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INTERACTIVE GENERATION OF OBJECT MODELS WITH A MANIPULATOR

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ABSTRACT

'Manipulator programs in a high level language consist of manipulation procedures and object model declarations. As higher level languages are developed, the procedures will shrink while the declarations will grow. This trend makes it desirable to develop means for automating the generation of these declarations. A system is proposed which would permit users to specify certain object models interactively, using the manipulator itself as a measuring tool in three dimensions. A preliminary version of the system has been tested.

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INTRODUCTION

Manipulator Languages and Object Models

The important problem areas for current research on manipulators are function, ease of programming, and speed and reliability of execution. The domain of function is concerned with whether or not certain tasks are technically feasible, without regard to economic issues. For the real world environment of industrial assembly, function was demonstated by assembling a water pump with the Stanford arm in 1973 and by similar experiments at other laboratories.

Since 1973, the main thrust of the Stanford effort has been directed at ease of programming, since this is a problem well suited to the skills and interests of the people here. The approach taken was to design a new high level language called AL in which assembly programs would be much simpler to code than in any previously existing manipulator language. The complete AL system is currently beginning to operate.

Most other laboratories and companies have chosen to pursue a teaching by doing approach to manipulator programming instead of developing high level languages. There is good reason to believe that in the long run the greater generality offered by a system incorporating formal languages will outweigh the short run ease of programming by guiding.

The ultimate goal of research on high level manipulator languages is a language in which very few statements are needed to describe a highly complex assembly. For an object with N parts, perhaps a realistic goal would be to have a language in which the assembly can be described in about N statements.

In view of this goal, the level of manipulator languages is best measured by the' number of source statements required, not by the richness of their computer science content. Based on this criterion, AL is the highest level manipulator language ever developed, in spite of the fact that it lacks arrays, lists, string variables, formatted I/O, and so forth.

It is instructive to extrapolate from AL to an absurd ultimate high level language. In this ultimate language, a program for assembling 1000 water pumps might have this form:

```
DECLARE WATER-PUMP etc;
MAKE_PLAN(WATER_PUMP,ASSEMBLY_PLAN);
EXECUTE_PLAN(ASSEMBLY_PLAN,1000);
```

Such a program presumes that all the relevant artificial intelligence problems have been solved and embodied in MAKE-PLAN and all the manipulation problems have been solved and embodied in EXECUTE-PLAN. The important observation to make with respect to this absurd example is that as far as the user of such a language is concerned, all the effort of writing the program would be in expanding the "etc" in the first line.

The expansion of the "etc" constitutes the world model used by MAKE-PLAN. The world model would include the specification of mechanical parts, component hierarchies, affixment relationships, geometric shapes, Cartesian transformations between features, material

properties, and so forth. It is clear that the declaration of such a detailed world model would be a lengthy process, possibly requiring hundreds of lines of text.

The development of high level manipulation languages, therefore, will shift the problem from writing procedures to writing declarations. Already in AL a sufficiently high level has been reached that this new problem is becoming significant.

A rough measure of the importance of declarations as compared to procedures may be obtained by looking at sample AL programs[1] and taking the ratio of lines of code in the two categories. Neglecting comments, three low level AL examples have declaration to procedure ratios of 1:2, 1:6, and 1:3. A "very high level" AL example, however, has a declaration to procedure ratio of 6:1. Actually, the importance of declarations is even greater than these ratios would indicate, since the declarative statements tend to be far more difficult to code than the procedural statements. Even at the lowest level of AL, appreciable time can be spent in defining simple models for the initial locations of objects and their affixment structure.

Since the motivation behind high level manipulator languages is ease of programming, and since these languages are shifting the problem from procedures to declarations, it is natural to consider means for simplifying the generation of these declarations. This report proposes in some detail a prototype system which would semi-automate the process of specifying a large class of AL declarations. It is believed that a system of this type would be general enough to be applicable to other high level manipulation languages also.

Attributes of AL World Models

The AL language has evolved considerably during implementation over the past year, and the AL Manual[1] has become somewhat obsolete. Nevertheless, in order to keep the discussion on a concrete footing, it will be assumed that AL declarations take exactly the form shown in the AL Manual, and it will also be assumed that the reader is familiar with this manual.

A section of the "very high level" AL example is reproduced below:

```
FRAME beam, bracket, bolt;
FRAME bracket-bore, beam-bore;
FRAME bolt-grasp, bracket-handle;

ASSERT FORM (TYPE, beam, object);
ASSERT FORM (GEOMED, beam, "beam.B3D");
ASSERT FORM (SUBPART, beam, beam-bore);
AFFIX beam-bore TO beam RIGIDLY
      AT TRANS(ROT(Y,90),VECTOR(0,1.5,6));

ASSERT FORM (TYPE, bracket, object);
ASSERT FORM (CEOMED, bracket, "BRACK.B3D");
ASSERT FORM (SUBPART, bracket, bracket-bore);
```

```
ASSERT FORM (SUBPART, bracket, bracket-handle);
AFFIX bracket-bore TO bracket RIGIDLY
      AT TRANS(ROT(X, 180),VECTOR(5.1,2,0));
AFFIX bracket-handle TO bracket RIGIDLY
      AT TRANS(ROT(X, 180),NILVEC);

ASSERT FORM (TYPE, bolt, SHAFT); --
ASSERT FORM (DIAMETER, bolt, 0.5*CM);
ASSERT FORM (TOP-END, bolt, head_type1);
ASSERT FORM (BOTTOM-END, bolt, tip_type1);
ASSERT FORM (TYPE, tip-type], FLAT-END);

. . .

bracket ← FRAME(NILROT,VECTOR(20,40,0));
beam ← FRAME(NILROT,VECTOR( 10,60,0));
bolt ← FRAME(ROT(Y,180),VECTOR(30,50,5));
```

All of the above statements are considered to be declarations of the world model since they occur prior to the first motion of the manipulator.

The method of automating declarations to be described here is inappropriate for specifying information about the geometric shape of objects. Therefore, all statements which relate to geometric shape either in the form of GEOMED files[2] or in the form of generic parts such as SHAFT will be omitted from further consideration.

