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(NASA-Case-MSC-21379-1-SB) GENERATION OF ANIMATION SEQUENCES OF THREE DIMENSIONAL MODELS Patent Application (NASA) 36 p CSCL 09B

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MSC-21379-1-SB
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Print Fig 2A

AWARDS ABSTRACT

MSC-21379-1

# GENERATION OF ANIMATION SEQUENCES OF THREE DIMENSIONAL MODELS


The invention relates to an apparatus and a method for the creation and recording of computer generated animation sequences. It provides a method and an apparatus for performing spatial transformations and rotations upon a multiplicity of three dimensional object models within a given three dimensional "workspace" which may be selectively linked and unlinked to graphically simulate the movement of physical systems and which permits viewing the transformations and rotations from a multiplicity of viewpoints.

The invention is directed toward a method and apparatus (10) for generating an animated sequence through the movement of three dimensional graphical models. A plurality of pre-defined graphical models are stored and manipulated in response to interactive commands or by means of a pre-defined command file (38). The models may be combined as part of a hierarchical structure to represent physical systems without need to create a separate model which represents the combined system. System motion is simulated through the introduction of translation, rotation and scaling parameters upon a model within the system. The motion is then transmitted down through the system hierarchy of models in accordance with hierarchical definitions and joint movement limitations. The present invention also calls for a method of editing hierarchical structure in response to interactive commands or a command file such that a model may be included, deleted, copied or moved within multiple system model hierarchies. The present invention also calls for the definition of multiple viewpoints or "cameras" which may exist as part of a system hierarchy or as an independent camera. The simulated movement of the models and systems is graphically displayed on a monitor (26) and a frame is recorded by means of a video controller (40). Multiple movement and hierarchy manipulations are then recorded as a sequence of frames which may be played back as an animation sequence on a video cassette recorder (36).

Novelty resides in the capability of selectively creating model structures and hierarchies without having to substitutes combined models for individual models within the structure. It will be appreciated that the invention results in an increase in efficiency in creating animated sequences which accurately depict kinematic motion of linked structures.



Inventors: Sharon D. Poi
*Brad N. Bell

Employer: NASA Johnson Space Center
*Barrios Technology


Initial Evaluator: Charles J. Gott

 Print fig 2A



# GENERATION OF ANIMATION SEQUENCES OF THREE DIMENSIONAL MODELS

## Origin of the Invention

The invention described herein was made in the performance of work under a NASA contract and is subject to Public Law 96-517 (35 U.S.C. 200 et seq.). The contractor has elected not to retain title to the invention.

## Technical Field

The present invention relates to an apparatus and a method for the creation and recording of computer generated animation sequences. Specifically, the present invention relates to a method and an apparatus for performing spatial transformations and rotations upon a multiplicity of three dimensional object models which may be selectively linked and unlinked within a given three dimensional "workspace" to graphically simulate the movement of physical systems and to simulate viewing the transformations and rotations from a multiplicity of viewpoints.

## Background Art

The use of computerized systems for the generation of animated sequences is a known art commonly used in the entertainment industry. The systems are also used to perform engineering analysis and simulation of physical systems. The common practice was to create a graphical model of the physical system or systems and to perform various spatial transformations and rotations upon the models. The spatial transformations for any one model could be described in terms of x, y, z translations, roll, pitch and yaw and scaling transformations. Techniques for performing complex spatial transformations have been previously developed and are set forth in references such as Principles of Interactive Computer Graphics, by W. Newman and R. Sproull. The spatial transformation of a model has generally been observed from a selected view point with the model transformation being under a single light source.

One characteristic of prior art systems was the manner in which two or more models were joined or linked to undergo a joint spatial transformation. Typically, an additional model was required to represent the constituent models for the purposes of spatial transformations. The additional model was substituted when the constituent models were linked. Similarly, when the combined model was "unlinked" the original models were substituted back into the active workspace. The substitution of models required that prior art systems maintain information on the individual models which were used to update the position of models later substituted in the workspace. The point at which the models were linked created a "joint" which defined the ability of the constituent models to move with respect to each other within the linked model. Prior art systems, such as U.S.Patent No. 4,600,919, included means for defining joint hierarchy and for displaying the three dimensional movement of one joint relative to another. However, these prior art systems lacked the capability of redefining joint movement hierarchy during an interactive session without the creation and substitution of additional models. Another characteristic of prior art systems was the manner in which spatial transformations were depicted or "viewed." Typically, prior art systems were limited to one viewpoint or "camera" with the ability to move the camera in three dimensional space independent of the model. Prior art systems required either the camera or the model(s) being viewed undergo spatial transformations to obtain a different view of the object model(s). Generally, prior art systems defined a camera as being independent of the model(s) being viewed. Thus, the rotation and translation of the composite model was viewed external from the moving composite model.

## Statement of the Invention

The present invention is directed to a two dimensional presentation of a multiplicity of three dimensional models and the spatial transformation of the models in three dimensional space to create an animated presentation of the movement of the models. A model comprises one or more "cells" which includes the graphical modeling information for the model. The present invention permits two or more models and constituent "cells" to be selectively linked together forming a model "structure" without the creation and substitution of additional models. The point at which a model is linked to another model is described as a joint. Joint movement hierarchies are established for each model link point, thereby defining the movement of constituent models relative to each other within the linked model structure. The movement hierarchies are defined as part of each model cell. The present invention also permits the editing of model structures and joint movement hierarchies in response to a command file or interactive editing without the creation and substitution of additional models. Thus, in the present invention, two or more models may be linked together to undergo complex spatial transformations according to the linked model structure and joint movement hierarchical rules. The model hierarchy is achieved through the creation of a forest of linked cells. The models may be subsequently "unlinked" for further independent movement. Further, the present invention permits the modification of joint movement hierarchies within the linked model. The modifications may take the form of a "one time" override command or the hierarchies may be permanently modified. The joint movement hierarchies may be modified without disrupting the structure of the linked model.

The present invention permits models, and any spatial transformations they may undergo, to be viewed from a multiplicity of different viewpoints or cameras without moving the camera relative to the model or vice-versa. The present system permits the user to select from any number of previously defined cameras or to define a new camera view during the animation sequence itself. As with prior art systems, each of the independent cameras may undergo independent spatial transformations. However, unlike prior art systems, the multiple cameras may exist as independent models or may themselves be included in a model structure. Thus, the present system permits cameras to exist on a model within a linked model structure and be subject to the linked model structure and joint movement hierarchies. When a camera is linked to a model, a camera's ability to undergo independent spatial transformations is limited to a subset of normal spatial transformations as the camera is subject to the translations and rotations of the model to which it is linked. Further, a camera may be selectively linked or unlinked within a model or model structure.

The present invention also permits the user to select multiple light sources from a number of pre-defined lighting sources in the work space or to create new light sources during the animation sequence. A light source in the present invention exists as a non-visible source of parallel light beams of selectable color and intensity. An independent light source may undergo a limited set of spatial transformations, in this case limited to x, y and z axis translations.

