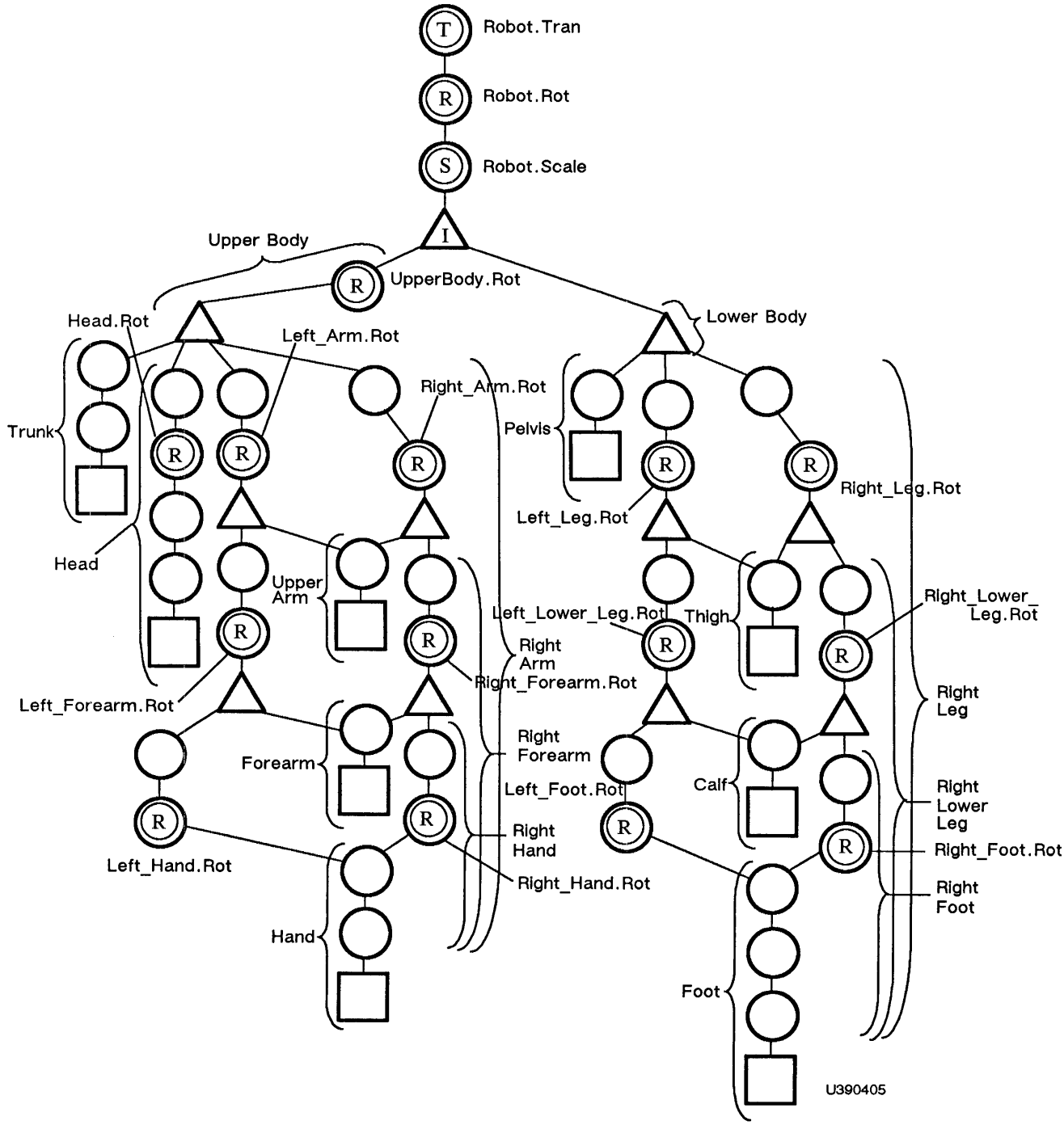


Figure 7-1. Robot Display Tree

The first step in doing this is to determine exactly how many additional dials you will need by deciding how many more interactions in the model you want to control. In addition to Robot.Rot, the robot has 14 rotation

nodes. Ten of them require three dials each (three rotations for X, Y, and Z). The two nodes for elbows and the two for knees only use X rotations, requiring only one dial each. The result is a total of 34 additional interactions. To handle these interactions, each dial would have to be connected to about six nodes.

There is nothing to prevent you from connecting a dial to more than one destination. For example, you could hook dial 1, already updating X rotations for the Robot.Rot node, to other rotate nodes. But of course turning that one dial would cause multiple unrelated updates. Following is one way the dials might logically be assigned to control the interactions. In Mode 1, the dials would work as presently assigned:

```
Whole model:  1. Rotation in X      5. Translation in X
              2. Rotation in Y      6. Translation in Y
              3. Rotation in Z      7. Translation in Z
              4. Scale              8. Not Assigned
```

Mode 2:

```
Head:   1. Rotation in X      Trunk:   5. Rotation in X
        2. Rotation in Y               6. Rotation in Y
        3. Rotation in Z               7. Rotation in Z
        4. Not Assigned                8. Not Assigned
```

Mode 3:

```
Right arm:  1. Rotation in X      Left arm:  5. Rotation in X
            2. Rotation in Y                 6. Rotation in Y
            3. Rotation in Z                 7. Rotation in Z
            4. Elbow Rot. in X               8. Elbow Rot. in X
```

Mode 4:

```
Right hand:  1. Rotation in X    Left hand: 5. Rotation in X
             2. Rotation in Y               6. Rotation in Y
             3. Rotation in Z               7. Rotation in Z
             4. Not Assigned                8. Not Assigned
```

Mode 5:

```
Right leg:   1. Rotation in X    Left leg:  5. Rotation in X
             2. Rotation in Y               6. Rotation in Y
             3. Rotation in Z               7. Rotation in Z
             4. Knee Rot. in X              8. Knee Rot. in X
```

Mode 6:

```
Right foot:  1. Rotation in X    Left foot: 5. Rotation in X
             2. Rotation in Y               6. Rotation in Y
             3. Rotation in Z               7. Rotation in Z
             4. Not Assigned                8. Not Assigned
```

This configuration leaves several dials unassigned in a few modes. Obviously, you could assign every dial in every mode, but this organization establishes a pattern that makes the functions of the dials easy to remember.

Another way to diagram this same dial assignment would be as follows. The names of the nodes on the right are linked to the dials on the left.

```
DIALS<1>     Rotation in X          Whole body (1)
                                     Head (2)
                                     Right arm (3)
                                     Right hand (4)
                                     Right leg (5)
                                     Right foot (6)

DIALS<2>     Rotation in Y          Whole body (1)
                                     Head (2)
                                     Right arm (3)
                                     Right hand (4)
                                     Right leg (5)
                                     Right foot (6)

DIALS<3>     Rotation in Z          Whole body (1)
                                     Head (2)
                                     Right arm (3)
                                     Right hand (4)
                                     Right leg (5)
                                     Right foot (6)

DIALS<4>                            Whole body scale (1)
                                     Right elbow Rotation in X (3)
                                     Right knee Rotation in X (5)

DIALS<5>                           Whole body Translation in X (1)
                                    Trunk Rotation in X (2)
                                    Left arm Rotation in X (3)
                                    Left hand Rotation in X (4)
                                    Left leg Rotation in X (5)
                                    Left foot Rotation in X (6)
```

```
DIALS<6>                    Whole body Translation in Y (1)
                             Trunk Rotation in Y (2)
                             Left arm Rotation in Y (3)
                             Left hand Rotation in Y (4)
                             Left leg Rotation in Y (5)
                             Left foot Rotation in Y (6)

DIALS<7>                    Whole body Translation in Z (1)
                             Trunk Rotation in Z (2)
                             Left arm Rotation in Z (3)
                             Left hand Rotation in Z (4)
                             Left leg Rotation in Z (5)
                             Left foot Rotation in Z (6)

DIALS<8>                    Left elbow Rotation in X(3)
                             Left knee Rotation in X (5)
```

If the connections were made from the dials as shown, a dial would control several interactions simultaneously. If you turned dial 4, for instance, the robot would become larger or smaller, or its right knee and elbow would move. Dial 1, connected to six nodes, would cause six separate X rotations in the model.

What is needed now is the equivalent of a switch in a railroad yard to route values so that they are not routed down all function network paths at once. For example, you might want to send values to the Robot.Rot node only in dials mode 1, or just to Head.Rot node in mode 2.

Associated with all the function keys is one system function, FKEYS. FKEYS has one output. When you press a function key, the number of that key is output. For example, pressing key F4 causes an integer 4 to be output.

The value could be output to an instance of function F:CROUTE(n) (Figure 7-2). This switching function allows you to channel the values from the dials (or anything else) to any number (n) of destinations.

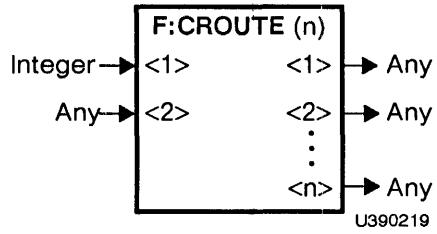


Figure 7-2. F:CROUTE(n) Function

Specifically, when F:CROUTE(n) receives an integer from 1 to n on input <1>, it routes what it receives on input <2> to the output with the same number as the integer. So if you instance F:CROUTE (n), connect FKEYS to input <1> of the function instance, connect the dials to input <2>, and press function key F5, the values from the dials arriving on input <2> will travel out on output <5> (Figure 7-3).

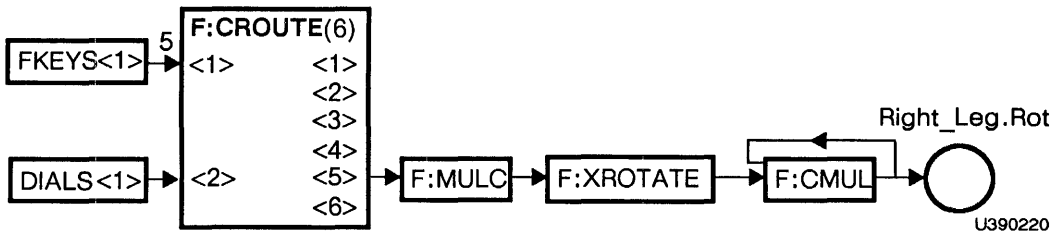


Figure 7-3. F:CROUTE(n) Network —Example 1

Pressing function key F3 routes the values from dial 1 to output <3> (Figure 7-4).

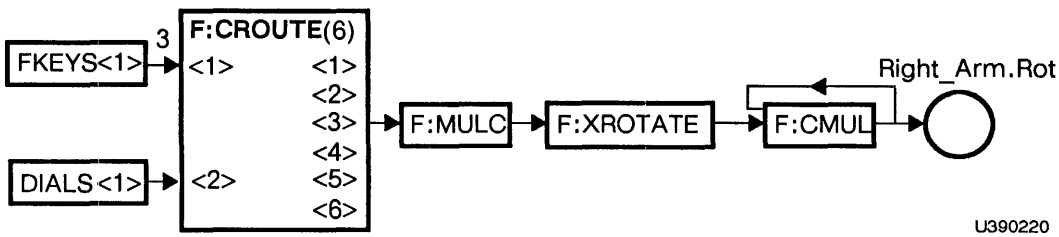


Figure 7-4. F:CROUTE(n) Network — Example 2

In this example, the number of destinations from a routing function is the same as the number of modes among the function switches. For dial 1, that is six modes, so dial 1 will use an instance of F:CROUTE(6), as shown in the above diagrams.