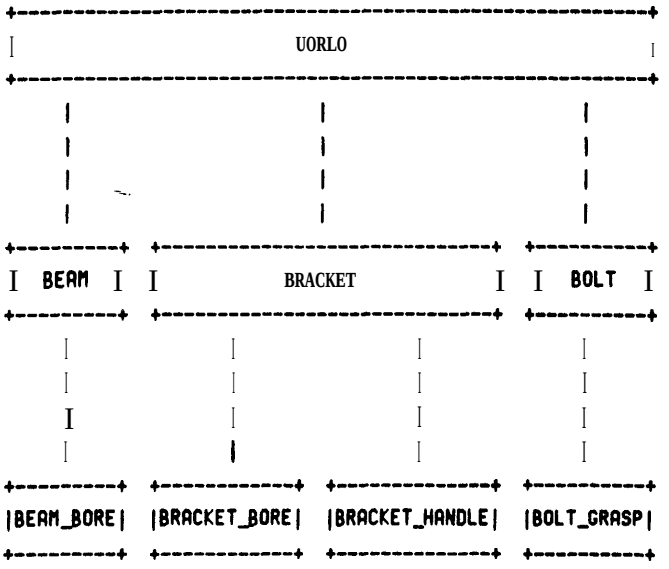
Fortunately, it is possible to write fairly high level AL programs which do not need shape information, although in an ultimate high level language, of course, geometric shape declarations will 'have to be provided. The eventual automation of shape declaration will some day come about through advanced interactive graphics and vision systems. It is important to realize, however, that while this major problem area is being bypassed in this discussion, the problems which remain are still substantial, and their practical solution would make it significantly easier to code AL programs.

The remaining statements may be rearranged according to their function in the following manner:

```
FRAME beam, bracket, bolt;
FRAME bracket-bore, beam-bore;
FRAME bolt-grasp, bracket-handle;

ASSERT FORM (TYPE, beam, object);
ASSERT FORM (TYPE, bracket, object);

ASSERT FORM (SUBPART, beam, beam-bore);
ASSERT FORM (SUBPART, bracket, bracket-bore);
ASSERT FORM (SUBPART, bracket, bracket-handle);

AFFIX beam-bore TO beam RIGIDLY
      AT TRANS(ROT(Y ,90),VECTOR(0,1.5,6));
AFFIX bracket-bore TO bracket RIGIDLY
```

```
        AT TRANS(ROT(X, 180),VECTOR(5.1,2,0));
    AFFIX bracket-handle TO bracket RIGIDLY
        AT TRANS(ROT(X,180),NILVEC);

    bracket ← FRAME(NILROT,VECTOR(20,40,0));
    beam ← FRAME(NILROT,VECTOR( 10,60,0));
    bolt ← FRAME(ROT(Y, 180),VECTOR(30,50,5));
```

The net effect of these statements is to describe a tree in which the nodes represent physical objects and the arcs are relationships between them. The root of the tree is an implicit object which may be called "world", and all objects which are not subparts of anything else are subparts of world. The subpart hierarchy is shown in graphical form below:



The arcs have the implication of subpart or, equivalently, of subfeature. Each arc also must contain information concerning the relative transformation between the Cartesian frame of the parent and that of the son. For those arcs which emanate from world, these transformations are AL frames, while for all other arcs they are AL transes. Finally, each arc must specify whether the relationship is rigid, non-rigid, or independent.

The principal difficulty for the programmer in specifying this tree lies in the symbolic definition of the frames and transes:

```
FRAME(NILROT,VECTOR(20,40,0))
FRAME(NILROT,VECTOR( 10,60,0))
FRAME(ROT(Y, 180),VECTOR(30,50,5))

TRANS(ROT(Y,90),VECTOR(0,1.5,6))
TRANS(ROT(X,180),VECTOR(5.1,2,0))
TRANS(ROT(X, 180),NILVEC)
```

Some indication of the magnitude of the difficulty of accurately coding frames and transes is

given by the fact that the figure in the AL Manual which purports to show the initial world defined by these declarations is actually inconsistent with them. What the figure shows corresponds instead to the following declarations:

```
FRAME(ROT(Z,60*DEG),VECTOR(40,30,0))
FRAME(ROT(Z,90*DEG),VECTOR(30,24.2,0))
FRAME(ROT(Z,90*DEG)*ROT(X,180*DEG),VECTOR(30,60,5))

TRANS(ROT(X,-90*DEG),VECTOR(5.1,0,15))
TRANS(ROT(X,180*DEG),VECTOR(5.1,5,0))
TRANS(ROT(X,180*DEG),VECTOR(0,5,5))
```

Of these declarations, the third one is the only one which contains composite rotations. This example, however, involves objects with nice rectangular shapes, so that relative transformations between features are comparitively simple. In the real world of industrial parts, complex composite transformations will occur frequently, increasing the likelihood of programmer error, and vastly increasing the labor of accurate coding. The solution of this specific problem is the motivation behind the method of automating world model declarations proposed here.

Alternative Approaches To Generating The Models

There are at least three fundamentally different approaches to the problem: graphics, vision, and pointing.

Graphics is concerned with building the required data structures with an interactive graphics system. There have been several publications describing graphics systems which have the potential to be applied to this problem.[2,3,4,5] The main difficulty with this approach is that it is impossible to use a graphics system to specify frames and transes without first specifying the shapes of all the objects. Even though the systems cited allow complex object shapes to be represented by unions and intersections of simpler shapes, the specification of an object's shape is bound to be more difficult than the specification of a few of its features. One possible way of simplifying the shape encoding process would be to use some sort of 3-dimensional automatic drafting system.

Vision is concerned with showing the workstation and the component parts to a camera, and having vision programs automatically or interactively generate the data structure. In the environment of complex industrial parts, a completely automatic vision system capable of constructing AL world models is far beyond the current state of the art. However, one can imagine an interactive vision system in which the user identifies features by simply pointing to them, either in the original scene or in a projected image of the scene. Suitable pointers for the original scene include arrays of light emitting diodes[6], a lighted wand[7,8] or other easily identified stick, a laser, or even a specially marked glove. For pointing in a reprojected image, a movable cursor or some commercial digitizer could be used. In either case, accurately locating a feature on an object of unmodelled shape in three dimensions rquires stereo vision, so that building such a- system would not be a trivial undertaking.

Pointing, which is the method proposed here, involves an interactive system in which the data structure is built by using the manipulator and a special tool to point to the objects and features. The manipulator may be moved about manually, or under joystick or pushbutton control. It is possible to infer the position of the feature from the known joint angles of the manipulator. The accuracy of this method is inherently comparable to the accuracy with which the manipulator can perform the assembly itself.