The models used in the present invention are created using an external graphics design system. For example, the "Solid Surface Modeler" (SSM) (available from NASA's Computer Software Management and Information Center (COSMIC) at the University of Georgia, Athens, GA 30602) creates a file representation for the individual model which is read and updated by the present invention. The present invention permits individual models to be selectively displayed in various modes such as, for example, wire frame, shaded surface or as high resolution, anti-aliased, two- dimensional representations. The wire frame presentation of models may be used to effectively preview the animation sequence due to the decreased time required to display the wire frame mode as compared with other display modes. A shaded surface representation may be selected at any time during the animation or development sequence. The high resolution anti-alias mode is frequently used in the invention's batch animation recording mode due to the amount of time required to display each frame.

In the present invention, models, cameras, joints, lights and other aspects of the system are controlled by means of either a command file or through interactive means. Both means of control are capable of performing the same system functions, including linking/unlinking, spatial transformations, joint hierarchy control, and model/camera/light selection and control. Interactive means include the use of analog input means to the system, including the use of potentiometers, relays and/or interactive keyboard commands. The interactive mode can be used to build, select and preview discrete animation sequences to be used in a later animation sequence. In order to improve user response times, interactive animation is typically performed in the wire-frame mode. The shaded surface mode may be selected at any time during an interactive session. Longer animation sequences are created in response to a command file. The command file may be used to generate the sequences in any of the three display modes.

The present invention also includes means for controlling a single frame video recorder which is used to record the animation sequence. The system places a video recorder in record mode once a compete frame has been generated and displayed by the invention. The video recorder is then placed in a standby mode until the next video frame has been generated and displayed. This process is repeated until the command file has been completed, at which time the video recorder is turned off.

Brief Description of the Drawings

Fig. I is a block diagram of the apparatus used in an embodiment of the invention and supports the method of the present invention.

Fig. 2A - 2V represents the command tree for the set of function menus displayed by apparatus of an embodiment of the invention for practicing the method described herein.

Fig. 3 represents a typical model structure showing a model with a number of constituent models.

Fig. 4 represents the same model structure described in Fig. 3, but described in terms of the constituent data cells and the cells' relationship in the model structure to each other.

Fig. 5A represents the initialization file format for the structural hierarchy described in Fig. 4.

Fig. 5B represents the input file for specifying permissable movements, or joint hierarchy, for the RMS where the shoulder joint may only yaw.

Fig. 5C represents the input file for specifying permissable movements, or joint hierarchy, for the RMS where the shoulder joint may roll or pitch as well as yaw.

Fig. 6 represents viewing parameters for cameras specified in Fig. 4 and viewing parameters relative to a new independent camera.

Fig. 7A and 7B are flow diagrams of the method by which the present invention creates model structures.

Fig. 8A and Fig 8B show a flow diagram of the method by which the present invention deletes one or more model cells from an existing model structure.

Fig. 9 is a flow diagram of the method by which the present invention moves one or more model cells from one model structure to another.

## Detailed Description of the Invention

Referring to Fig. 1, a block diagram for a workstation apparatus 10 for practicing the method of the present invention. The workstation 10 includes a central processing unit (CPU) 20, a high speed image processor 22, disk storage 24 and any of a number of input/output (I/O) devices 38, such as a tape drive. The method of the present invention for manipulation of various graphic models 44 is stored as a program instruction set on disk 24. In the preferred embodiment, the workstation 10 includes five different operator Input/Output (I/O) devices 18, including a raster scan display monitor 26, a keyboard 28, a set of potentiometers or "dials" 30, a mouse 32 and set of switches or "buttons" 33. These I/O devices are used by an operator (not shown) to interact with the program instruction set 44 when the present invention is being operated in an interactive mode. The apparatus 10 also includes a video controller 36 and video cassette recorder 40 to record frames which are generated by the apparatus 10 in response to a predefined command file or "batch mode." The controller 36 is controlled by the CPU 20, such that controller 36 is activated only when a complete frame has been generated by apparatus 10 and displayed on monitor 26.

Models used within the present invention may be created on apparatus 10 using a separate set of program instructions 46 which are directed primarily at the generation of solid surface models such as the Solid Surface Modeler program available from NASA's COSMIC. The model creation set of instructions 46 are stored on the workstation disk 24. The preferred embodiment also permits models to be created in a similar fashion and be included in the method of the present invention by reading model data via I/O device 38 or via a communications link 50 with other like workstations 52.

The method of the invention may be practiced in response to a set of predetermined commands, or "batch mode." In this mode, a "command file", which may be stored on disk 24 or read via I/O device 38 are processed by CPU 20 and graphics processor 22, to load the specified models, the cameras and lights, and to perform the specified spatial transformations including linking of models and cameras and modification of various display attributes. The CPU 20 also processes a set of instructions which control the operation of the video controller 36 when the command file specifies that the animation sequence is to be recorded on video cassette recorder 40.

The operator I/O devices 18 are used to create and preview short animation sequences prior to the development of longer animation sequences which are created in the command file mode. In the interactive mode, the model manipulation instruction set 44 guides the operator through a series of function menus which are displayed on display monitor 26. The operator may select function choices by means of either the keyboard 28 or mouse 32. Models, cameras and lights may be interactively controlled through the use of potentiometers 30 and switches 34.

The menus which are displayed in the interactive modeof apparatus 10 are displayed in Figs. 2A - 2V. The series of command trees in Figs. 2A - 2V demonstrate the functions available to the operator in the interactive mode of model manipulation set 44. The operator may load and select models, lights, cameras and background information, perform spatial transformations, link models, lights and cameras, and edit animation parameters in the interactive mode.

In Fig. 3 Orbiter 50 represents a model of the Space Shuttle Orbiter which has been created using the solid surface modeler 46. Three models are depicted as being first level dependents (children) of the orbiter model: the starboard shuttle bay door 52, the port shuttle bay door 54 and the Remote Manipulator System (RMS) or shuttle robotic arm 74. The RMS 74 is analogous to the human arm in that it has an upper element which is attached to the shoulder, a lower element or "forearm" attached to the upper element at the elbow and a highly flexible wrist. The model representation of arm 74 comprises a model named swing out 56, which models the mechanical joint used in the initial linkage of the arm 74 to the orbiter 50. The "upper element" of the arm 74 comprises two models, each of which models a mechanical linkage in the upper element, the shoulder yaw 58 and the shoulder pitch 60. The lower element of the arm 74 comprises model elbow pitch 62, which is connected to model shoulder pitch 60. The elbow pitch model 62 is shown as having an elbow camera 70 mounted on the elbow pitch model. The camera 70 is linked or dependent on elbow pitch 62. Thus spatial transformations on elbow pitch 62, or any of the higher models in the structure, will effect the ultimate position of camera 70. However, camera 70 does not effect the structure of any of the models dependent on elbow pitch 62, as it represents only a viewing point and not a physical model. A wrist is located at the end of the lower element of arm 74. The wrist has three degrees of freedom: pitch, yaw and roll. The mechanical implementation of the wrist requires three separate mechanical assemblies which are reflected by the models wrist pitch 64, wrist yaw 66 and wrist roll 68. In Fig. 3, a second camera 72 is also shown as being mounted on, and therefore dependent on and linked to, wrist roll model 68. The above model structure represents the shuttle arm system without a payload. Further, two cameras are mounted on various components of the arm for selective viewing. In the preferred embodiment of the invention, the shuttle arm 74 and its component models would undergo spatial transformations to permit wrist roll 68 to come into contact with a payload (not shown). The payload would be unlinked from any dependencies that may exist between it and the orbiter 50 and a new link would be created making the payload dependent on wrist roll 68. Thereafter, movement of the payload would be dependent upon wrist roll 68 and other models within the structural hierarchy.