Not all dials need to work in all six modes. Dial 4 must operate in mode 5, however, so you must use 5 as a minimum value for n, as shown below. The unused outputs (for modes in which dial 4 is unassigned) are left unconnected (Figure 7-5).

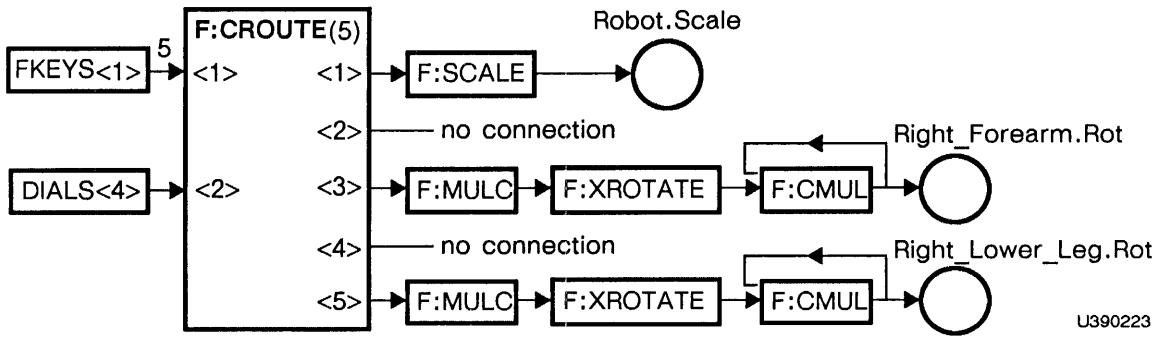


Figure 7-5. F:CROUTE(n) Network With Unused Outputs

The diagram indicates that the values from dial 4 will be routed to the scaling node, Robot.Scale, when FKEYS sends 1 to F:CROUTE(5) input <1>. Values from dial 4 will go to the right knee when a 5 arrives on input <1> and to the right elbow when a 3 arrives. If you push function keys F2 or F4 to go into mode 2 or 4, dial 4 has no effect.

Dial 8 is similar to dial 4, but instead of working in three modes, it only works in two. One of the two modes it works in is mode 5, so be sure to use an instance of F:CROUTE(5) with dial 8 too.

Connect all six modes for dial 1 to the outputs of F:CROUTE(6) so that FKEYS will control routing for this dial. Figure 7-6 illustrates the F:CROUTE(n) network of dial 1.

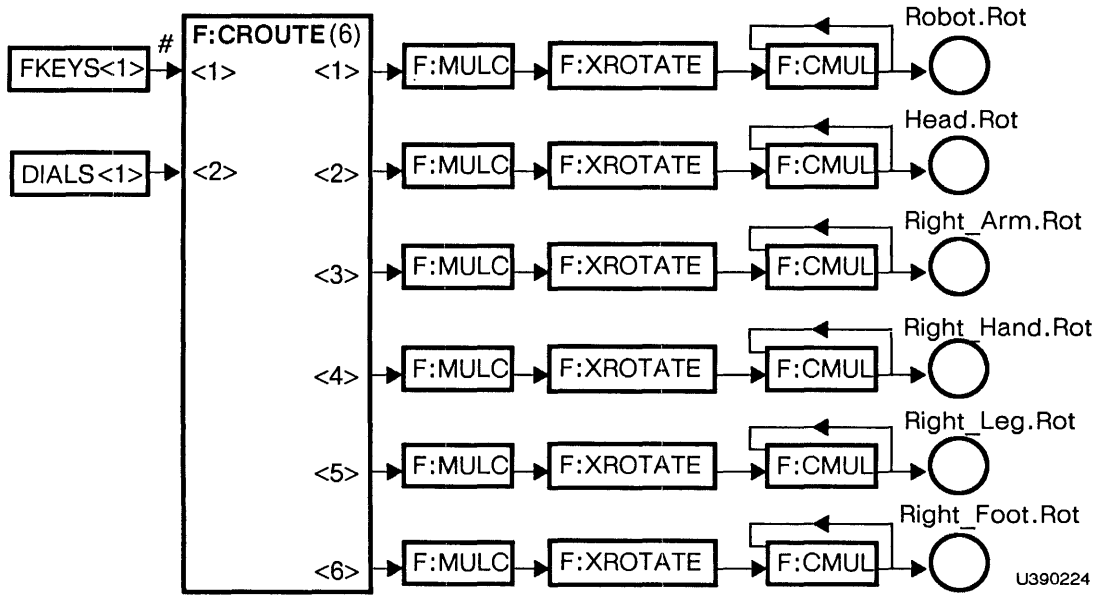


Figure 7-6. F:CROUTE(n) Network of Dial 1

Notice that the F:MULC and F:XROTATE functions in all six modes are exactly alike. The F:CMUL functions are not, since each one accumulates rotations for a different rotation node. What is exactly alike can be used once on the input side of the routing function, as shown in Figure 7-7.

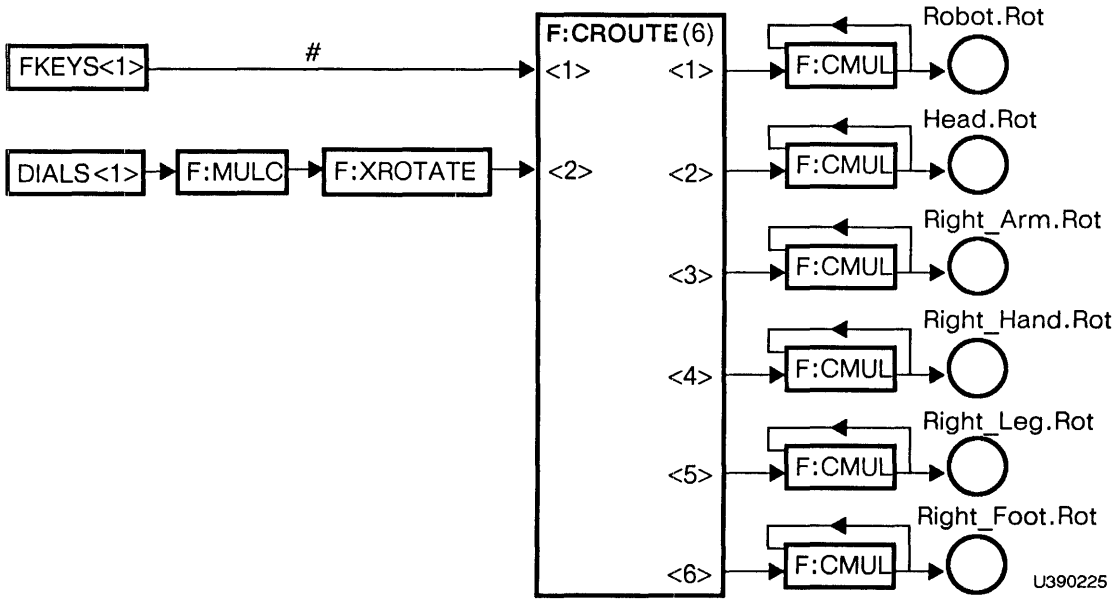


Figure 7-7. F:CROUTE(n) Network of Dial 1 With Shared Functions

Either of the above two configurations would work. The second one is much less trouble to diagram and program, since it requires only one instance of F:MULC and F:XROTATE instead of six. The previous two diagrams show that a routing function is necessary only when a path must split, which occurs when functions need to be unique, as in the case of the instances of F:CMUL.

Now diagram networks for dials 2 and 3, using the diagram from dial 1 as a guide. Since all three dials have the same destination nodes, you can route them through the same switching function, as in Figure 7-8.

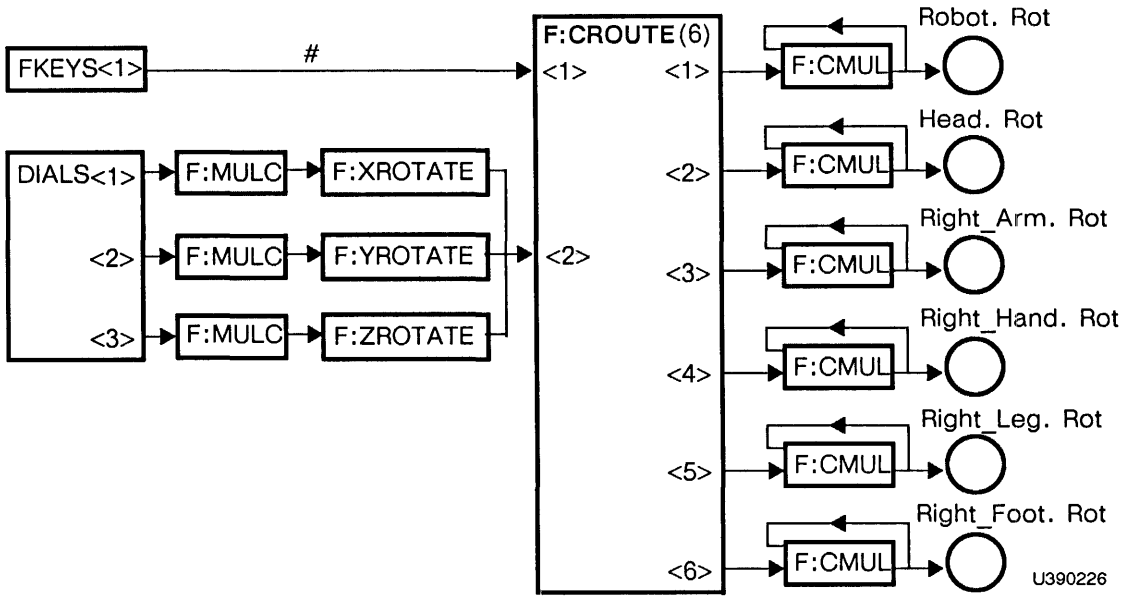


Figure 7-8. Final Network for Dials 1–3

This diagram completely accounts for the first three dials in all six modes. To implement it in the PS 390, you only need to fill in detail familiar from Section *GT6 Function Networks I*: connections, function instance names, and so on.

Next, look at dial 4. Since it performs rotations, you might think to use the same rotation network for it as the first three dials, namely as shown in Figure 7-9.

Figure 7-9. Possible Network for Display

No other dials feed into that node, though, or the other rotation node for the knee that dial 4 controls. So it would be simpler to use the F:DXROTATE function here. It is the function that combines all features of F:MULC, F:XROTATE, and F:CMUL into one package. The network for dial 4 can be diagrammed as Figure 7-10.