Pointing with the manipulator would be much easier than vision to implement, although it would be somewhat 'less convenient to use. Aside from the fact that vision and pointing use different techniques to determine positions, the two approaches are fundamentally similar, and any system built for one approach could be adapted for the other.

POINTING WITH A MANIPULATOR

Implicit Specification of Frames

The typical manipulator has 6 degrees of freedom, which allow it to be positioned at an arbitrary position and in an arbitrary orientation. Frames also have 6 degrees of freedom, corresponding to 3 directions of translation and 3 angles of rotation. It follows that if a single pointing of the manipulator is to imply a unique frame explicitly, there are no spare degrees of freedom. The absence of spare degrees of freedom makes it quite difficult to position the manipulator accurately.

This problem frequently arises in the context of manipulators which are programmed by guiding them through the motions. It is not hard to guide a manipulator manually to a good grasping position to pick a part out of a pallet. However, it can be quite difficult to guide it manually to a good orientation such that when the manipulator attempts to remove the part from the pallet there is no binding. The need for orientation accuracy becomes much more crucial when it is being used to define a world model, since any angular error may be multiplied by some long moment arm in the AL program, whereas in a guiding system the process of grasping is always spatially localized at the point where the angular error was made.

In order to avoid this difficulty, it is convenient to use multiple pointings to define each frame implicitly. The first, pointing may define the origin of the frame, the second may define one axis of the frame, and the third may define one plane of the frame. In this manner, each pointing determines position only, and there is no need to have orientation accuracy.

The Bendy Pointer

The manipulator extremity must be provided with some sort of sharp pointer so that it can be used as a 'precise measuring tool. The pointer must have a shape suitable for reaching into awkward places such as the inside of a screw hole, the interior of a box, and so forth. In order to make the shape of the pointer compatible with all kinds of unforseen obstructions, it is desirable to design a pointer which may be bent by the user into an arbitrary shape. Such a special device will be referred to as a bendy pointer.

Whenever the user wishes, he may deform the bendy pointer into any new configuration which appears to be convenient for the next pointing operation. Having deformed the pointer, the user must calibrate its new end position by using the pointer to point to a standard fiducial mark at a known location in the laboratory. From the frame of the fiducial and the frame of the gripper, the system can infer the translation which takes the gripper frame into the bendy pointer.

A possible refinement to the bendy pointer would be to provide it with some sort of terminal

sensor. For example, if the object being measured were metallic, one could construct an electric circuit and measure current through the pointer. Another possibility would be to use some sort of infra red or fluidic device. Adding a sensor would improve the sensitivity of locating the pointer accurately, but it would also create problems of compatibility with being able to bend the device. For this reason, it will be assumed that there is no terminal sensor, and the user is required to eyeball the positioning.

One way of fabricating a bendy pointer would be to have a 6 inch length of wire coat hanger protruding from a metal block which is suitably shaped for grasping by the manipulator. Another possibility would be to use a linkage made from 2 or 3 thin rods connected by ball joints with clamps. A bead and tendon chain might also be suitable. An alternative to the bendy pointer would be a tool set consisting of an assortment of rigid pointers of commonly useful shapes which could be quickly attached or detached. Whatever type of pointer is used, it must be reasonably rigid under gravity.

Prior Art

The idea of guiding a manipulator to teach it a sequence of motions is well known and in common use at many laboratories and in several commercial products. However, adopting a guiding approach towards the generation of world models as proposed here has not been previously reported.

The idea of using a bendy pointer with a manipulator has not appeared in the literature, although this idea is related to the previous use of a rigid retractable pointer. Such a rigid pointer with a sensing capability was initially installed on the IBM arm in 1973 as a means for detecting touch with low inertia, a capability which was used, for example, to determine orientation of parts.[9] Subsequent to its installation, this sensing device was frequently used as a pointer to a set of fiducial marks in order to verify that the manipulator's calibration had not drifted.

Positioning a mechanical pointer in 3-d space is in some sense analogous to the action of moving and rotating a cursor in a 2-d graphics system. In a 3-d graphics system, the cursor has 3 translational and 3 rotational degrees of freedom. While there is no mathematical difficulty in moving a 3-d cursor, there is a substantial human engineering problem in orienting the cursor or even in simply visualizing an oriented frame. One of the authors has dealt with this problem in the context of representing 3-d objects[3] and' found it desirable to use implicitly defined frames rather than explicitly defined frames to specify how objects were to be attached. The actual coding of the implicit frame definition routines was done by Roger Evans, who subsequently coded similar routines into the ML language used with the IBM arm. The latter routines are used to specify absolute frames, but there is no notion of subpart hierarchies with affixment relations, and no notion of relative transes.

Conversations with members of the Stanford Hand-Eye project indicate that several people had considered many if not most of these ideas back in 1973, but at that time the need to design and implement AL superseded the need for interactive world model generation.

HYPOTHETICAL PROTOCOLS

Initial State

This section presents hypothetical protocols between the proposed system and a user who wishes to generate the world model corresponding to the tree shown earlier. The subpart hierarchy is indicated below:

```
WORLD
    FIDUCIAL
    ARM
        POINTER
    BEAM
        BORE
    BRACKET
        BORE
        HANDLE,
    B O L T
        GRASP
```

The reasons for including the fiducial mark, the arm, and the pointer in this hierarchy will become clear later on when the topics of system architecture and display facilities are discussed. At the start, when the system is first turned on, the subpart hierarchy is as shown below:

```
WORLD
    FIDUCIAL
    ARM
        POINTER
```

In the protocols which follow, system output is shown in upper case, user responses are shown in lower case, and explanatory material is contained in curly brackets {like this), When the system is ready for further user input, it prompts the user with an asterisk (I).

Protocol To Build Subpart Hierarchy

*new bracket

{This means that a new object called bracket is to be added to the subpart hierarchy.)