Fig. 4 is a block diagram of a model structure set forth in Fig. 3, demonstrating model dependencies and multiple cameras which are dependent on various models within thelinked model structure. A model structure is created by means of a "linked list." The linked list includes information which identifies each model or "cell" in the structure and identifies the cells that immediately precede (previous) or follow (next) the cell within the structure. The identification of the "next" and "previous" cell sets the dependencies for that particular cell. The linked list includes the cell information or the structural information. The linked list comprises a series of "pointers," including a "current" cell pointer, a "next" cell pointer and a "previous" cell pointer. Link list techniques are well known in computer applications.

The present invention utilizes a forest of trees which contain linked lists at various tree levels. The structural hierarchy is defined by placing the root cell or "parent" cell of a particular structure at the top of the tree. Direct descendants, or children (child cells), which are dependent on the root cell are placed at the next tree level. These children are connected to each other using a circular linked list and each "child" cell contains a pointer to it's "parent" cell and at every level there is a pointer to a lower level if these cells have children of their own. Further tree levels are defined as above. All cells at same level are connected in a circular linked list.

Referring now to Fig. 4, Orbiter 50 is shown as the "root" cell in a structural hierarchy. As it is the highest cell within the structure, it does not have a parent pointer(up arrow). Orbiter 50 has 3 first level children: starboard door 52, port door 54, and swing out 56. Thus there is one child pointer (down arrow) 500. Each of the 3 children have parent pointers (up arrows) 502, as well as, next pointers (right arrow) 504 and previous pointers (left arrow) 505 to their siblings. The swing out cell 56 contains a child pointer 506 to the shoulder yaw cell 58. This cell is a second level child of the Orbiter 50. Likewise down the tree, shoulder Yaw 58 has a child pointer 508 to shoulder pitch 60, which has a child pointer 510 to elbow pitch 62, which has a child pointer 512 to wrist pitch 64, which has a child pointer 514 to wrist yaw 66, which has a child pointer 516 to wrist roll 68. The elbow camera 70 contains a pointer 518 to the elbow pitch cell 62. Thus, movement of the elbow camera cell 70 is affected by the elbow pitch cell 62 and all of its predecessors (higher levels), but none of the elbow pitch cell's successors (lower levels). The wrist camera cell 72 is connected to the wrist roll cell 68 in a similar manner.

Fig. 5A represents the initialization file format for the structural hierarchy described in connection with Fig. 4. Lines 1 through 5 define the model for the Orbiter. Line 1 indicates the name of the model, line 4 indicates the models above it in the hierarchy (here none, "NULL" indicating it is a root cell (having no parent). Lines 6 through 10 define the next model (STARBOARD DOOR) and Line 9 indicates that STARBOARD DOOR is a child of ORBITER, likewise, as indicated by lines 14 and 19, PORT DOOR and SWING OUT, respectively, are also children of ORBITER because of their dependency thereon.

Referring now to Fig. 5B the connections or "joints" within the structural hierarchy depicted in Fig. 3 also permit movement of the component models of the RMS arm 74 relative to each other. The various joints movement hierarchies may be described specifying the various degrees of freedom for each joint. Fig 5B represents a file which would specify the movement hierarchies for the RMS arm 74 where, for example, the shoulder joint may yaw but not pitch or roll. Joint movement hierarchies may be stored as files or created and edited interactively. The degrees of freedom allowed each model correspond with the names of the various models. In Fig. 5B line 1 specifies the name of the joint system (RMS arm 74 in this case), which corresponds to the model structure defined in Fig. 3. [Line 2 corresponds to the joint movement permitted for the shoulder yaw model 58 namely, yaw only (SHY y).] Each line indicates the permitted movement of the joint --either yaw (y), pitch (p) or roll (r). Though not illustrated in Fig. 5B it should also be noted that it is possible to specify more than one joint movement parameter. Given the designation system of the present invention, a perfect ball and socket joint would permit yaw, pitch and roll joint movement. For example Fig. 5C illustrates the case where the shoulder joint may yaw (SHY y), pitch (SHY p) and roll (SHY r). In Fig. 6, a camera or viewpoint may be described in terms of its name, its position, rotation, zoom and any model dependencies. Three cameras are defined by the file in Fig. 6: the Elbow camera 70 and wrist roll camera 72 of Fig. 3, and an independent camera 78 (ICAM). Line 1 of the listing names elbow camera 70, line 2 specifies the x (0.0), y (0.0), and z (0.0) positions relative to the model to which it is linked (elbow pitch 62). However, it does have an absolute position in the workspace dependent upon the position of elbow pitch 62 and all precedent models within the model structure. Elbow camera 70, also has the ability to tilt, pan and roll relative to its mounting (all 0.0) as specified in line 3. Further, the camera can "zoom" up or down on (apparent extention or compression of) the object being viewed. The degree of zoom is specified in line 4 (1.0). Lastly, line 5 indicates that elbow camera 70 is linked to, and dependent on, model elbow pitch 62. Lines 6 through 10 define a similar structure for wrist camera 72. For example, line 7 specifies that wrist camera 72 is mounted 0.0 feet in the x direction, 0.0 feet in the y direction, and 1.0 feet in the z direction relative to the wrist roll model 68. As defined in lines 11 through 15, camera ICAM is an independent camera, as it has no dependency ("null", line 15). Further, ICAM has an x, y, and z position, line 12, (in this case an absolute position); it has a roll of 20.0 degrees (20.0), but no pan (0.0) or tilt (0.0), line 13; and zoom, line 14; relative to the workspace coordinate axes. The method of the present invention includes means by which model structures may be selectively created, deleted, or moved. It is this capability that permits the method of the present invention to link models and create joint systems interactively or in response to a command file without the necessity of substituting models to represent the combined model.

Figure 7A is a flow diagram which represents the means by which new links are created. In step 100 a new model to be created is specified. In step 102 the new model's spatial transformations and "link" or "parent" are specified. If the model is to be independent of the rest of the models in the forest of trees, step 104, the new cell is added as a new root in the current forest, step 106. If not, the forest of trees is then searched, step 110, for the parent model. If the parent does not currently exist in the forest, step 112, the cell is added as a new root in the forest, step 114. Otherwise, in step 118, the cell is added as the first child of its parent. This is accomplished as illustrated in Fig. 7B through 7G. Assume that the Orbiter 50 has only two children, the Port Door 54 and the Starboard Door 52 (Fig. 7B), and it is desired to add the Swing Out 56 as another child of the Orbiter, Fig. 7C. Set the new child (Swing Out) next pointer 601 to the existing first child (Port Door), Fig. 7D; set the existing first child (Port Door) previous pointer 603 to the new child, Fig. 7E; set the last child (Starboard Door) next pointer 605 to the new child and set the new child previous pointer 606 to the last child (Starboard Door) Fig. 7F; set the parent (Orbiter) child pointer 607 to the new child and set the new child parent pointer 609 to the parent (Orbiter), Fig. 7G.