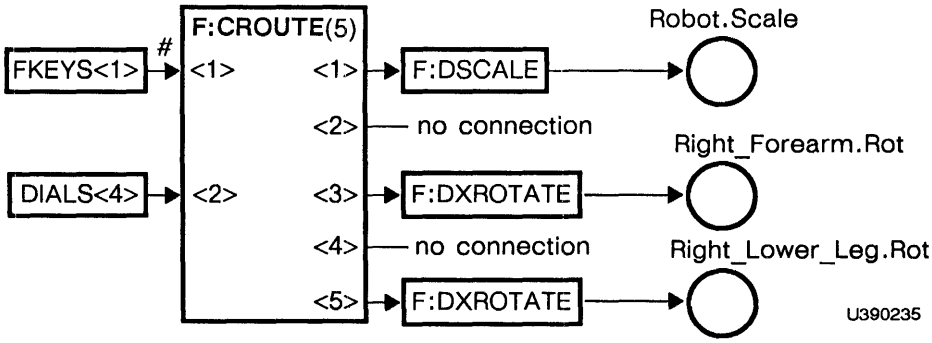


Figure 7-10. Final Network for Dial 4

With dial 4, there are no functions on the output side of the routing function that can be shared and moved over to the input side, as with F:MULC and rotation functions used with dials 1, 2, and 3. The above diagram completely specifies what dial 4 will do in all modes. To implement it, you must supply function instance names, initial values, and so on.

Dials 5, 6, and 7 do almost exactly what dials 1, 2, and 3 do, but to the left side of the model; in mode 1, they translate instead of rotate. In mode 1, all three dials feed into one node, Robot.Tran. In the other five modes, dials 5, 6, and 7 do X, Y, and Z rotations. Figure 7-11 illustrates how a routing function for dial 5 might work.

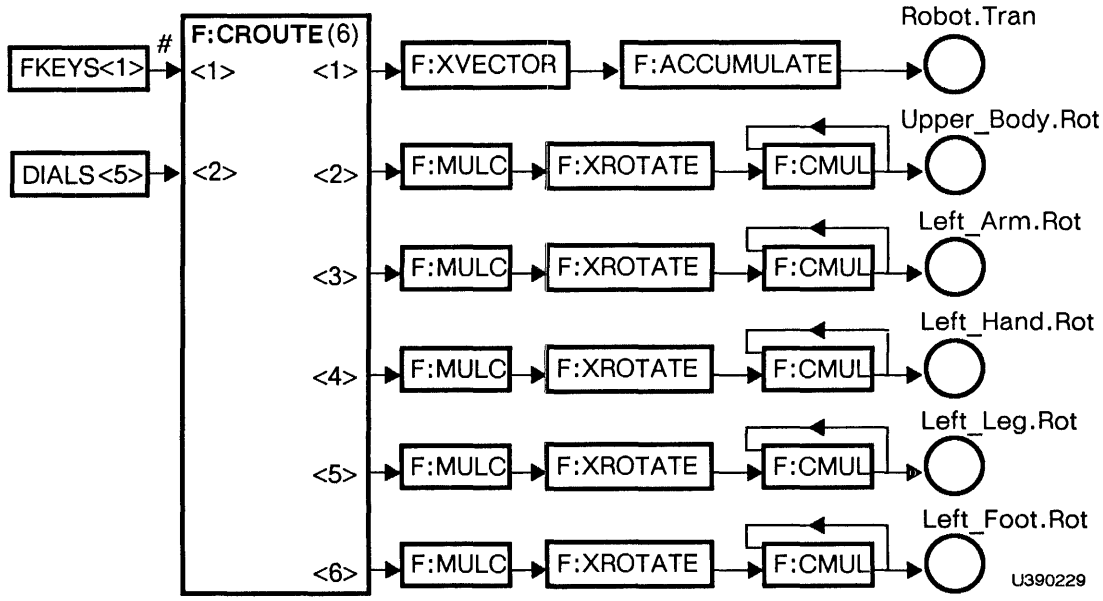


Figure 7-11. Sample Function Network for Dial 5

Of course, the diagram would be similar for dials 6 and 7, with Y and Z rotations substituted for X.

Note that the F:MULC and F:XROTATE functions in modes 2 through 6 above are exactly the same and could be shared as in Figure 7-12.

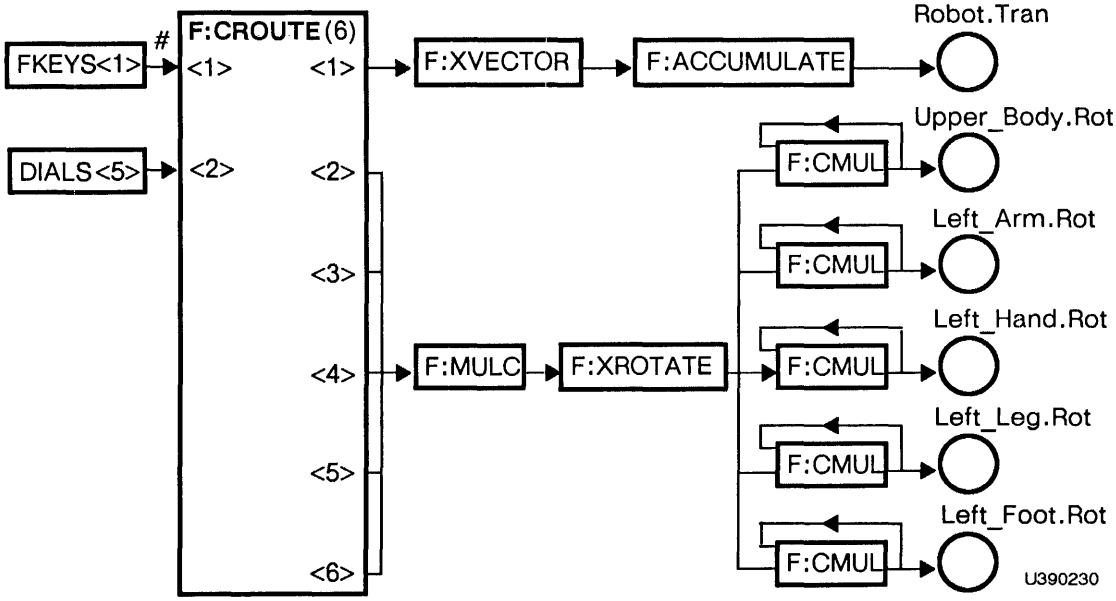


Figure 7-12. Network for Dial 5 With Shared Functions

This will save you having five sets of F:MULC and F:XROTATE function instances when one can do the job. But the output from F:XROTATE will have to be routed, so you need another routing function. The final network for dial 5 is shown in Figure 7-13.

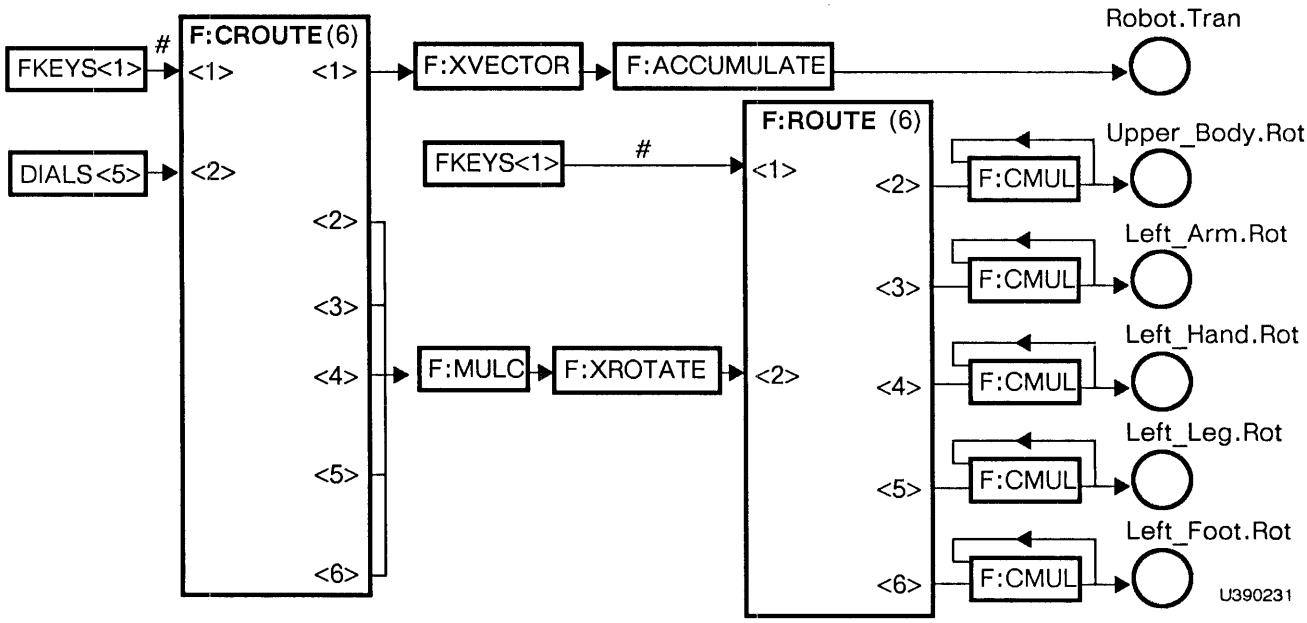


Figure 7-13. Final Function Network for Dial 5

Functionally, this completely specifies what dial 5 does.

1.1 Exercise

Complete the network for dials 6 and 7 using dial 5 as a pattern. Then diagram the network for the dial 8, using dial 4 as a pattern.

Next, code the networks for all eight dials. Include all the details, such as instancing functions, connecting functions, and sending initial values to functions when needed. Remember that the DIALS and FKEYS functions have already been instanced by the system and do not need to be named by you. To save these commands, do this in a text file.

Once the commands to implement the network for one dial are detailed, you can copy them over again for each of the other dials and delete or add only the details you want. For example, all the commands to implement this network for dial 1 (X rotations) are the same as for dial 2, except you need to change X to Y, and so on.

Figure 7-14 illustrates the final function network for dials 1–8.