*nonrigid

{ This specifies that bracket is nonrigidly affixed to world,)

*{*Here the user moves the manipulator to point to the bracket frame, The details of the protocols for this type of operation are given in the next section.)*

***d:←bracket**

{ *This sets a context in which all future new objects ate subparts of bracket until the context is changed. Here "d:" stands for dad. When the system was first turned on, the initial context was d:←world.*}

***new** bore
***rigid**

{ *These two steps add a new object called bore to the hierarchy as a subpart of bracket and cause bore be affixed rigidly to bracket.*}

*{*Here the user moves the manipulator to point to the bore frame. The details. of the protocols for this type of operation are given in the next section.)*

***new** handle
***rigid**

*{*Here the user moves the manipulator to point to the handle frame.)*

***d:←world**

{*All future new objects are subparts of world again.*}

***new** beam
*nonrigid

*{*The user points to the beam frame.)*

***d:←beam**

{ *Future new objects are subparts of beam.)*

***new** bore

{ *The system is capable of distinguishing beam-bore from bracket-bore)*

***rigid**

*{*The user points to the bore frame.)*

***d:←world**
***new** bolt
***nonrigid**

*{*The user points to the bolt frame.)*

*d:←bolt
*new grasp
*rigid

*{*The user points to the grasp frame.)*

*

Protocol To Point To Frame

{ *Suppose the user bends the pointer into a new shape. He now wishes to calibrate it.)*

*setfid

{ *This macro expands into "free; a:←arm; +-fiducial; inverse; *; pointer:←a:↑". The "free" releases the arm brakes so the user can move the manipulator manually so that the pointer points to the fiducial mark. When he has done so, he pushes the "stop arm" button to proceed. The remaining primitive stack operations compute the correct pointer transform and are described more fully in the next section.)*

*record

{ *This macro records the point. It expands into "free; a:←|pointer;". The user moves the arm to make the pointer touch the current frame origin and again pushes the "stop arm" button. The pointer location is then read and remembered.)*

*record

{ *This time the user records any other point on x-axis of the current frame.)*

*record

{ *This time the user records any other point on xx-plane of the current frame. There would be other commands to select a different axis and plane.)*

*construct

{ *This computes a trans from the three recorded pointings.*}

***bracket:←a:**

{ *This gives BRACKET the computed trans.)*

Protocol To Move In A Frame

. { *The user may prefer to have the pointer moved by computer control rather than moving it himself manually. For example, suppose he is defining the frame of BRACKETHOLE when As has already defined that of BRACKET.)*

*free

{ *He manually brings the pointer near the correct place, and pushes the "stop arm" button to proceed.)*

***r:←bracket**

{ *This says that the user wants to make motions with respect to the BRACKET frame.)*

***m:←poin** ter

{ *This says that the frame which is to do the moving is the pointer. This is the main reason for including POINTER in the subpart hierarchy.)*

***dz -.01**

{ *This says move the pointer by a distance of .01 units in the minus z direction* of *the BRACKET frame. This macro expands into "b:←v 0 0 -.01; dmove; ↑". Again the commands will be explained later.)*

***x** 0

{ *This says move the pointer along the x axis of the BRACKET frame until it has x=0 in that frame. Again, x is a macro.)*

Extensions

The proposed system might be extended in several possible ways.. For example, pointing by vision could be provided to augment the manipulator pointing capability. Provision could be made for the user to define other attributes of object models besides location and affixment. Perhaps generic shapes such as cuboids, cylinders, or machine screws could be specified in this fashion. If visualizing frames proved to be difficult for some users, some form of graphics capability could be added to display frames of the objects in the subpart hierarchy, or possibly to display even some of the generic shapes. A more speculative extension would be a means for keeping track of a succession of world models, since such a **sequence** could be interpreted as an entirely new way of specifying an assembly procedure.

SOFTWARE DESIGN DETAILS

System Architecture

The proposed system contains three principal "working" modules: the affixment editor, arithmetic routines, and manipulator interface routines.

The affixment editor contains facilities for creating and modifying the subpart hierarchy. The principal data structures associated with this section are the tree used to represent the hierarchy and a set of stack-structured context pointers (called "cursors").

The arithmetic section contains a full set of arithmetic operations for scalars, vectors, and transes, together with routines for modifying the location attributes of parts. The principal data structures associated with this section are a pair of stacks used to hold operands. Typically, one stack is used to hold values specifying incremental motions for the manipulator, while the other is used for computing new location values.

The manipulator interface contains facilities for moving the manipulator under either system or user control and for retrieving the current location of the manipulator for use by the rest of the system. For the latter purpose, the node ARM in the subpart hierarchy always contains the current location of the manipulator.

In addition, there are three "service" modules: a command interpreter, display facilities, and output facilities.

The command interpreter accepts commands typed in from the terminal and translates them into calls on appropriate routines: Most commands' have mnemonic text names (e.g., "getdad" to move a cursor from a subpart node to its parent). In addition, many have single character abbreviations (e.g., "^" for "getdad"). A macro facility for stringing together commonly occurring sequences of primitive operations is assumed to be present but will not be discussed in detail in this document, although definitions for some assumed built-in macros will be given.

The display routines update the screen of the user's terminal to reflect the current state of the affixment editor, arithmetic section, and manipulator interface.

The input/output facility contains routines for saving and restoring subpart hierarchies in files. In addition, it contains routines for translating a subpart tree into a text file of AL declarations.

Subsequent subparts of this section will describe the display routines and the primitive user commands for invoking the facilities provided by the various modules.

Display Facilities

The display routines are used to provide the user with an up-to-date picture of the current system state. To do this, the display screen is broken into an affixment editor reigon, an arithmetic reigon, and a terminal interface reigon, as is shown in figure 1, below.