Figure 8A is a flow diagram which represents the manner in which the present system deletes one model or cell in a structural hierarchy. In step 160, the model to be deleted is specified. Step 162 checks to see if the specified model exists. If the model exists, step 166 checks to see if the model has children. If the model has no children the model is deleted; for example, by resetting the previous cell's next pointer to the cell's next pointer and resetting the previous cell's previous pointer to the cell's previous pointer in step 168. The memory which was used to store the cell is deleted in step 170. If the model has children the children are relinked into the data structure as roots of trees in the forest. This is done in steps 174 through 180.

The new spatial transformations for the children of the removed cell are computed in the function described by Figure 8B. Step 182 checks to see if there is to be a new parent for the child. If there is no new parent, as is the case with cell deletion, the current position and attitude of the child is computed using matrix multiplications of the spatial transformations from the root of the tree in which the child resides down to the child. The resulting transformation matrix is then decomposed into the position and attitude for the child. This is done in steps 184 through 190. If there is a new parent, step 192 checks to see if the child has a current parent. If there is no current parent, step 194 computes a reverse transformation matrix for the child model by using matrix multiplies from the new parent up to the root of the corresponding tree. This matrix is then decomposed in step 196 and the new transformations are stored into the model structure in step 198. If there is a new parent, step 202 computes the current position and attitude for the child in the same manner as step 184, and then computes the new position for the child in the same manner as step 194. Again the matrix is decomposed in step 206 and the information stored into the child cell in step 208.

Figure 9 is a flow diagram of the routine used to change the parent of a given model. In step 240 the name of the new parent is input. Step 242 checks the current tree to make sure that the new parent is not a child of the current model. If the parent is a child of the current model, step 244 prints an error message and returns, If the new parent is not a child of the current model, steps 182-210, Figure 8B are called and the new link position is computed in step 248. In step 250 the new parent model adds the current model to its child list and the child sets its parent pointer to the new parent model.

The simulation of motion of three dimensional models for a two dimensional presentation, by means of geometric transformations of the models is well known in the field of computer graphics. Reference can be made to the text "Principles of Interactive Computer Graphics," as well as U.S. Patent No. 4,600,919, relevant portions of which are incorporated herein by reference. In a similar fashion, the present invention utilizes matrix transformations to model motion in a multi-model structure.

The position of body in space can be described in terms of a universal coordinate system. However, the body itself has a local coordinate system. Further, the body can be referenced in terms of a viewing position or camera coordinate system. The description of motion of a body with respect to a universal, local or camera coordinate system is well described in the above text and patents. What follows is a brief description of the techniques used to simulate motion when motion vector is applied to a selected model within a particular structure. The movement of a point within the selected model can be expressed in terms of the matrix transformation:

$$[x'\ y'\ z'\ 1] = [x\ y\ z\ 1] \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ m_x & m_y & m_z & 1 \end{vmatrix}$$

where $m_x$, $m_y$, $m_z$ represent the motion vector applied to the model; x, y, z the initial model coordinates; and x', y', z' the resultant coordinates. Similarly, rotation about a particular axis may be achieved using the transformation.

The following transformation represents new position of which has undergone a rotation about the z-axis (roll) of degrees:

$$[x'\ y'\ z'\ 1] = [x\ y\ z\ 1] \begin{vmatrix} \cos & -\sin & 0 & 0 \\ \sin & \cos & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

A scaling transformation matrix is also used to represent any "compression" or "extension" of a model which represents an apparent compression or extension of the model during movement with respect to the local coordinate system. Where there is no compression or extension, the scaling factors are set to a unitary value. Accordingly, the scaling transformation used to scale dimensions with respect to local coordinate systems is represented by the following matrix transformation:

$$[x' \; y' \; z' \; 1] = [x \; y \; z \; 1] \begin{vmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

The transformation matrix [N] which represents the total movement of the three dimensional object as viewed in a two dimensional frame may be represented by the multiplication of the matrices representing translation [T], rotation [R] and scaling [S]. Thus, the total transformation matrix for the movement of a single model may be represented as follows:

$$[N] = [T]\,[R]\,[S]$$

The above matrices represent the composite transformation for a single model body. The present invention utilizes multiple models in creating a simulated system. Thus, where motion has been induced for any single model within a hierarchical structure, its transformation affects the presentation of other models lower in the hierarchical structure. Where motion has been introduced in a model within a structure, the above transformation matrices may be determined for each lower model in the structure. Accordingly, transformation of an entire system in universal coordinates may be expressed as a concatenation of the transformation matrices for all of the models in the structure:

$$[N_0] = [N_1]\,[N_2]\,[N_3]\ldots[N_n]$$

One other consideration is the viewpoint from which the system is to be viewed. A composite viewing transformation, with translational, rotational and scaling matrices similar to the above matrices for models, [V] = [T] [R] [S], may be used to express camera position. in the present invention, the camera may exist as an adjunct to the model structure. Therefore, the camera composite matrix would include the transformation of higher structure models, including the one to which it is linked. Where the camera exists as an independent viewpoint, its composite transformation matrix is not dependent upon the model structure. As pointed out in the previously referenced text, given a known viewing translation, for either a dependant or independent camera, a two dimensional representation of the model may be determined by the transformation:

$$[x_c, y_c, z_c, w_c] = [x_u, y_u, z_u, 1] [V]$$

where, subscript c refers to the camera coordinate system and subscript u refers to the universal coordinate system. The term $w_c$ refers to a homogeneous coordinate used to convert the apparent $x_c$ and $y_c$ coordinates into two dimensional x, y coordinates for display and recordation by the present invention.