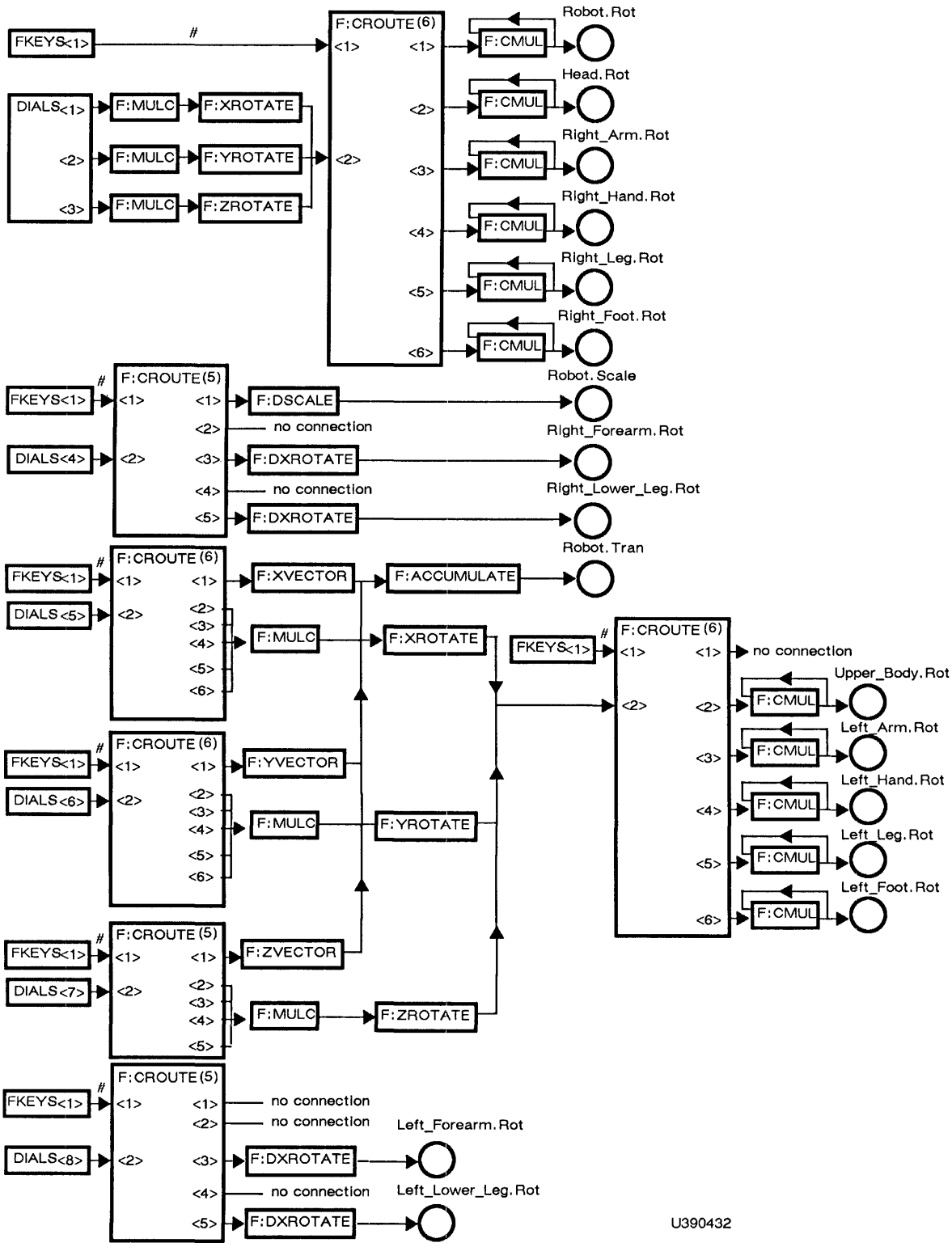


Figure 7-14. Final Function Network for Dials 1–8

The following commands are needed to code the function network. The code has been organized by dial so that functions are instanced, connected, and primed for each dial or group of dials before proceeding to the next dial. The names are suggestive of what each function instance does. Comment lines have been provided for clarification.

{CODE FOR DIALS 1-3}

```
X_Mul_D1 := F:MULC;                          {Instance F:MULC and}
Y_Mul_D2 := F:MULC;                          {rotation functions}
Z_Mul_D3 := F:MULC;

X_Rot_D1 := F:XROTATE;
Y_Rot_D2 := F:YROTATE;
Z_Rot_D3 := F:ZROTATE;

Switch1 := F:CROUTE(6);                      {Instance F:CROUTE(n)}
                                             {and F:CMUL functions}
Acc_Rot_Robot := F:CMUL;
Acc_Rot_Head := F:CMUL;
Acc_Rt_Arm := F:CMUL;
Acc_Rt_Hand := F:CMUL;
Acc_Rt_Leg := F:CMUL;
Acc_Rt_Foot := F:CMUL;

CONNECT FKEYS<1>:<1>Switch1;                 {Connect FKEYS and}
                                             {DIALS}
CONNECT DIALS<1> : <1>X_Mul_D1;
CONNECT DIALS<2> : <1>Y_Mul_D2;
CONNECT DIALS<3> : <1>Z_Mul_D3;

CONNECT X_Mul_D1<1> : <1>X_Rot_D1;           {Connect rotation}
CONNECT Y_Mul_D2<1> : <1>Y_Rot_D2;           {accumulator to}
CONNECT Z_Mul_D3<1> : <1>Z_Rot_D3;           {rotation function}

CONNECT X_Rot_D1<1> : <2>Switch1;            {Connect rotation}
CONNECT Y_Rot_D2<1> : <2>Switch1;            {function to switch}
CONNECT Z_Rot_D3<1> : <2>Switch1;

CONNECT Switch1<1> : <2>Acc_Rot_Robot;       {Connect switch to}
CONNECT Switch1<2> : <2>Acc_Rot_Head;        {X,Y,Z accumulator}
CONNECT Switch1<3> : <2>Acc_Rt_Arm;
CONNECT Switch1<4> : <2>Acc_Rt_Hand;
CONNECT Switch1<5> : <2>Acc_Rt_Leg;
CONNECT Switch1<6> : <2>ACC_Rt_Foot;
```

```
CONNECT Acc_Rot_Robot<1> : <1>Acc_Rot_Robot;   {Connect X,Y,Z}
CONNECT Acc_Rot_Robot<1> : <1>Robot.Rot;       {accumulator back to}
                                                {self and to display}
                                                {tree node}

CONNECT Acc_Rot_Head<1> : <1>Acc_Rot_Head;
CONNECT Acc_Rot_Head<1> : <1>Head.Rot;

CONNECT Acc_Rt_Arm<1> : <1>Acc_Rt_Arm;
CONNECT Acc_Rt_Arm<1> : <1>Right_Arm.Rot;

CONNECT Acc_Rt_Hand<1> : <1>Acc_Rt_Hand;
CONNECT Acc_Rt_Hand<1> : <1>Right_Hand.Rot;

CONNECT Acc_Rt_Leg<1> : <1>Acc_Rt_Leg;
CONNECT Acc_Rt_Leg<1> : <1>Right_Leg.Rot;

CONNECT Acc_Rt_Foot<1> : <1>Acc_Rt_Foot;
CONNECT Acc_Rt_Foot<1> : <1>Right_Foot.Rot;

SEND 200 TO <2>X_Mul_D1;                       {Prime F:MULC function}
SEND 200 TO <2>Y_Mul_D2;
SEND 200 TO <2>Z_Mul_D3;

SEND M3d (1,0,0 0,1,0 0,0,1) TO <1>Acc_Rot_Robot;  {Prime F:CMUL}
SEND M3d (1,0,0 0,1,0 0,0,1) TO <1>Acc_Rot_Head;   {function}
SEND M3d (1,0,0 0,1,0 0,0,1) TO <1>Acc_Rt_Arm;
SEND M3d (1,0,0 0,1,0 0,0,1) TO <1>Acc_Rt_Hand;
SEND M3d (1,0,0 0,1,0 0,0,1) TO <1>Acc_Rt_Leg;
SEND M3d (1,0,0 0,1,0 0,0,1) TO <1>Acc_Rt_Foot;
```

{CODE FOR DIAL 4}

```
Switch2:= F:CROUTE(6);                         {Instance switch}
                                                {function}

Scale_Robot:= F:DSCALE;                        {Instance scaling &}
Rot_Rt_Elbow := F:DXROTATE;                    {rotation functions}
Rot_Rt_Knee := F:DXROTATE;

CONNECT FKEYS<1> : <1>Switch2;                 {Connect FKEYS and}
CONNECT DIALS<4> : <2>Switch2;                 {DIALS}

CONNECT Switch2<1> : <1>Scale_Robot;           {Connect switch to}
CONNECT Switch2<3> : <1>Rot_Rt_Elbow;          {scaling and rotation}
CONNECT Switch2<5> : <1>Rot_Rt_Knee;           {functions}
```

```
CONNECT Scale_Robot<1> : <1> Robot.Scale;        {Connect scaling &}
CONNECT Rot_Rt_Elbow<1> : <1>Right_Forearm.Rot; {rotation functions}
CONNECT Rot_Rt_Knee<1> : <1>Right_Lower_Leg.Rot;{to display tree nodes}

SEND .075 TO <2>Scale_Robot;                    {Prime scale function}
SEND .02 TO <3>Scale_Robot;
SEND .1 TO <4>Scale_Robot;
SEND .025 TO <5>Scale_Robot;

SEND 0 TO <2>Rot_Rt_Elbow;                      {Prime rotation}
SEND 200 TO <3>Rot_Rt_Elbow;                    {functions}
SEND 0 TO <2>Rot_Rt_Knee;
SEND 200 TO <3> Rot_Rt_Knee;
```

{CODE FOR DIAL 5}

```
Switch3:= F:CROUTE(6);                          {Instance both switch}
Switch6:= F:CROUTE(6);                          {functions}

X_Vec_D5:= F:XVECTOR;                           {Instance X vector for}
X_Mul_D5:=F:MULC;                               {translation}
X_Rot_D5 := F:XROTATE;                          {Instance F:MULC and}
                                                {rotation function}

Acc_Trans:= F:ACCUM;                            {Instance translation}
                                                {accumulator function}

Acc_Rot_Trunk:= F:CMUL;                         {Instance F:CMUL}
Acc_Lt_Arm:=F:CMUL;                             {functions}
Acc_Lt_Hand:=F:CMUL;
Acc_Lt_Leg:= F:CMUL;
Acc_Lt_Foot:=F:CMUL;

CONNECT FKEYS<1> : <1>Switch3;                  {Connect FKEYS and}
CONNECT FKEYS<1> : <1>Switch6;                  {DIALS}
CONNECT DIALS<5> : <2>Switch3;

CONNECT Switch3<1> : <1>X_Vec_D5;               {Finish connections}
CONNECT X_Vec_D5<1> : <1>Acc_Trans;             {translation network}
CONNECT Acc_Trans<1> : <1>Robot.Tran;

CONNECT Switch3<2> : <1>X_Mul_D5                {Connect switch to}
CONNECT Switch3<3> : <1>X_Mul_D5;               {F:MULC functions}
```

```
CONNECT Switch3<4> : <1>X_Mul_D5;
CONNECT Switch3<5> : <1>X_Mul_D5;
CONNECT Switch3<6> : <1>X_Mul_D5;

CONNECT X_Mul_D5<1> : <1>X_Rot_D5;              {Connect F:MULC to}
                                                {rotation function}

CONNECT X_Rot_D5<1> : <2>Switch6;               {Connect rotation}
                                                {function to other}
                                                {switch}

CONNECT Switch6<2> : <2>Acc_Rot_Trunk;          {Connect switch to}
CONNECT Switch6<3> : <2>Acc_Lt_Arm;             {F:CMUL functions}
CONNECT Switch6<4> : <2>Acc_Lt_Hand;
CONNECT Switch6<5> : <2>Acc_Lt_Leg;
CONNECT Switch6<6> : <2>Acc_Lt_Foot;

CONNECT Acc_Rot_Trunk<1> : <1>Acc_Rot_Trunk;    {Connect F:CMUL}
CONNECT Acc_Rot_Trunk<1> : <1>Upper_Body.Rot;   {functions back to}
                                                {self and to display}
                                                {tree nodes}
CONNECT Acc_Lt_Arm<1> : <1>Acc_Lt_Arm;
CONNECT Acc_Lt_Arm<1> : <1>Left_Arm.Rot;

CONNECT Acc_Lt_Hand<1> : <1>Acc_Lt_Hand;
CONNECT Acc_Lt_Hand<1> : <1>Left_Hand.Rot;

CONNECT Acc_Lt_Leg<1> : <1>Acc_Lt_Leg;
CONNECT Acc_Lt_Leg<1> : <1>Left_Leg.Rot;

CONNECT Acc_Lt_Foot<1> : <1>Acc_Lt_Foot;
CONNECT Acc_Lt_Foot<1> : <1>Left_Foot.Rot;

SEND 200 TO <2>X_Mul_D5;                        {Prime F:MULC function}

SEND M3d (1,0,0 0,1,0 0,0,1) TO <1>Acc_Rot_Trunk;      {Prime F:CMUL}
SEND M3d (1,0,0 0,1,0 0,0,1) TO <1>Acc_Lt_Arm;         {function}
SEND M3d (1,0,0 0,1,0 0,0,1) TO <1>Acc_Lt_Hand;
SEND M3d (1,0,0 0,1,0 0,0,1) TO <1>Acc_Lt_Leg;
SEND M3d (1,0,0 0,1,0 0,0,1) TO <1>Acc_Lt_Foot;

SEND V3d (0,0,0) TO <2>Acc_Trans;               {Prime translation}
SEND 0 TO <3>Acc_Trans;                         {accumulator function}
SEND 1 TO <4>Acc_Trans;
SEND 10 TO <5>Acc_Trans;
SEND -10 TO <6>Acc_Trans;
```