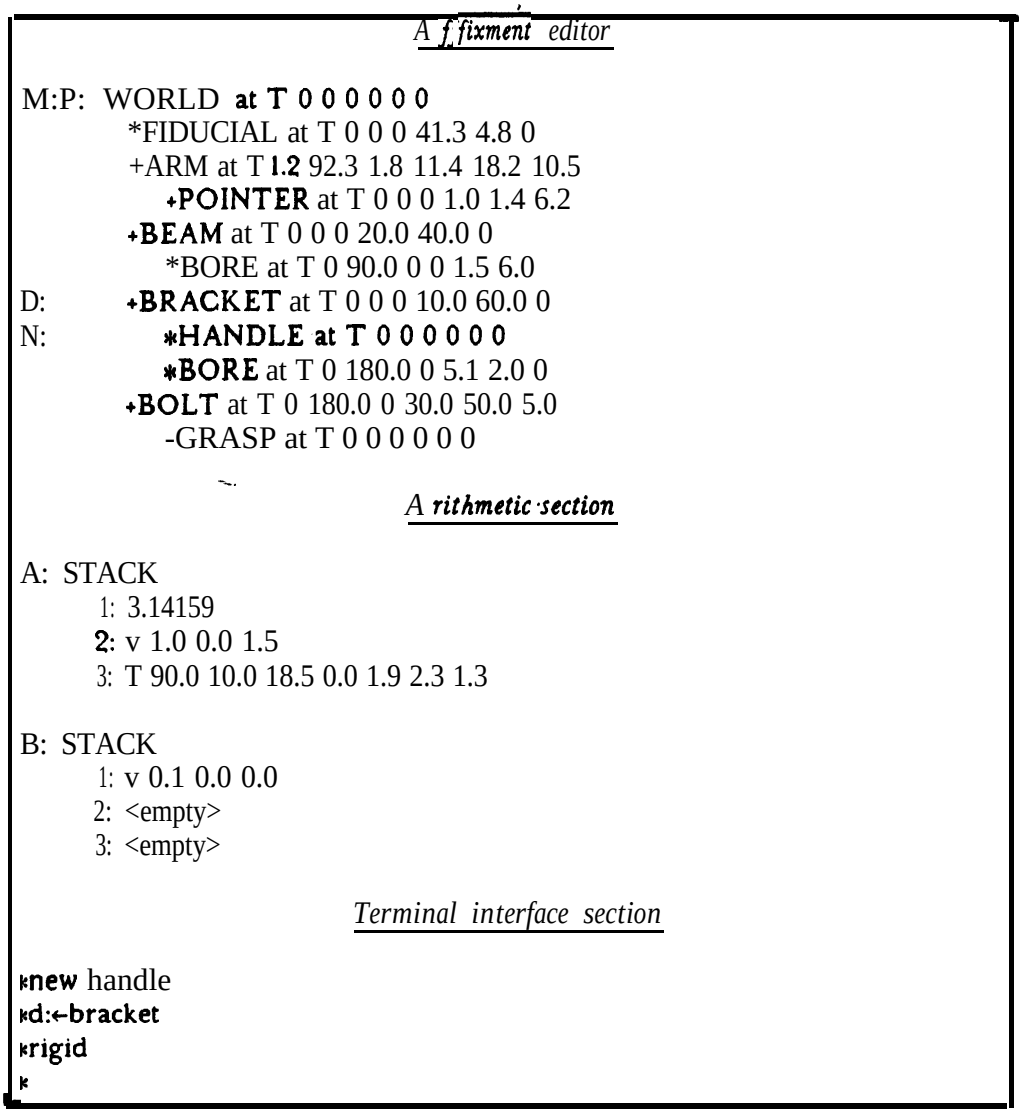


Figure 1. Typical display scene

In the affixment editor section, subpart relations are indicated by paragraphing. The type of affixment is indicated by preceeding the part name by a "*" for rigid affixment, "+" for nonrigid affixment, and "-" for independent affixment. Cursor positions are indicated by placing the cursor name on the appropriate line. Finally, the location attributes for each node are indicated in the “at” expression. In the case of rigid or non-rigid affixment, relative position of with respect to the parent is printed. For independent affixment, location with respect to the WORLD node is shown.

The arithmetic section displays the current contents of the top three locations in the stacks. Values are shown in the same format in which they would be read in from the terminal, i.e.,

scalars are merely typed out, vectors have "V" followed by three scalars, and transes have "T" followed by three rotation angles and three displacement values.

The terminal interface section is simply an area for the operating system's page printer to go, and shows the last few commands typed by the user. As characters are typed by the user, this is where they are put.

For efficiency, random access graphics would be used to update only those parts of the display that are changed from command to command. However, it should be pointed out that the design shown uses only text characters for typeout. Thus, one reasonable alternative would be simply to type out the whole screen each time. On reasonably fast terminals (300 baud or greater) this shouldn't prove too much of a burden.

Affixment Editor

The affixment editor contains facilities for creating and modifying the subpart hierarchy, which is stored internally as a tree of part nodes. Each such node contains the following information:

PNAME -- The print name of the node. For instance, "BORE". Notice that these names are, not necessarily unique.

DAD -- Pointer to the parent node. The special node WORLD acts as an ultimate ancestor.

SON -- Pointer to the node most recently affixed to this one.

EBRO and YBRO -- Pointers to the elder and younger brother nodes, , respectively. For example, EBRO[N] points to the node that was SON[DAD[N]] when N was affixed to DAD[N].

HOWAFFIXED -- An integer telling how the node is affixed to its parent. There are three kinds of affixment: *rigid* (1) an&nonrigid (2) have essentially the same meaning as given in the AL document. *independent (0)* is a special kind of affixment used for nodes that have a subpart relationship with their parents but whose locations are independently specified. Independent affixment is primarily useful as an intermediate step in editing a structure.

XF -- A homogeneous transformation used to specify the location of the node. This is internally stored as a 4 by 4 matrix. If the affixment is rigid or nonrigid, XF specifies the location of the node with respect to its parent node. If the affixment is independent, XF specifies the location with respect to WORLD.

Primitive commands are provided for creating new nodes, deleting old ones, modifying the affixment links, copying structures, and various other useful editing functions. These commands will be discussed in a moment. A number of context pointers, called *cursors*, are used to specify some of the arguments to the editing primitives. Such cursors are stack structured and typically are named by a single character followed by a colon. The following cursors are included in the current design:

CURNODE("N:") -- gives the node on which the user is currently working.

CURDAD ("D:") -- gives node to which subparts are to be affixed.

CURPATH("P:") -- gives root node of current **subtree** for name recognition.

CURREF **("R:")** -- gives the current motion reference frame. All motion commands are to be made with respect to the location frame of this node.

CURMOVE ("M:") -- gives the current motion frame. All motion commands actually move the location frame of this node.

CURTOP ('IT:") -- gives the root node of the displayed **subtree.**

CURKILL("K:") -- gives the root node of the most recently deleted **subtree.**

As mentioned before, cursors are stack-stuctured. This means that typically whenever a new value is assigned to a cursor, the old value is saved away (to a depth of four) where it **can** be recalled if need be. **This** facility provides a nice way for a user to recover from errors, **as** well as **to** suspend temporarily one editing sequence and go do something else.