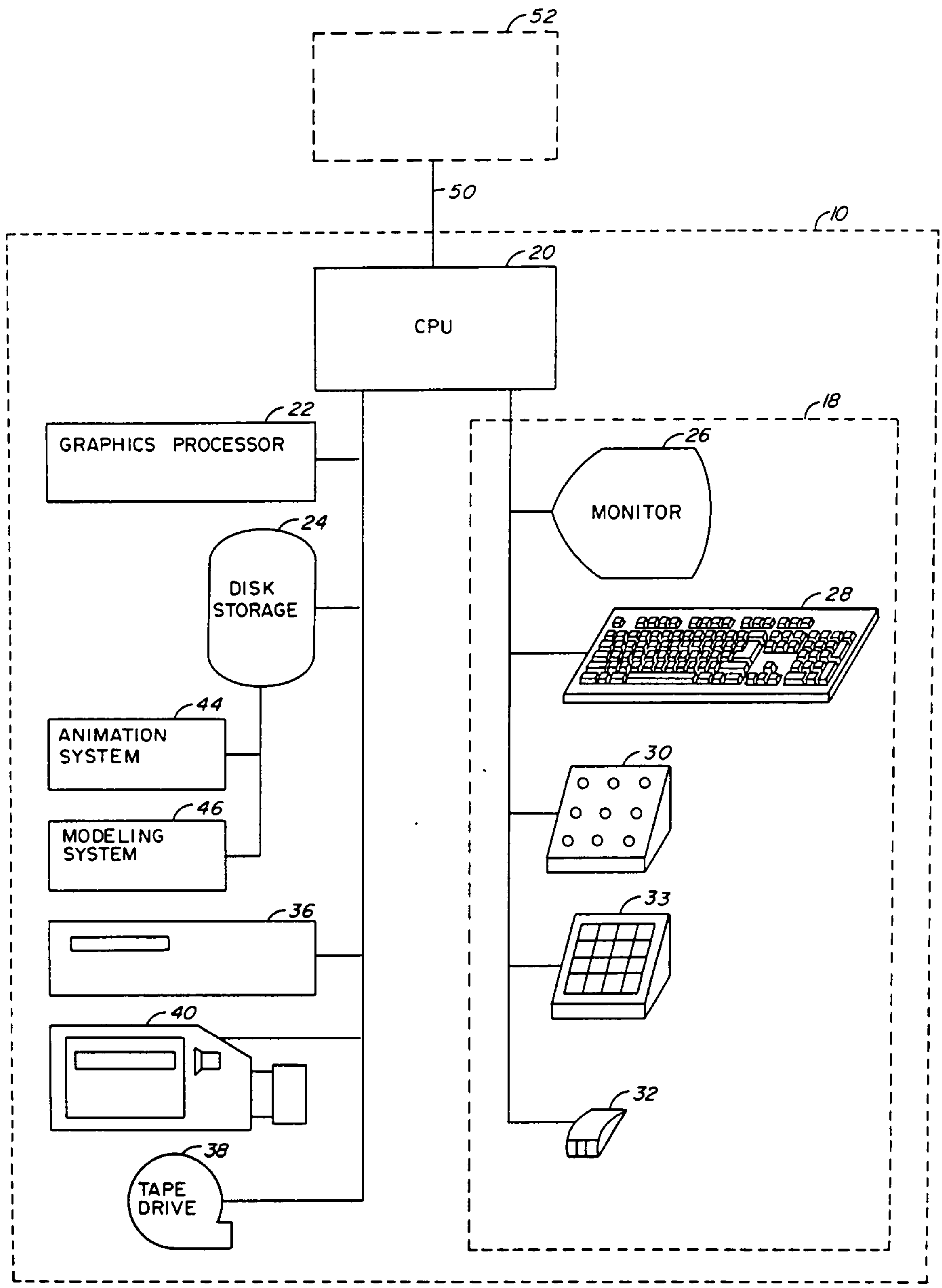
The present invention as described above provides a means of selectively creating model structures and hierarchies without having to substitute combined models for individual models within the structure. It will be appreciated that the invention results in an increase in efficiency in creating animated sequences which accurately depict kinematic motion of linked structures.

The invention has been described with reference to a particular embodiment. although different embodiments of the invention may vary in detail, they are still intended to be within the scope of the inventive concept described above. The details described in the foregoing preferred embodiments are intended to be illustrative and not limiting in any sense.

# GENERATION OF ANIMATION SEQUENCES OF THREE DIMENSIONAL MODELS

## ABSTRACT

The invention is directed toward a method and apparatus (10) for generating an animated sequence through the movement of three dimensional graphical models. A plurality of pre-defined graphical models are stored and manipulated in response to interactive commands or by means of a pre-defined command file (38). The models may be combined as part of a hierarchical structure to represent physical systems without need to create a separate model which represents the combined system. System motion is simulated through the introduction of translation, rotation and scaling parameters upon a model within the system. The motion is then transmitted down through the system hierarchy of models in accordance with hierarchical definitions and joint movement limitations. The present invention also calls for a method of editing hierarchical structure in response to interactive commands or a command file such that a model may be included, deleted, copied or moved within multiple system model hierarchies. The present invention also calls for the definition of multiple viewpoints or "cameras" which may exist as part of a system hierarchy or as an independent camera. The simulated movement of the models and systems is graphically displayed on a monitor (26) and a frame is recorded by means of a video controller (40). Multiple movement and hierarchy manipulations are then recorded as a sequence of frames which may be played back as an animation sequence on a video cassette recorder (36).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50
10
20
CPU
22
GRAPHICS PROCESSOR
18
26
MONITOR
24
DISK
STORAGE
28
44
ANIMATION
SYSTEM
30
46
MODELING
SYSTEM
33
36
40
32
38
TAPE
DRIVE