{CODE FOR DIAL 6}

```
Switch4:= F:CROUTE(6);                    {Instance switch function}
                                          {Note: 2nd switch already}
                                          {instanced}

Y_Vec_D6:= F:YVEC;                        {Instance X vector for}
                                          {translation}

Y_Mul_D6:=F:MULC;                         {Instance F:MULC and}
                                          {rotation functions}
Y_Rot_D6:= F:YROT;

CONNECT FKEYS<1> : <1>Switch4;            {Connect FKEYS and}
                                          {DIALS}
CONNECT DIALS<6> : <2>Switch4;

CONNECT Switch4<1> : <1>Y_Vec_D6;         {Finish connections for}
                                          {translation network}
CONNECT Y_Vec_D6<1> : <1>Acc_Trans;

CONNECT Switch4<2> : <1>Y_Mul_D6;         {Connect switch to}
CONNECT Switch4<3> : <1>Y_Mul_D6;         {F:MULC functions}
CONNECT Switch4<4> : <1>Y_Mul_D6;
CONNECT Switch4<5> : <1>Y_Mul_D6;
CONNECT Switch4<6> : <1>Y_Mul_D6;

CONNECT Y_Mul_D6<1> : <1>Y_Rot_D6;        {Connect F:MULC to}
                                          {rotation function}

CONNECT Y_Rot_D6<1> : <2>Switch6;         {Connect rotation}
                                          {function to other switch}

SEND 200 TO <2>Y_Mul_D6;                    {Prime F:MULC function}
```

{CODE FOR DIAL 7}

```
Switch5:= F:CROUTE(6);                    {Instance switch function}
                                          {Note: 2nd switch already}
                                          {instanced}

Z_Vec_D7:= F:ZVEC;                        {Instance Z vector for}
                                          {translation}

Z_MUL_D7 := F:MULC;                       {Instance F:MULC and}
                                          {rotation functions}
Z_ROT_D7 := F:ZROT;
```

```
CONNECT FKEYS<1> : <1>Switch5;                {Connect FKEYS and DIALS}
CONNECT DIALS<7> : <2>Switch5;

CONNECT Switch5<1> : <1>Z_Vec_D7;             {Finish connections for}
                                              {trans network}
CONNECT Z_Vec_D7<1> : <1>Acc_Trans;

CONNECT Switch5<2> : <1>Z_Mul_D7;             {Connect switch to}
CONNECT Switch5<3> : <1>Z_Mul_D7;             {F:MULC functions}
CONNECT Switch5<4> : <1>Z_Mul_D7;
CONNECT Switch5<5> : <1>Z_Mul_D7;
CONNECT Switch5<6> : <1>Z_Mul_D7;

CONNECT Z_Mul_D7<1> : <1>Z_Rot_D7;            {Connect F:MULC to}
                                              {rotation function}

CONNECT Z_Rot_D7<1> : <2>Switch6;             {Connect rotation}
                                              {function to other switch}

SEND 200 TO <2>Z_Mul_D7;                      {Prime F:MULC function}
```

{CODE FOR DIAL 8}

```
Switch7 := F:CROUTE(6);                       {Instance switch}
                                              {function}

Rot_Lt_Elbow:= F:DXROTATE;                    {Instance rotation}
Rot_Lt_Knee:= F:DXROTATE;                     {functions}

CONNECT FKEYS<1> : <1>Switch7;                {Connect FKEYS and}
                                              {DIALS}
CONNECT DIALS<8> : <2>Switch7;

CONNECT Switch7<3> : <1>Rot_Lt_Elbow;         {Connect switch to}
CONNECT Switch7<5> : <1>Rot_Lt_Knee;          {rotation functions}

CONNECT Rot_Lt_Elbow<1> : <1>Left_Forearm.Rot;    {Connect rotation}
CONNECT Rot_Lt_Knee<1> : <1>Left_Lower_Leg.Rot;   {function to display}
                                                  {tree node}

SEND 0 TO <2>Rot_Lt_Elbow;                    {Prime rotation functions}
SEND 0 TO <2>Rot_Lt_Knee;
SEND 200 TO <3>Rot_Lt_Elbow;
SEND 200 TO <3>Rot_Lt_Knee;
```

The foregoing includes all the necessary code for a function network which will manipulate Robot. However, there is one other function you could add so that you can interactively reset Robot to its original position, before any transformations were applied, at any time. Connecting an F:XROTATE function to the F:CMUL (rotation accumulator) function will do this (see Figure 7-15).

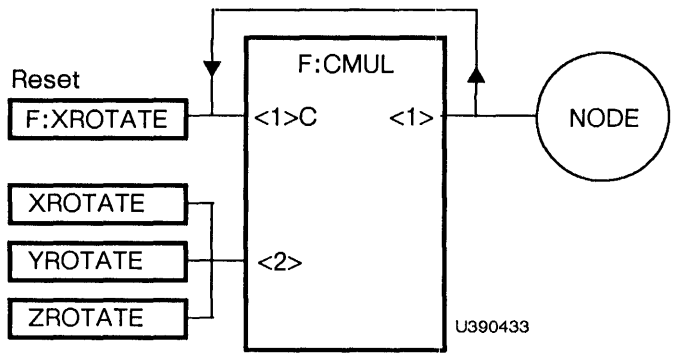


Figure 7-15. RESET Function Network

Add the following code:

```
Reset := F:XROTATE;

CONNECT Reset<1> : <1>Acc_Rot_Robot;
CONNECT Reset<1> : <1>Acc_Rot_Head;
CONNECT Reset<1> : <1>Acc_Rt_Arm;
CONNECT Reset<1> : <1>Acc_Rt_Hand;
CONNECT Reset<1> : <1>Acc_Rt_Leg;
CONNECT Reset<1> : <1>Acc_Rt_Foot;
CONNECT Reset<1> : <1>Acc_Rot_Trunk;
CONNECT Reset<1> : <1>Acc_Lt_Arm;
CONNECT Reset<1> : <1>Acc_Lt_Hand;
CONNECT Reset<1> : <1>Acc_Lt_Leg;
CONNECT Reset<1> : <1>Acc_Lt_Foot;
```

This will reset the network value but not the display nodes of the robot. The nodes will be reset once the dials are moved again. To reset the display nodes at the same time as you reset the network, also connect this reset function to all of the rotation nodes in the display tree:

```
CONNECT Reset<1> : <1>Robot.Rot;
CONNECT Reset<1> : <1>Head.Rot;
```

```
CONNECT Reset<1> : <1>Upper_Body.Rot;
CONNECT Reset<1> : <1>Right_Arm.Rot;
CONNECT Reset<1> : <1>Left_Arm.Rot;
CONNECT Reset<1> : <1>Right_Hand.Rot;
CONNECT Reset<1> : <1>Left_Hand.Rot;
CONNECT Reset<1> : <1>Left_Leg.Rot;
CONNECT Reset<1> : <1>Right_Leg.Rot;
CONNECT Reset<1> : <1>Left_Foot.Rot;
CONNECT Reset<1> : <1>Right_Foot.Rot;
CONNECT Reset<1> : <1>Right_Forearm.Rot;
CONNECT Reset<1> : <1>Left_Forearm.Rot;
CONNECT Reset<1> : <1>Left_Lower_Leg.Rot;
CONNECT Reset<1> : <1>Right_Lower_Leg.Rot;
```

To RESET Robot, then, simply enter:

```
SEND 0 TO <1>Reset;
```

2. Labeling the Control Dials

The function network that labels the dials also involves routing, except that the output of the network will be routed to function instances associated with the control-dial labels instead of into display-tree nodes.

Section *RM3 Initial Function Instances* explains that there are eight DLABEL initial function instances, one for each dial, named DLABEL1...DLABEL8 (see Figure 7-16).

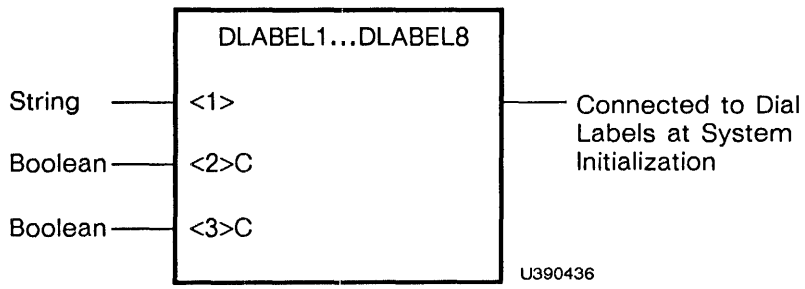


Figure 7-16. DLABEL Function

If you send the string of characters you want to appear in the label of a dial to input <1> of a DLABEL function, the string will appear in the LEDs above the dial. (The second and third DLABEL inputs, not used in this

example, allow you to blink the label or display it flush left. The default is nonblinking and centered in the available space above each dial.)

These character strings should be no more than 8 characters long. No connections need to be made out of DLABEL function instances; their "outputs" are the LEDs on the control-dials box.

Note

The Soft_labels network redefines the dynamic viewport on the PS 390 to allow the left edge of the display screen to be used as a display area for the function key labels (flabels) and dial labels (dlabels). This network can be useful for PS 390 systems with control dials and function keys that do not have LEDs. For details of the Soft_labels network refer to Section *TT2*.

To build a function network using these functions, first determine what type of output the network needs to produce; that is, what sort of values a DLABEL function will accept. In this case, it is a string of characters. These strings need to be sent to the DLABEL functions. Each time you change modes, you will want a new set of LED labels to appear that correspond to the new operations handled by the dials.