The following operations are supplied for modifying the contents of cursors:

Operation	*Typein*	*Description*
Set cursor	**c:←<node spec>**	Pushes down the old value of cursor c:, then sets the new value <node **spec>,** , which may be a node name or a cursor name. For instance, **"n:←beam"** followed by **"d:←n:"** would set the current value of both N: and D: to BEAM.
Pop cursor	**c:↑**	Restores the previous value of c:. May be combined with assignment, as in **"d:←n:↑",** which pops N: into D:.
Get father	**c:∧**	Replaces c: with **DAD[c:].** Does not save previous value.
Get son	*c : v*	Replaces c: with **SON[c:]** Does not save previous value.
Get brothers	**c:<** and **c:>**	Replace c: with **YBRO[c:]** and **EBRO[c:],** respectively. Do not save previous value.

Here c: has been used to stand for any cursor name. An additional property of the cursor

commands is that they remember the last cursor operated on. If a cursor designation is left off of a command, then the last cursor specified will be used. For instance, "n:^^>" will move the cursor N: so that it points at its great uncle. One fine point here is that value fetching is done before assignment. Thus, for a sequence like

```
n:cbracket
n:←beam
d:←n:↑
A
```

D: will wind up pointing to WORLD (The DAD of BEAM) and N: will point at BRACKET.

Earlier, it was stated that node names need not be unique. This can cause difficulties in cases where a user wishes to address a node by its name. For instance, in our example structure, a user might want to type,

```
n:←bore
```

Here, there are two possibilities: one a subpart of BEAM and one a subpart of BRACKET, and the system will not know which is meant. Such ambiguities may be resolved by naming an ancestor node whose subtree contains only one node with the name in question. Thus, the sequence

```
n:tbracket.bore
<
```

would place the cursor N: as shown in figure 1. In many cases, one wishes to work for an extended period in one subtree. To facilitate this, the cursor P: may be used to supply a default ancestor node. Thus, the sequence

```
p:tbracket
n:←bore
<
```

would also place the cursor N: as shown in figure 1. Note, however, that it is still possible to have inherently ambiguous namings. For instance:

```
BEAM
   HOLE
   HOLE
```

This situation arises quite naturally as an intermediate state in cases where a previously defined structure is being copied and modified Therefore, it is not outlawed. If a user wished to point at such nodes, he must get to a nearby node and then use cursor moving operations to get the rest of the way.

The following primitives are used to edit the tree structure:

Operation	*Typein*	*Description*
Make new node	new <name>	Creates a new node with the specified name and affixes it as an independent subnode of WORLD. Sets N: to point at the new node. (Old value of N: is pushed).
Affixment	<affixment type>	Affixes the node pointed to by N: to that pointed to by D: in the indicated manner. Leaves N: and D: as they were. Updates links and location attributes appropriately. (Discussed further below).
Kill structure	kill <node spec>	Deletes the subtree rooted at the named node. Sets K: to point at deleted structure. (Previous value of K: is pushed). If <node spec> is omitted, then N: will be assumed.
Un kill	k:↑	Popping a node off the K: stack restores the subtree rooted there to life. The restored structure will be linked back onto its parent in the same way as during its previous existence.
Copy structure	copy <node spec>	Copies the subtree rooted at <node spec> and sets N: to point at the copy. (The previous value of N: is pushed.) If <node spec> is omitted, then N: will be assumed.
Merge structure	merge	Unlinks all subparts from the node pointed to by N: and makes the corresponding affixments to the node pointed to by D:. Leaves N: and D: alone.

The affixment operation comes in three flavors: rigid, nonrigid, and independent. In the first two cases, the XF attribute of the node must be set to the current relative position of the node with respect to its new parent, while in the last case, the XF must be set to the current absolute location of the node, i.e., its location relative to WORLD. This is done as follows:

1. Check to be sure that the affixment requested will not cause a circular structure by verifying that N: is equal to D: and is not an ancestor of D:. If a circular link is being proposed, print an error message and quit. Otherwise, go on to step 2.

2. Compute the current absolute location of the node pointed to by N: and store the result away in XF[N:]. A 'method for computing absolute locations will be

given later.

3. Unlink the node pointed to by N: from its current parent. Set YBRO[N:] and EBRO[N:] to null.

4. Set HOWLINKED[N:] to the new link type.

5. If the new link type is rigid or nonrigid, compute the absolute location of the node pointed to by D:, call it T, and replace XF[N:] by T^{-1}*XF[N:].

6. Link the node pointed to by N: as the youngest son of the node pointed to by D:.

Note that one side effect of the way the kill command is defined is that storage for a deleted structure will not be reclaimed until the structure falls out the bottom of the K: stack (i.e., after four deletions). If this should ever get to be a problem, then a "purge the kill stack" operation is easy to add. (In fact, repeating "k:←k:" three times will flush all but the most recently killed object).

The "merge" command provides a useful way to perform editing operations on sets of nodes. For instance, suppose we have an affixment structure like this:

```
WORLD
  +BOX
     *HOLE 1
        +APPROACH
     *HOLE2
     +GRASP
     +BOTTOM
     ...
  +COVER
  +GASKET
```

and suppose that we wish to make holes HOLE 1 and HOLE2 in the corresponding position in parts COVER and GASKET. This can be done by the following editing sequence:

```
new tmp          {Use TMP as a "bin" for holding the set of of holes.)
d:←n:            {Affixing to TM P}
p:←box           (Don't keep having to type "BOX "}
copy hole1
rigid            {Affix a copy of HOLE I rigidly to TMP)
n:↑              (Gets HOLE 1 off of N: stack, which reverts to TMP.}
copy hole2       (Repeat sequence for HOLE 2 }
rigid
n:↑
```

At this point the affixment structure looks like this:

```
WORLD
  -TMP
     *HOLE 1
        +APPROACH
     *HOLE2
  +BOX
     *HOLE 1
        +APPROACH
     *HOLE2
     +GRASP
     +BOTTOM
     ...
  +COVER
  +GASKET
```

with N: and D: both pointing at TMP. Now we will merge a copy of **TMP** into **COVER** and TMP itself into CASKET.

copy	*{N: points at a copy now)*
d:←cover	*(Will merge into COVER }*
merge	*{Perform merge operation]*
kill	*(Kill off copy of TMP, which at this point has no subnodes left}*
n:↑	*(Get pointer back at TMP)*
d:←gasket	*(Will merge TMP onto GASKET)*
merge	
kill	*{Kill off TMP, which is now childless.)*

The final affixment structure is:

```
WORLD
  +BOX
     *HOLE1
        +APPROACH
     *HOLE2
     +GRASP
     +BOTTOM
     ...
  +COVER
     *HOLE 1
        +APPROACH
     *HOLE2
  +GASKET
     *HOLE1
        +APPROACH
     *HOLE2
```

Arithmetic Section

The arithmetic section provides the user with a means for performing computations on scalars, vectors, and transes. All operations are performed in Polish on one of two operand stacks, and the results are stored back in the stack on which the operation was performed. In addition, facilities are provided for the user to enter values from the terminal and to retrieve and modify the location attributes of nodes in-the affixment structure. Since the current value of ARM and POINTER always give the positions of the manipulator and the pointer, respectively, this means that the user can use the results of pointing operations to define relative or absolute part locations.