FIG. 1

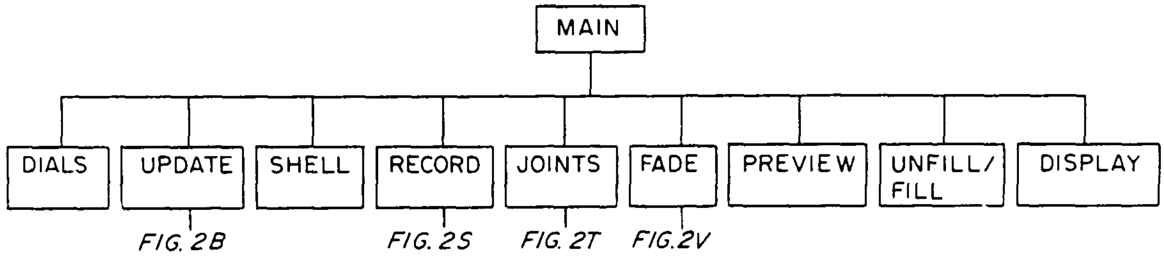



FIG. 2A

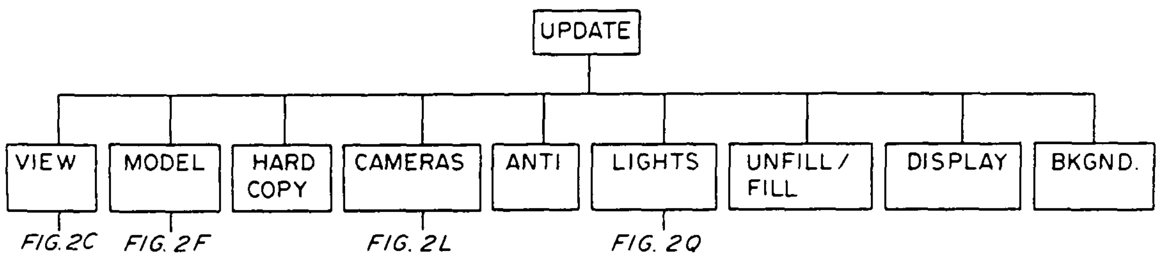



FIG. 2B

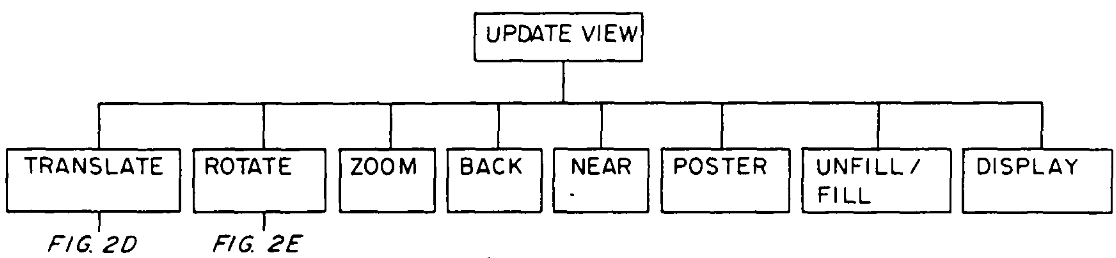



FIG. 2C

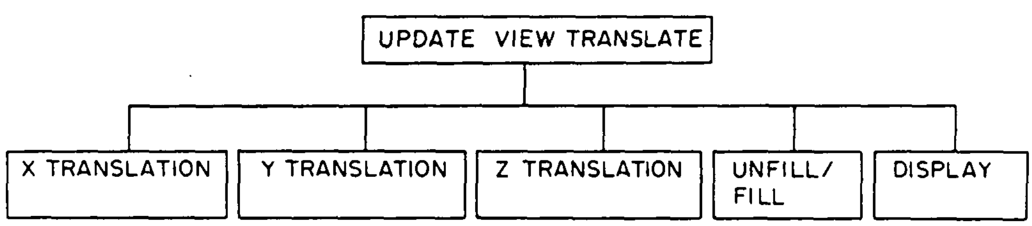



FIG. 2D

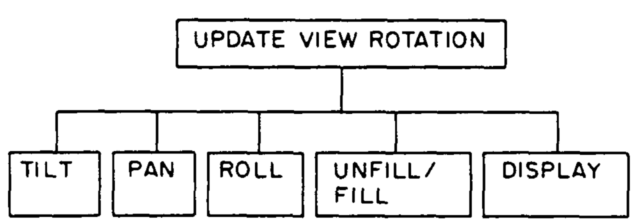



FIG. 2E

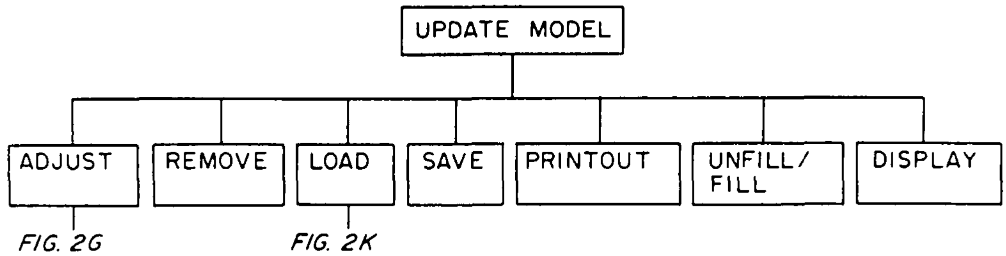



FIG. 2F

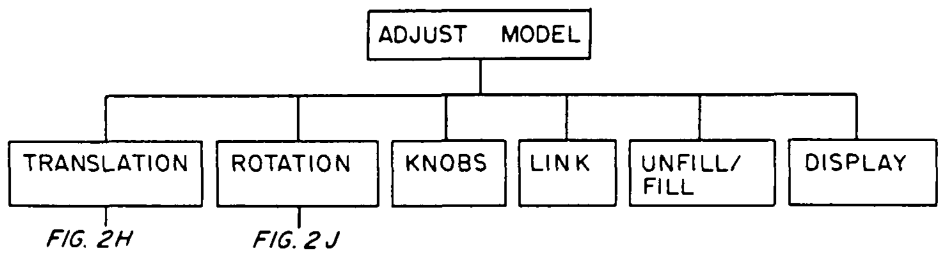



FIG. 2G

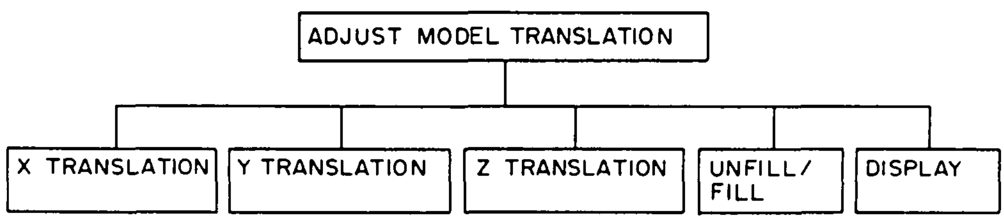



FIG. 2H

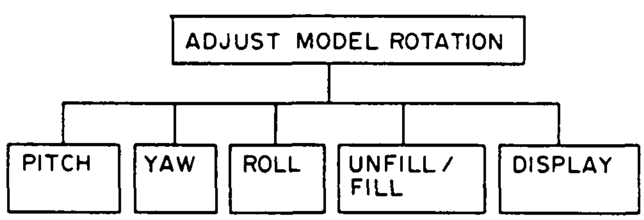



FIG. 2J

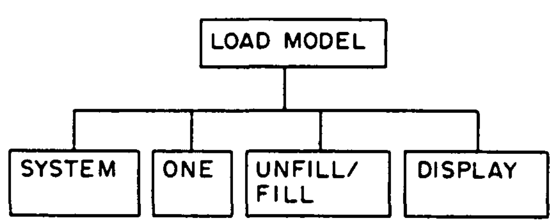



FIG 2K

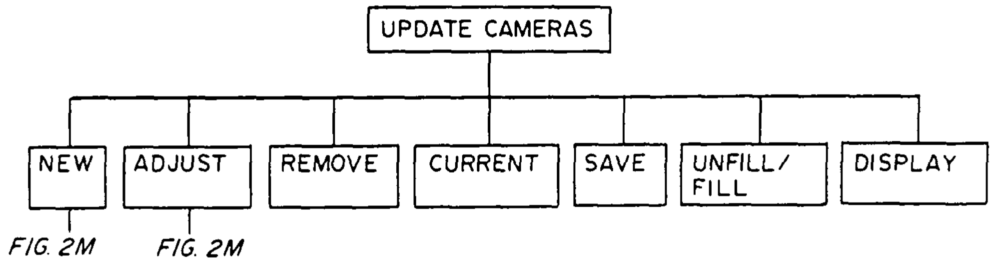



FIG. 2L

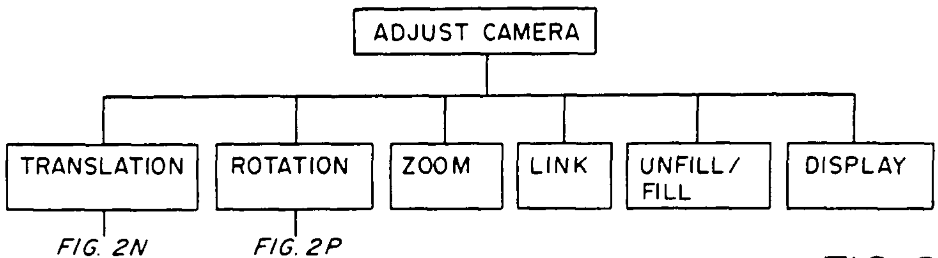



FIG. 2M

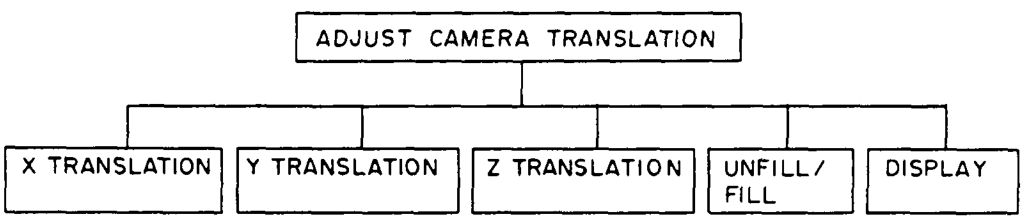



FIG. 2N

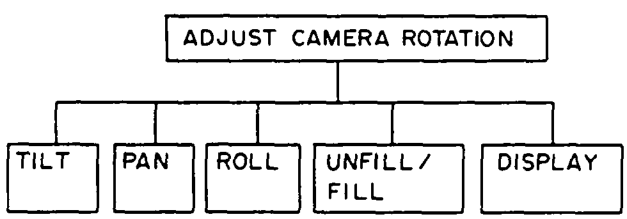



FIG. 2P

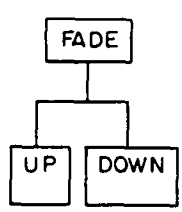



FIG. 2V

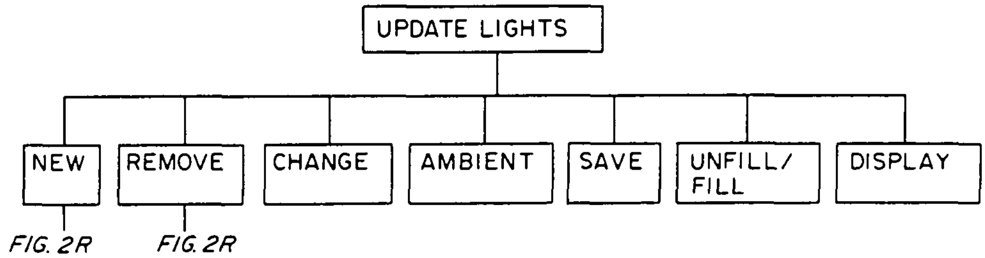



FIG. 2Q

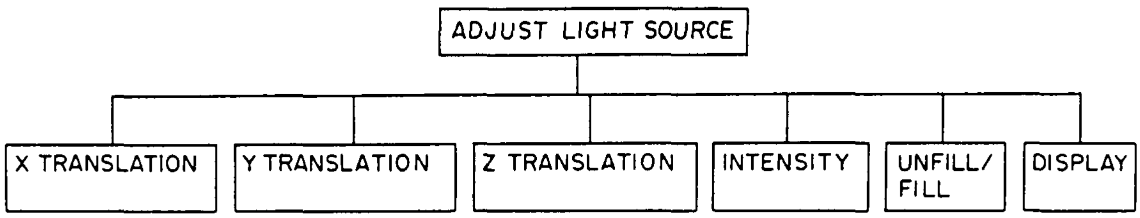



FIG. 2R

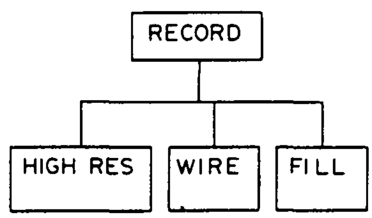



FIG. 2S

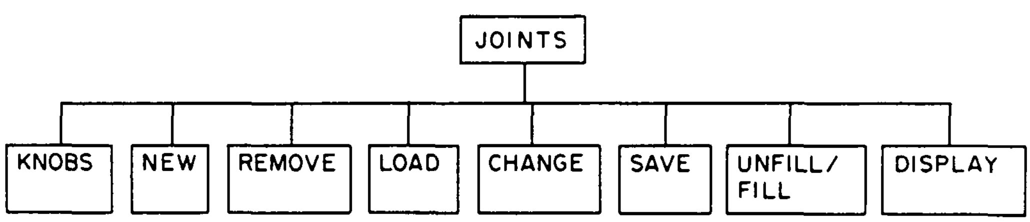