Begin with the first mode. Here, seven dials control overall movements for the robot. Though the eighth dial is not labeled, a blank string is needed for the eighth label to erase any existing labels above dial 8 which appear in other modes.

The following are sample labels that might appear in the dial LEDs during mode 1:

1—XRot_BOD
2—XRot_HD
3—XR_ARM
4—XR_HAND
5—XR_LEG
6—XR_FOOT

Once you identify labels to be sent to the LEDs, an efficient way to send them is to use an instance of F:INPUTS_CHOOSE(n) (Figure 7-17) for each DLABEL function.

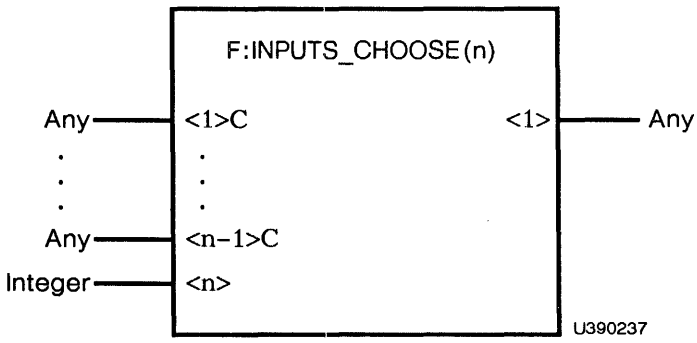


Figure 7-17. F:INPUTS_CHOOSE(n) Function

Make n one number larger than the number of modes you need. With six modes, use an instance of F:INPUTS_CHOOSE(7).

This function can house six different labels on its first six inputs, one for each mode. The seventh input is the "routing signal." An integer on input <7> indicates which of the labels to send out. Connect FKEYS to that input.

Now when you press a function key, FKEYS not only switches the dials into a different mode, it switches labels for the dials. Figure 7-18 illustrates the network for dial 1, with string outputs to DLABEL1 and integer inputs from FKEYS.

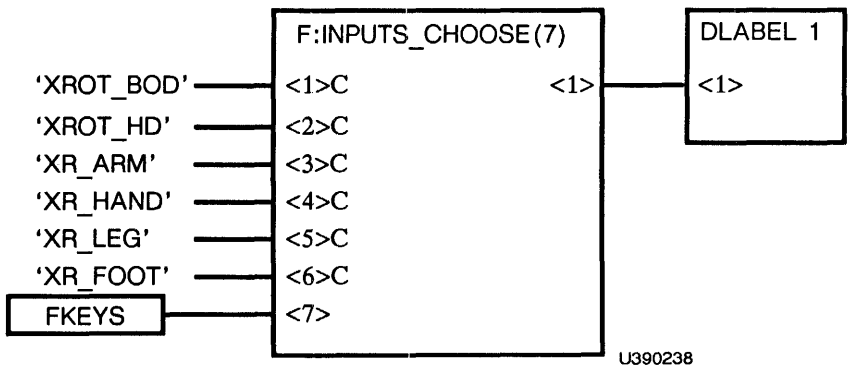


Figure 7-18. LED Labels for Dial 1

2.1 Exercise

The above diagram suggests how an instance of F:INPUTS_CHOOSE(7) can handle the labels for dial 1 in all modes. Design a network with additional instances of F:INPUTS_CHOOSE(n) that will handle DLABEL2 through DLABEL8. Design labels for the dials in each mode that use 8 or fewer characters to describe the functions of the dials.

Figure 7-19 illustrates the rest of the function network needed to label LEDs. Following that is the code needed to implement the complete network.

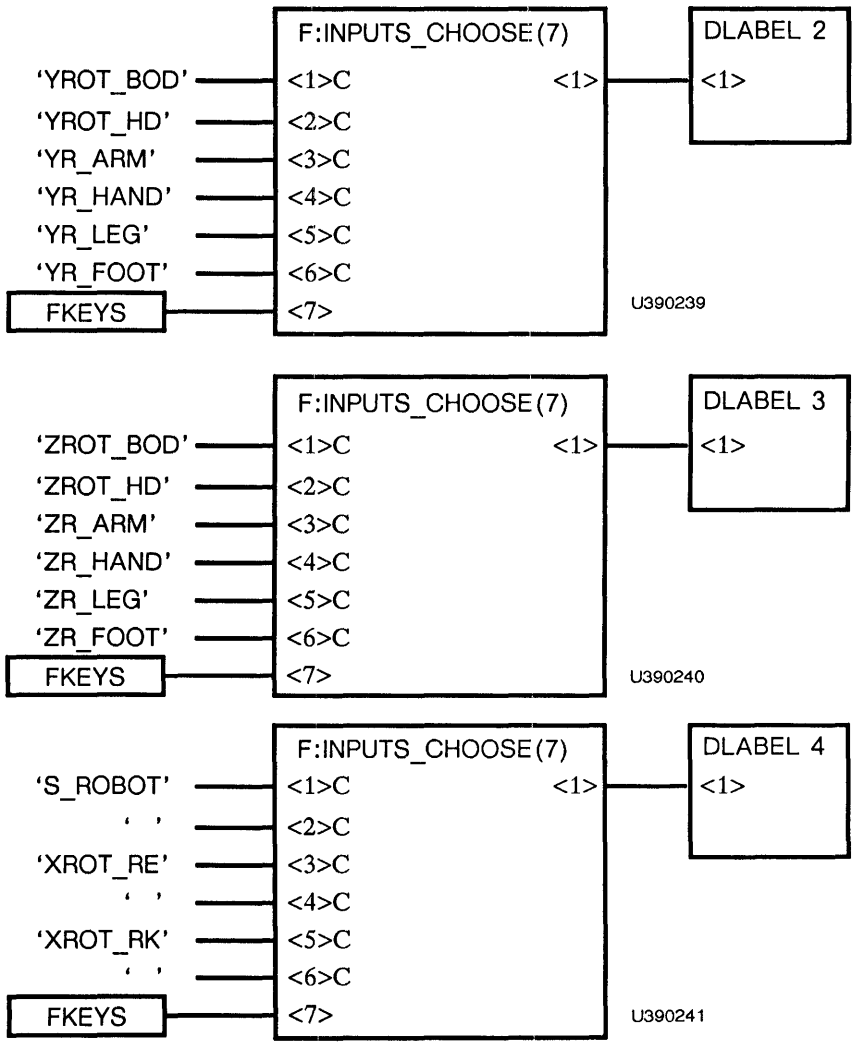


Figure 7-19. LED Labels for Dials 2–8 (continued on next page)

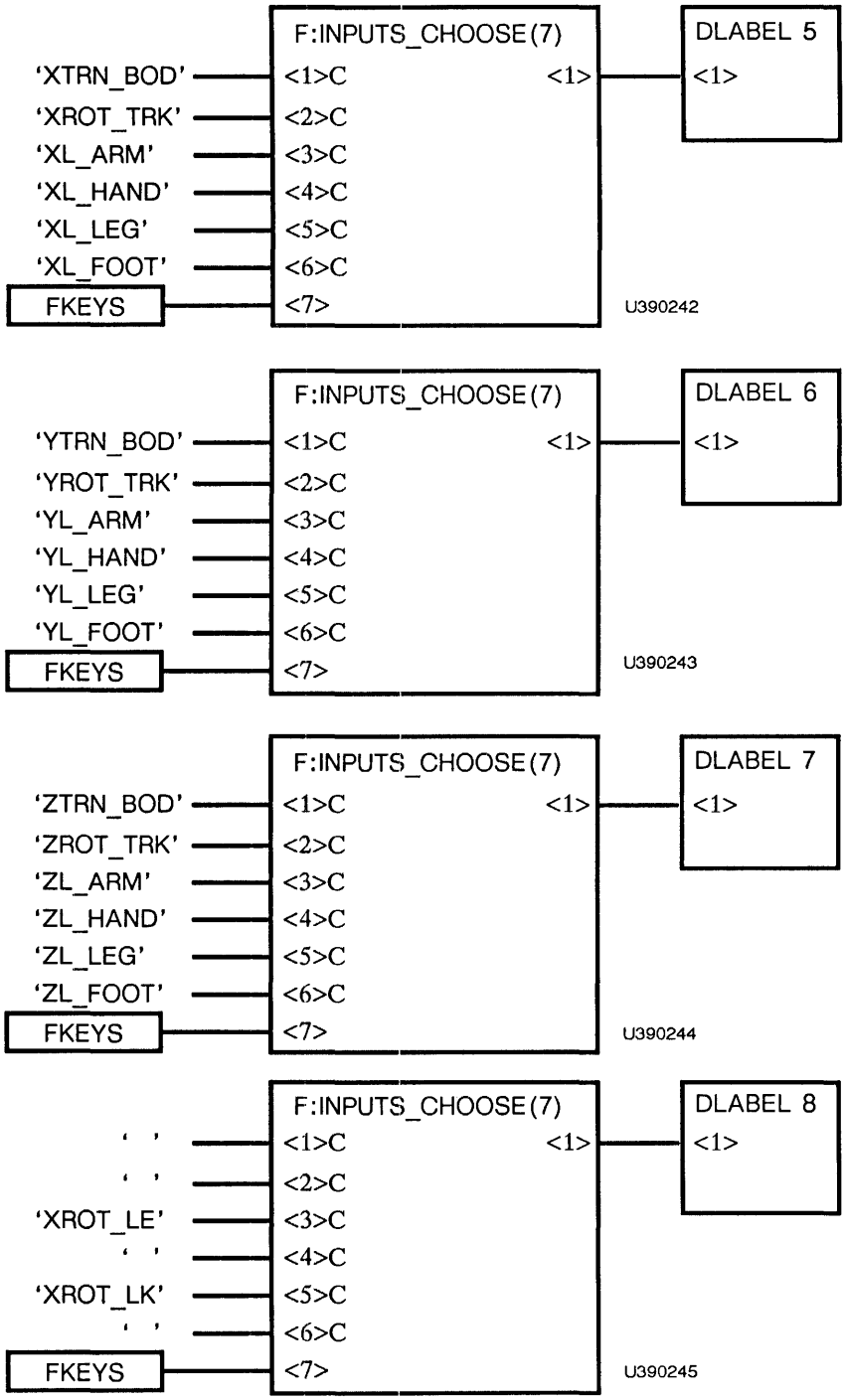


Figure 7-19. LED Labels for Dials 2–8 (continued)