The arithmetic section contains two functionally identical 100 element operand stacks, called "A:" and "B:". A third and somewhat shorter stack, called "0:" (for 'hops"), is provided to facilitate error recovery. Any time a value is popped off one of the operand stacks, it is pushed onto 0:. Thus, if a careless user makes a mistake and invokes the wrong operator, he can get his operands back by popping them off 0:. As with all stacks in the system, overpushing causes the oldest element to fall out the bottom.

The following elementary stack operations are provided for manipulating values. Here, S: stands for any arithmetic stack.

Operation	*Typein*	*Description*
Fetch value	s:←<value>	Pushes <value> onto the stack. <value> may be a literal (described below), a register name (as in "a:←b:" or a:←o:↑), or an absolute or relative node location.
Relative locn.	s:←@<node spec>	Push the XF attribute of the specified node to the stack.
Absolute locn.	s:←|<node spec>	Pushes the location of the specified node with respect to WORLD.
Pop	s:↑	Pops the previous contents of S: into S:.
Edit	edit <lhs>	Places the string "<lhs>←<value>" into system line editor. (see below)
Exchange	s:↔	Exchange top two elements of S:
Store relative	@<node>←<value>	Copy the specified value into the XF attribute of the specified node.
Store absolute	|<node>←<value>	Modify the affixment structure so that the absolute location of the specified node will have the specified value.

The format, used for typein of literal values is the same as that used by the display routines' to type them out. For instance,

a:←3.14159 *(pushes the scalar value, 3.14159, onto A:)*

a:tv x y z *(pushes vector (x,y,z), where x,y,z are scalars onto A:)*

a:←t ω θ φ x y z *{pushes a trans corresponding to a rotation of ω degrees about the z-axis, then θ degrees about the y-axis, then φ degrees about the r-axis again, followed by a translation by vector (x,y,z). A gain, ω, θ, φ, x, y, and z are a&l scalars.)*

The "edit" command is intended to facilitate modification of values that may be a little off, due to inaccuracies in pointing. Essentially, the line editor is a facility maintained by the time sharing system that allows a user to perform local editing operations on text that has been typed ahead 'but not yet activated.[10] (Some "smart" terminals offer similar local editing of text input). One principal advantage of such a facility is that it provides users with an efficient, flexible, and uniform set of editing conventions. For instance, suppose that the current location of HANDLE (with respect to BRACKET) is "T 0 179.3 1.8 0 0 0.01". We "know" that this just cannot be quite right, since rotation angles are assumed (for the moment) to come out to even fives of degrees. Also, we strongly suspect that the final displacement value ought to be "0". The value can be patched up by the following command sequence:

edit @handle *{This loads the line editor with the text:*

"@handle.←t 0 179.3 1.8 0 0 0.01"

and puts the user in local editing mode.)

shandlett 0 180 0 0 0 0

{The user has edited the line to the form shown here and activated by typing carriage return.)

In cases where the thing being edited is a stack register, the stack value is *popped* into the line editor (without affecting the "O:" stack). For instance, our example could also have been performed by:

```
a:←@handle
edit a:
a:tt 0 1800000
@handle←a:↑
```

Except for nodes whose immediate parent is WORLD or which are independently affixed, absolute locations are not directly available in the affixment editor's data structure. However, the required computation is very straightforward. The system uses the following algorithm, expressed here in an informal procedural notation.

```
(Assume N is a node whose absolute position is to be computed.)
X←XF[N]; {X will eventually be the absolute location.}
WHILE HOWLINKED[N]≠"independent" DO
    BEGIN
    N←DAD[N];
    X←XF[N]*X;
    END;
(Here, X = absolute location of N, i.e., location with respect to WORLD. }
```

A somewhat similar problem arises when storing away the absolute location of a node, since non-independent nodes keep the relative location with respect to their parent node. Here, the effect desired in asserting that a node N has a new absolute location X is implicitly to update the absolute location of all non-independent descendents of N. Also, if N is rigidly affixed to its parent, then the absolute location of the latter must also be updated. The following algorithm for updating absolute locations will do all this:

```
{Assume N is a node whose absolute location is to be set to X, i.e., we have
just executed a statement like "N ← X".}

WHILE HOWLINKED[N]="rigid" DO
    BEGIN
    X←X*XF[N]^-1;
    N←DAD[N];
    END;

, (Here, N is a nonrigidly affixed node whose absolute location must be set to
X}

IF HOWLINKED[N]="nonrigid" THEN
    XF[N]←(absolute loc of DAD[N])^-1*X
ELSE
    XF[N]←X;
```

Arithmetic operations provided include:

Operation	*Typein*	*Description*
Binary ops	s:+ - * /	Computes S:[1] <op> S:[0] Does the "usual" thing if the top two elements on the stack are scalars. If one operand is *a* scalar and the other is a vector, performs the scalar operation element-wise. If both are vectors, then "+" and "-" work on corresponding elements, "*" gives vector inner product, and "/" is undefined. If operands are both transes, then "*" returns the product, and "+", "-", and "/" are all undefined. If the top operand is a vector and the second operand is a tram, "*" returns T*v. Otherwise, the operation is undefined.
Cross product	s:cross	Computes S[11 cross S[0]
Jnary minus	s: -	Computes 0-S:[0], provided that is defined.
Inverse	s:in verse	Computes S:[0]$^{-1}$, providing S:[0] is a trans
Magnitude	s:magn	Gives sqrt(S:[0]*S:[0])
Displacement	s:dpart	Requires S:[0] to be a trans. Returns *a* vector equal to the displacement. e.g., for S:[0] = T 0 180 30 1 3 5, returns V 1 3 5.
Rotation	s:rpart	Requires S:[0] to be a trans. Produces a trans with zero displacement but the same rotation as S:[0]. E.g., if S:[0] = T 0 180 30 1 3 5, returns T 0 180 30 0 0 0.
Vector trans	s:vtrans	Converts vector S:[0] into a trans with zero rotation and S:[0] as the displacement. E.g., if S:[0] = V 1 3 5, produces T 0 0 0 1 3 5.
Construct trans	s:construct	Constructs a new trans T from vectors S:[0], S:[11, and S:[2], such that T^{-1}*S:[2]=(V 0 0 0), T^{-1}*S:[1]=(V 0 0 z) for some z>0, and T^{-1}*S:[0]=(V x 0 z) for some x,z (x>0). This operation is essential for constructing implicitly defined frames.