FIG. 2T

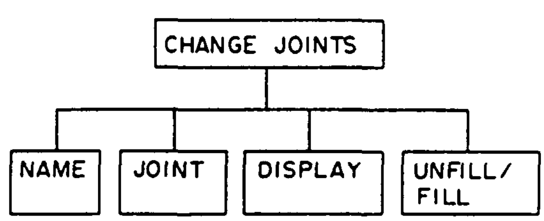



FIG. 2U

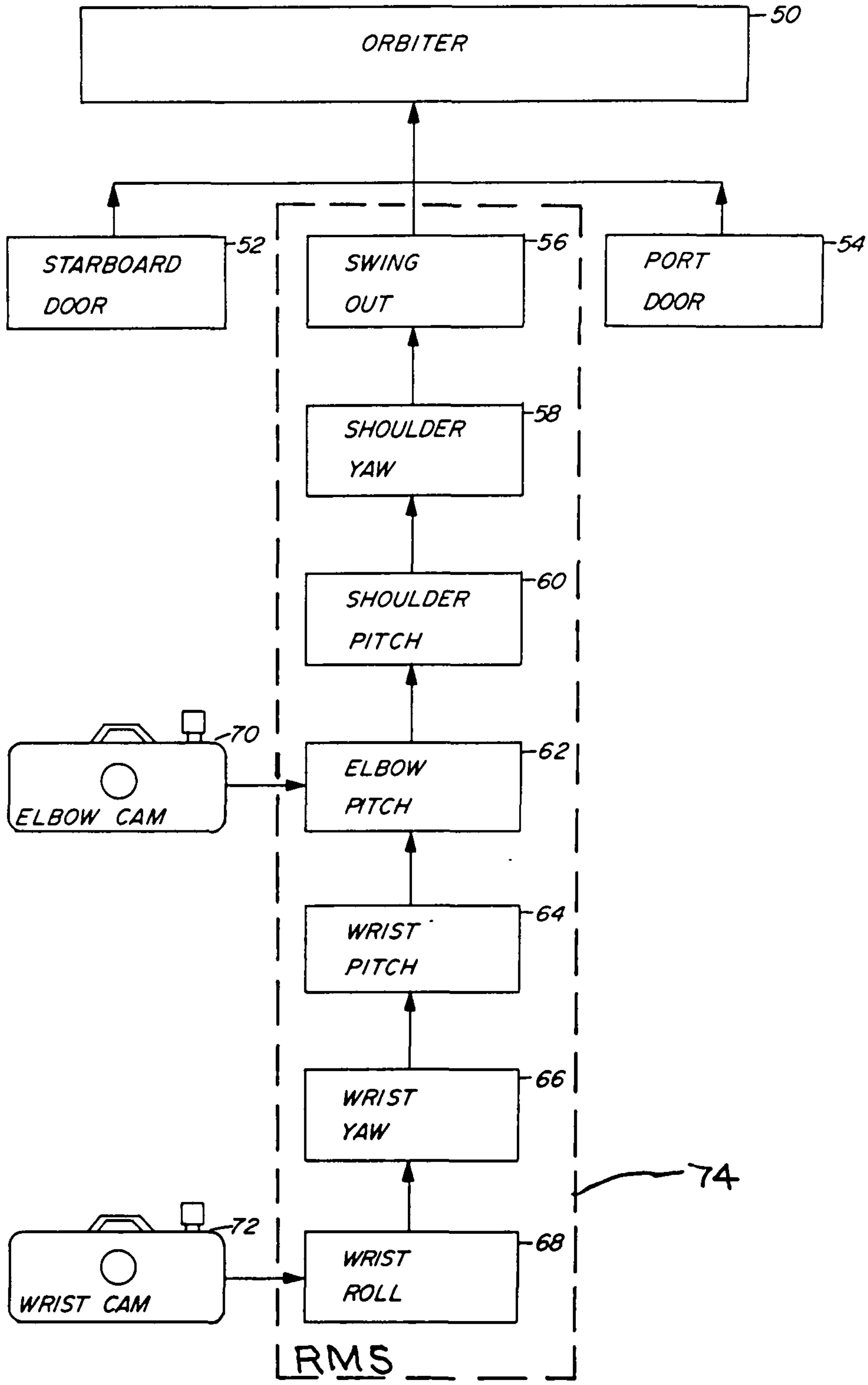
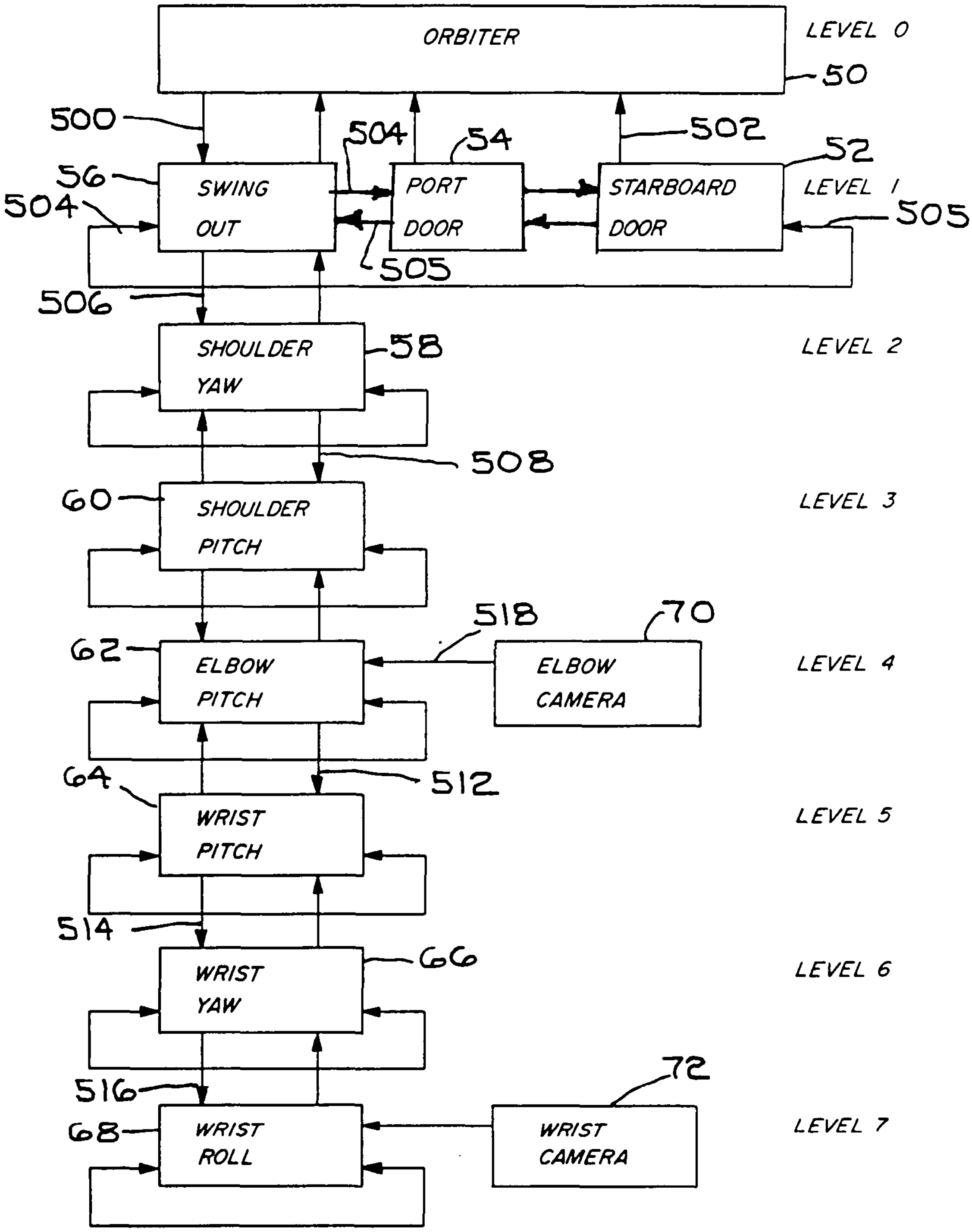

ORBITER
50
STARBOARD DOOR
52
SWING OUT
56
PORT DOOR
54
SHOULDER YAW
58
SHOULDER PITCH
60
ELBOW CAM
70
ELBOW PITCH
62
WRIST PITCH
64
WRIST YAW
66
74
WRIST CAM
72
WRIST ROLL
68
RMS

FIG. 3



ORBITER
LEVEL 0
50
500
502
504
54
52
56
SWING OUT
PORT DOOR
STARBOARD DOOR
LEVEL 1
504
505
505
506
SHOULDER YAW
58
LEVEL 2
508
60
SHOULDER PITCH
LEVEL 3
518
70
62
ELBOW PITCH
ELBOW CAMERA
LEVEL 4
64
512
WRIST PITCH
LEVEL 5
514
WRIST YAW
66
LEVEL 6
72
516
68
WRIST ROLL
WRIST CAMERA
LEVEL 7


FIG. 4

| | |
|---|---|
| ORBITER | NAME OF MODEL |
| 0.00.00.0 | TRANSLATION ALONG THE X,Y,& Z AXIS |
| 0.00.00.0 | ROTATION ABOUT THE PITCH, YAW AND ROLL AXIS |
| NULL | NAME OF REFERENCE MODEL (DEPENDENCY) |
| TPYR | ORDER OF ROTATIONS AND TRANSLATIONS |
| STARBOARD DOOR | |
| 0.00.00.0 | |
| 0.00.00.0 | DEFINITION OF NEXT MODEL |
| ORBITER | |
| TPYR | |
| PORT DOOR | |