The code follows for the eight labels in all six possible modes. Note that the DLABEL function does not have to be instanced by the user.

```
D1_LEDs := F:INPUTS_CHOOSE(7);
D2_LEDs := F:INPUTS_CHOOSE(7);
D3_LEDs := F:INPUTS_CHOOSE(7);
D4_LEDs := F:INPUTS_CHOOSE(7);          {Instance the switch function}
D5_LEDs := F:INPUTS_CHOOSE(7);
D6_LEDs := F:INPUTS_CHOOSE(7);
D7_LEDs := F:INPUTS_CHOOSE(7);
D8_LEDs := F:INPUTS_CHOOSE(7);

CONNECT FKEYS<1>:<7>D1_Leds;
CONNECT FKEYS<1>:<7>D2_Leds;
CONNECT FKEYS<1>:<7>D3_Leds;
CONNECT FKEYS<1>:<7>D4_Leds;            {Connect FKEYS to switch}
CONNECT FKEYS<1>:<7>D5_Leds;
CONNECT FKEYS<1>:<7>D6_Leds;
CONNECT FKEYS<1>:<7>D7_Leds;
CONNECT FKEYS<1>:<7>D8_Leds;

CONNECT D1_Leds<1>:<1>DLABEL1;
CONNECT D2_Leds<1>:<1>DLABEL2;
CONNECT D3_Leds<1>:<1>DLABEL3;
CONNECT D4_Leds<1>:<1>DLABEL4;          {Connect switch to LEDs}
CONNECT D5_Leds<1>:<1>DLABEL5;
CONNECT D6_Leds<1>:<1>DLABEL6;
CONNECT D7_Leds<1>:<1>DLABEL7;
CONNECT D8_Leds<1>:<1>DLABEL8;

SEND 'XRot_BOD' TO <1>D1_Leds;          {Send characters}
SEND 'XRot_HD' TO <2>D1_Leds;
SEND 'XR_ARM' TO <3>D1_Leds;
SEND 'XR_HAND' TO <4>D1_Leds;
SEND 'XR_LEG' TO <5>D1_Leds;
SEND 'XR_FOOT' TO <6>D1_Leds;

SEND 'YRot_BOD' TO <1>D2_Leds;
SEND 'YRot_HD' TO <2>D2_Leds;
SEND 'YR_ARM' TO <3>D2_Leds;
SEND 'YR_HAND' TO <4>D2_Leds;
SEND 'YR_LEG' TO <5>D2_Leds;
SEND 'YR_FOOT' TO <6>D2_Leds;
```

```
SEND 'ZRot_BOD' TO <1>D3_Leds;
SEND 'ZRot_HD' TO <2>D3_Leds;
SEND 'ZR_ARM' TO <3>D3_Leds;
SEND 'ZR_HAND' TO <4>D3_Leds;
SEND 'ZR_LEG' TO <5>D3_Leds;
SEND 'ZR_FOOT' TO <6>D3_Leds;

SEND 'S_ROBOT' TO <1>D4_Leds;
SEND '  ' TO <2>D4_Leds;
SEND 'XRot_RE' TO <3>D4_Leds;
SEND ' ' TO <4>D4_Leds;
SEND 'XRot_RK' TO <5>D4_Leds;
SEND ' ' TO <6>D4_Leds;

SEND 'XTrn_BOD' TO <1>D5_Leds;
SEND 'XRot_TRK' TO <2>D5_Leds;
SEND 'XL_ARM' TO <3>D5_Leds;
SEND 'XL_HAND' TO <4>D5_Leds;
SEND 'XL_LEG' TO <5>D5_Leds;
SEND 'XL_FOOT' TO <6>D5_Leds;

SEND 'YTrn_BOD' TO <1>D6_Leds;
SEND 'YRot_TRK' TO <2>D6_Leds;
SEND 'YL_ARM' TO <3>D6_Leds;
SEND 'YL_HAND' TO <4>D6_Leds;
SEND 'YL_LEG' TO <5>D6_Leds;
SEND 'YL_FOOT' TO <6>D6_Leds;

SEND 'ZTrn_BOD' TO <1>D7_Leds;
SEND 'ZRot_TRK' TO <2>D7_Leds;
SEND 'ZL_ARM' TO <3>D7_Leds;
SEND 'ZL_HAND' TO <4>D7_Leds;
SEND 'ZL_LEG' TO <5>D7_Leds;
SEND 'ZL_FOOT' TO <6>D7_Leds;

SEND '  ' TO <1>D8_Leds;
SEND '  ' TO <2>D8_Leds;
SEND 'XRot_LE' TO <3>D8_Leds;
SEND '  ' TO <4>D8_Leds;
SEND 'XRot_LK' TO <5>D8_Leds;
SEND '  ' TO <6>D8_Leds;
```

3. Setting Limits on the Motion of a Model

As the robot model now operates, its movements are unbounded: it can continue bending its knees until they pass through its thigh and return to initial position. This section demonstrates how to set a limit on that motion, so that a model will more realistically imitate the movements of the object it represents.

The knees of the robot provide a good illustration of how to do this. First, think of how a real leg bends (Figure 7-20).

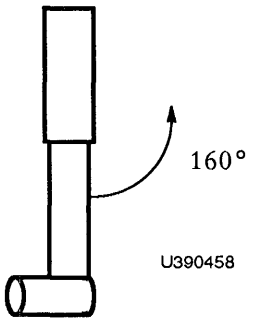


Figure 7-20. Realistic Limitations of Leg Movement

In a real leg, little or no forward bending is possible, but backward bending, through nearly 180 degrees, is. If you set a limit at 160 degrees, it would be fairly realistic. Figure 7-21 shows how 160 degrees of backward movement in a real leg corresponds to the rotation values in the robot's knee.

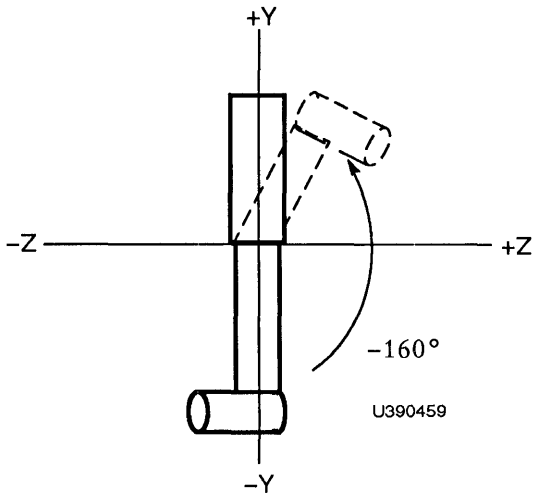


Figure 7-21. Limits for the Robot Leg

The rotations applied to it move it only around the X axis. Viewed from the positive X axis (the way it is in the diagram above), the "backward" rotation is counterclockwise. So the limits you want to impose are: no positive rotation in X at all, and only up to 160 in negative X.

You can modify the rotation network in the function network diagram for the robot. This requires the F:LIMIT function (see Figure 7-22). F:LIMIT will monitor values for degrees of rotation for the rotation functions and pass through only values between 0 and -160.

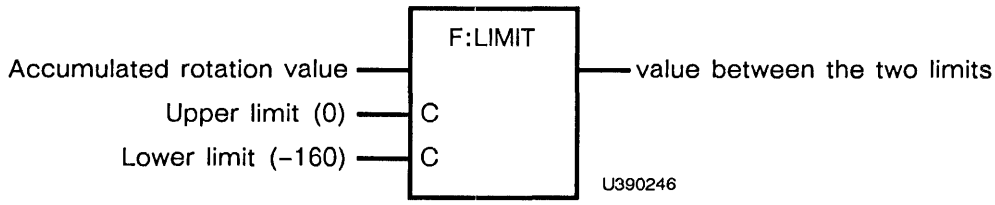


Figure 7-22. F:LIMIT Function

In this example, any value larger than 0 will cause F:LIMIT to send out a 0; anything less than -160 will output -160.

The networks for the knees of the robot use the F:DXROTATE function because they require rotations only in X. However, the accumulator is built into F:DXROTATE, so you cannot tap into it for the input to F:LIMIT (see Figure 7-23).

Figure 7-23. Rotation Node Using F:DXROTATE

To use F:LIMIT, begin with an XROTATE network such as the one used in Section *GT6 Function Networks I*, as shown in Figure 7-24.

Figure 7-24. Rotation Network Using F:MULC and F:XROTATE

Then modify it to accumulate rotation values with an add function as shown in Figure 7-25.

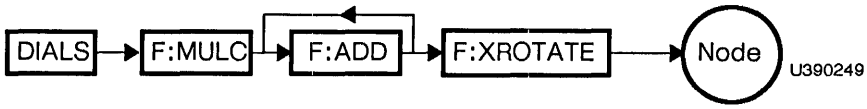


Figure 7-25. Rotation Network With F:ADD

Finally, add the F:LIMIT function. With this network, a stream of values from F:ADD (accumulated rotation values) can be output to F:LIMIT as shown in Figure 7-26.

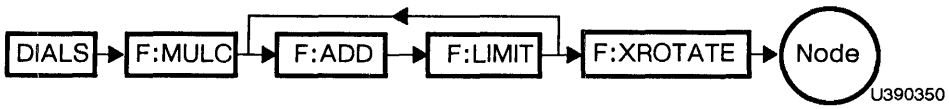


Figure 7-26. Function Network To Limit Movement

Though this network is bulkier (three functions now replace one), it allows you to limit the motion in the knee joint.

3.1 Exercise

Figure 7-27 illustrates two modified function networks that will limit rotations in both of the robot knees. Function instance names have been provided. Edit the existing code for Robot to incorporate these changes. Do not repeat any existing commands which create function instances; otherwise, all connections established by the original command are broken.

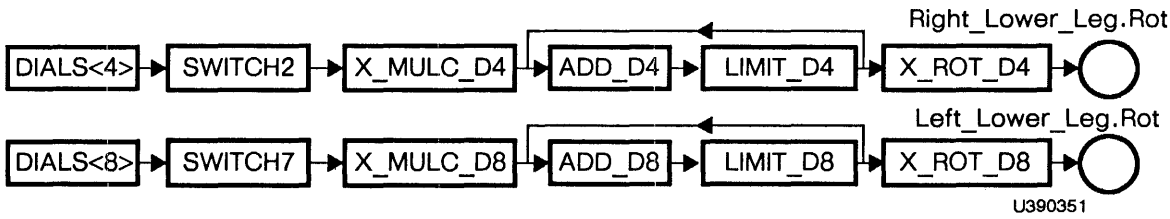


Figure 7-27. Function Networks To Limit the Robot Knee Movement

```
X_MulC_D4 := F:MULC;
X_MulC_D8 := F:MULC;
Add_D4 := F:ADD;
Add_D8 := F:ADD;                        {Instancing new functions}
Limit_D4 := F:LIMIT;
Limit_D8 := F:LIMIT;
X_Rot_D4 := F:XROTATE;
X_Rot_D8 := F:XROTATE;

DISCONNECT Switch2<5>:<1>Rot_Rt_Knee;
DISCONNECT Switch7<5>:<1>Rot_Lt_Knee;

CONNECT Switch2<5>:<1>X_Mulc_D4;
CONNECT Switch7<5>:<1>X_Mulc_D8;

CONNECT X_MulC_D4<1>:<1>Add_D4;
CONNECT X_MulC_D8<1>:<1>Add_D8;
CONNECT Add_D4<1>:<1>Limit_D4;          {Creating new network}
CONNECT Add_D8<1>:<1>Limit_D8;

CONNECT Limit_D4<1>:<2>Add_D4;
CONNECT Limit_D4<1>:<1>X_Rot_D4;
CONNECT Limit_D8<1>:<2>Add_D8;
CONNECT Limit_D8<1>:<1>X_Rot_D8;

CONNECT X_Rot_D4<1>:<1>Right_Lower_Leg.Rot;
CONNECT X_Rot_D8<1>:<1>Left_Lower_Leg.Rot;

SEND 200 TO <2>X_MulC_D4;
SEND 200 TO <2>X_MulC_D8;
SEND 0 TO <2>Limit_D4;                  {Priming functions}
SEND -160 TO <3>Limit_D4;
SEND 0 TO <2>Limit_D8;
SEND -160 TO <3>Limit_D8;

SEND 0 to <2>Add_D4;
SEND 0 to <2>Add_D8;
```

The next logical step would be to limit rotations in all of the joints of the robot. However, this is no trivial matter. The other rotate nodes accept three-dimensional rotations which are all accumulated using matrices. Matrices cannot go through the F:LIMIT function. This problem is not insurmountable, but solutions can be complex. (For example, you could have three rotation nodes, each limiting movement using the F:LIMIT function.)