Here, S: is used to 'stand for either A: or B:, S:[0] refers to the top element of stack S:, S:[1] refers to the next element down, and so forth. All these operations pop their operands off the stack, perform thecomputation, and the push the result.

As with cursors, the name of the last arithmetic stack referred to is remembered, and will be used as a default in subsequent stack operations. For instance:

```
azt2.54
t 10.0
*
```

will leave a result of 25.4 on the A: stack.

Manipulator Interface

The manipulator interface provides the user with facilities for making controlled motions of the manipulator. The principal data structures employed are the nodes ARM and POINTER provided in the affixment data structure, and the cursors M: and R:, which are used to request computer-controlled motions of the manipulator. The primitive commands involved are given below:

Operation	***Typein***	*Description*
Absolute move	s: amove	Requires that the S:[0] be a frame. (If not, an error is generated). Moves the manipulator so that (absolute location of M:) = (absolute location of k:) * S:[0].
Diff. motion	s: dmove	Moves' the manipulator so that the absolute location of M: is changed by (absolute location of R:) * S:[0].
Free arm	free	Releases brakes on manipulator joints, which can then be positioned manually. Completion of positioning is signalled by typing any activation character at the terminal or by means of a button on the manipulator
Joystick	joy	Places the manipulator under control of a joystick.

As was mentioned earlier, the current location of the manipulator is assumed to be always present in ARM. In actual practice, it is rather inconvenient to do this while the manipulator

is being moved. Therefore, it is assumed that the value is only updated at times when the system is at a convenient place, such as at the top of its command interpretation loop. Such a policy is unlikely to cause any difficulties for the user.

It is unlikely that the "joy" command would be implemented at Stanford, where manual positioning is used instead. The command is included to give some indication of where a joystick would fit into such a system.

Input/Output Facility

This module contains routines for saving subpart trees onto a file and for reading saved structures back into the affixment editor. This allows the user to spread his work over several terminal sessions without having to recreate the entire structure each time. In addition, a routine to translate a subpart tree into AL declarations is provided.

The commands are given below:

Operation	*Typein*	*Description*
save. structure	save <filename>	Saves the structure pointed to by N: on the file specified by <filename>. Has no effect on the affixment editor data structures.
restore	load <filename>	Reads the structure stored on the named file into the affixment editor's memory. Causes N: to point at the newly read structure, which is affixed as an independent subpart of WORLD. The previous value of N: is pushed'.
AL code	al <filename>	Translates the structure pointed to by N: into the appropriate set of AL declarations and writes the text on the specified file.

When writing the AL declarations, the system will use the subpart hierarchy to produce unambiguous names. For instance, if the structure is

```
WORLD
   BRACKET
      BORE
      HANDLE
   BEAM
      BORE
```

then the command sequence

```
n:←world
al decls.al
```

would produce declarations involving "BRACKET", "BRACKET_BORE", "BRACKETHANDLE", etc. For instance:

```
FRAME BRACKET, BRACKET_BORE,BRACKET_HANDLE;

    . . .

ASSERT FORM (SUBPART,BRACKET,BRACKET_BORE);
ASSERT FORM (SUBPART,BRACKET,BRACKET_HANDLE);

    . . .

AFFIX BRACKET-BORE TO BRACKET RIGIDLY
            AT TRANS(ROT(X,180),VECTOR(5.1,2,0));
AFFIX BRACKETHANDLE TO BRACKET RIGIDLY
            AT TRANS(ROT(X,180),VECTOR(0,0,0));

    . . .
```

IMPLEMENTATION STRATEGY

The proposed pointing system could be implemented in a minicomputer with at most 16k words of memory. However, at the Stanford University Artificial Intelligence Laboratory it would be substantially easier to implement, modify, and use the pointing system if it were implemented on the large time sharing machine. The only portion of the design which inherently assumes that this machine would be used is the line-edit feature in the arithmetic section.

A preliminary version of the system has been implemented in SAIL,[11] using record structures for the subpart hierarchy, and using available display primitives. The preliminary version only allows transes in the arithmetic stacks, has no user defined macros, and uses a symbolic debugger, BAIL,[12] for command scanning. With BAIL, instead of the command syntax described earlier, users type SAIL procedure calls which are then interpreted.

The more pessimistic of the authors believes that the full system could be operational with about 2 man months of effort. However, it is not clear that implementing the full system at the present time is necessarily the most desirable use of manpower.

The authors do not wish to be accused of succumbing to the Mikado syndrome which consists of saying that since the implementation is as good as done, for all practical purposes it is done, and if it's done, why not say so?[13] On the other hand, it should be stressed that whether or not the full system proposed here is actually ever implemented, tests with the preliminary version demonstrate the feasibility of generating object models in a resonably simple manner. What otherwise might have been a serious drawback to the use of high level languages for manipulation is, therefore, not a serious problem at all.

CONCLUSIONS

This paper has addressed the topic of generating object models for programs in a high level manipulator language. An interactive system was proposed in which the manipulator itself is used as a measuring tool in three dimensions. One component in this system is a bendy pointer whose deformation may be calibrated against a known fiducial mark. Hypothetical protocols involving such a system were presented, as well as details about the design of the underlying software.

Such a system would materially speed up the process of generating world models for AL programs. Most of the proposed system could be adapted for other methods of pointing or for other high level manipulation languages. The system could be expanded to permit additional descriptive data about objects, or to keep track of a sequence of world models as a new means of specifying an assembly procedure.

A preliminary version of the system has been implemented and tested. This preliminary system demonstrates that specifying object models can be a much easier process than might otherwise have been believed.

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