4. Using Variables to Store Values

One difference between programming with PS 390 function networks and programming a conventional language such as FORTRAN is that you almost never need to use variables. In a conventional program, you may represent two values to be added together as variables X and Y. In a function network, you would add these using the F:ADD function. The "variables" are the two inputs of the function.

Sometimes, though, you may want to use a variable value in a function network in a more conventional way. Often this can be done using the F:CONSTANT function (see Figure 7-28).

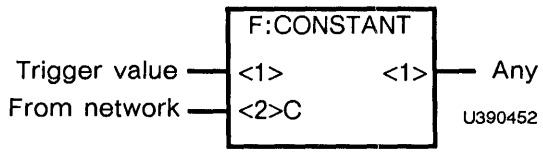


Figure 7-28. F:CONSTANT Function

In this setup, the value you want to save is sent to the constant input of the function. If you send a stream of values, each one will over-write the preceding one, so the value on the constant input will always be current (the latest one sent). When you need the variable somewhere else in the network, send any value to trigger F:CONSTANT input <1> and the value will fire out to wherever you connect the output.

It may be the case, however, that several areas in a network need to access the variable in an F:CONSTANT function. You might think that can be done by making numerous output connections to all the destinations that may use the variable (Figure 7-29).

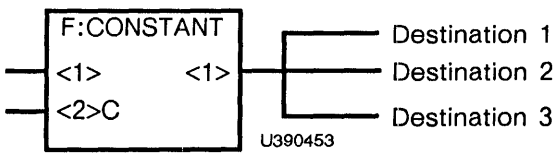


Figure 7-29. F:CONSTANT Connected to Several Destinations

However, this presents a problem of routing and selection. To send the variable value to destination 1, you must trigger F:CONSTANT, which sends out values to all destinations. One solution to this problem could be to use more instances of F:CONSTANT (Figure 7-30).

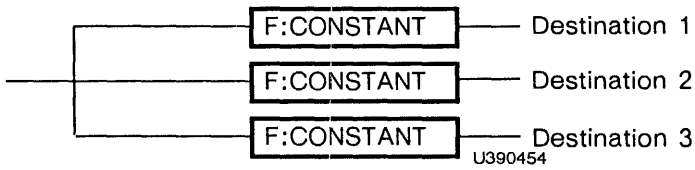


Figure 7-30. Multiple Instances of F:CONSTANT Function

A more efficient solution is to use the VARIABLE command in conjunction with the command STORE and the function F:FETCH. This section discusses how to do that.

The VARIABLE command creates a "holding tank" for a single value, much the same way the constant input of F:CONSTANT does. Look at the following command:

```
VARIABLE This, That, The_Other;
```

This command creates three variables named This, That, and The_Other. Variables have only one input and no outputs. Function networks can be connected to them, or they can receive values by means of the SEND command:

```
CONNECT Spinner<1>:<1>This;
SEND 4.5 TO <1>This;
```

If a network is connected to a variable, it can receive a stream of values and will retain the last one sent.

An alternate way to send a value to a variable is to use the STORE command. The following commands both do the same thing:

```
STORE 4.5 IN This;
SEND 4.5 TO <1>This;
```

There are two ways to retrieve a value stored in a variable: using the SEND VALUE command or using a function network with F:FETCH. For

example, if you want to send a value from the variable This to the third input of a function named Rot_X, you could enter:

```
SEND VALUE(This) TO <3>Rot_X;
```

Even more convenient is using F:FETCH (Figure 7-31).

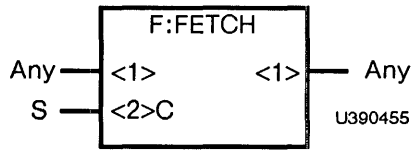


Figure 7-31. F:FETCH Function

F:FETCH accepts the name of the variable on its constant input (input <2>). When any value arrives on input <1>, the function is triggered. It fetches the latest value from that variable and sends it out.

For example, in Figure 7-32 below, values for the variable This are routed to the host using the F:FETCH function. (User-assigned names are written above the function box.)

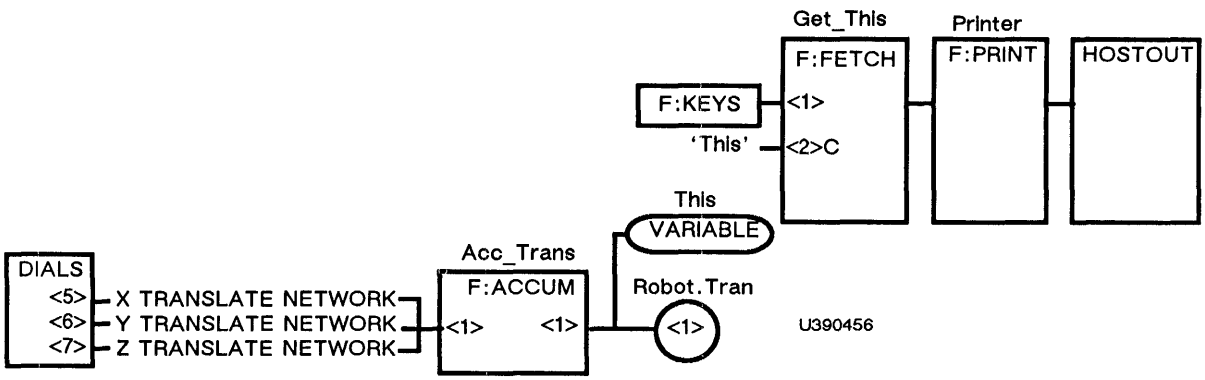


Figure 7-32. Routing Values From Variable "This" to the Host

The variable This holds a 2D vector that indicates the accumulated translation values sent out from Acc_Trans in mode 1. (The translation network has already been defined and coded in the robot code.)

HOSTOUT has one input, which accepts a string and routes it to the host. HOSTOUT is preceded by a function that turns PS 390 values into strings,

F:PRINT. (If the GSRs are being used, HOST_MESSAGE should be used in lieu of HOSTOUT.)

The additional code needed for this network is:

```
VARIABLE This;

Get_This := F:FETCH;
Printer := F:PRINT;

CONNECT Acc_Trans<1>:<1>This;
CONNECT FKEYS<1>:<1>Get_This;
CONNECT Get_This<1>:<1>Printer;
CONNECT Printer<1>:<1>HOSTOUT;

SEND 'This' to <2>Get_This;
```

4.1 Exercise

Using Figure 7-32 as a pattern, create a function network that uses a variable named Matrix which holds the most current rotation matrix from F:CMUL for the left arm of the robot (Acc_Lt_Arm) in mode 3. Retrieve this value and send it to HOSTOUT using an instance of F:FETCH named Retrieve. Specify any additional code needed (the rotation network for Robot has already been done).

Figure 7-33 illustrates the function network which retrieves values from the variable Matrix.

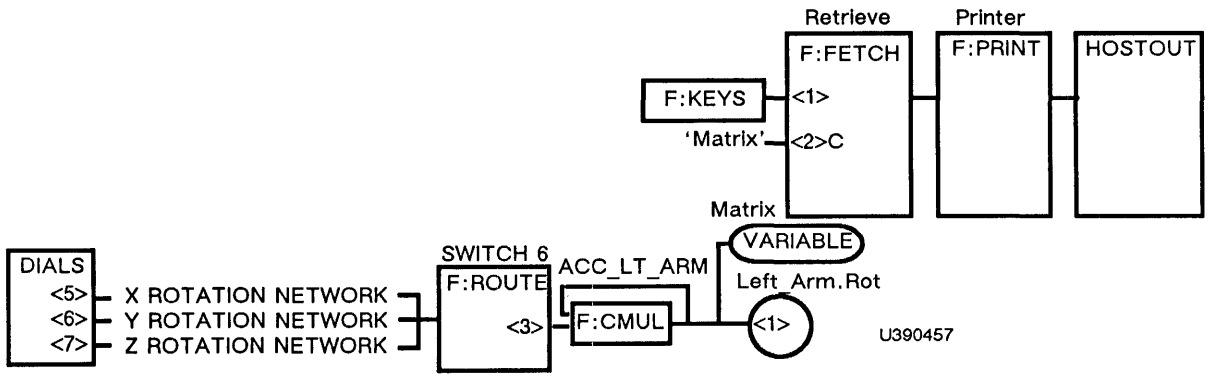


Figure 7-33. Routing Values From Variable "Matrix" to the Host

The additional code needed for this network is:

```
VARIABLE Matrix;

Retrieve := F:FETCH;
Printer := F:PRINT;

CONNECT Acc_Lt_Arm<1>:<1>Matrix;
CONNECT FKEYS<1>:<1>Retrieve;
CONNECT Retrieve<1>:<1>Printer;
CONNECT Printer<1>:<1>HOSTOUT;

SEND 'Matrix' to <2>Retrieve;
```

5. Summary

This section illustrates how to expand a function network so that a single dial can manipulate several movements of a model. This entails determining the number of dials needed for interactions in the model and assigning each dial several destinations (in this section, LED labels or interactive nodes in the display tree of the model).

Function keys and instances of F:CROUTE(n) are used to switch values from the dials to their various destinations. This prevents dial values from being routed to all function network destinations at once.

Specifically, the initial function instance FKEYS is connected to input <1> of the switching function F:CROUTE(n). Incoming values from the dials are connected to input <2>. The outputs of F:CROUTE(n) are connected to the various destinations.

LEDs above the dials can be labeled in each mode of operation. Specifically, labels in every mode for that dial are sent to the constant inputs of F:INPUTS_CHOOSE. FKEYS is connected to the last input of this function. The output of F:INPUTS_CHOOSE is connected to the DLABEL function associated with that dial. When the function key is pressed, to switch modes, the correct label for the dial in that mode is routed to DLABEL, which outputs to the LEDs.

Functions can serve more than one purpose. For example, in addition to controlling X rotations, the F:XROTATE function can be used to reset the model back to its original position before any transformations were applied.

The F:LIMIT function can be inserted into a network to set limits on the movement of a model. F:LIMIT requires that you establish upper and lower limits for transformation values. It then passes through only those values which lie within this range.

Finally, the VARIABLE command and F:FETCH functions allow you to store and retrieve a variable value in a function network.