| 0.00.00.0 | |
| 0.00.00.0 | |
| ORBITER | |
| TPYR | |
| SWING OUT | |
| 0.00.00.0 | |
| 0.00.00.0 | |
| ORBITER | |
| TPYR | |
| SHOULDER YAW | |
| 0.00.00.0 | |
| 0.00.00.0 | |
| SWING OUT | |
| TPYR | |
| SHOULDER PITCH | |
| 0.00.00.0 | |
| 0.00.00.0 | |
| SHOULDER YAW | |
| TPYR | |
| ELBOW PITCH | |
| 0.00.00.0 | |
| 0.00.00.0 | |
| SHOULDER PITCH | |
| TPYR | |
| WRIST PITCH | |
| 0.00.00.0 | |
| 0.00.00.0 | |
| ELBOW PITCH | |
| TPYR | |
| WRIST YAW | |
| 0.00.00.0 | |
| 0.00.00.0 | |
| WRIST PITCH | |
| TPYR | |
| WRIST ROLL | |
| 0.00.00.0 | |
| 0.00.00.0 | |
| WRIST YAW | |
| DONE | END OF FILE |

*FIG. 5A*

| | | | |
|---|---|---|---|
| 1 | -RMS-1 | | (The name of the joint system) |
| 2 | SHY | y | (Shoulder yaw with a rotation of yaw) |
| 3 | ELP | p | (Elbow pitch with a rotation of pitch) |
| 4 | WRP | p | (Wrist pitch with a rotation of pitch) |
| 5 | WRY | y | (Wrist yaw with a rotation of yaw) |
| 6 | WRR1 | r | (Wrist roll with rotation of roll) |
| 7 | DONE | | |

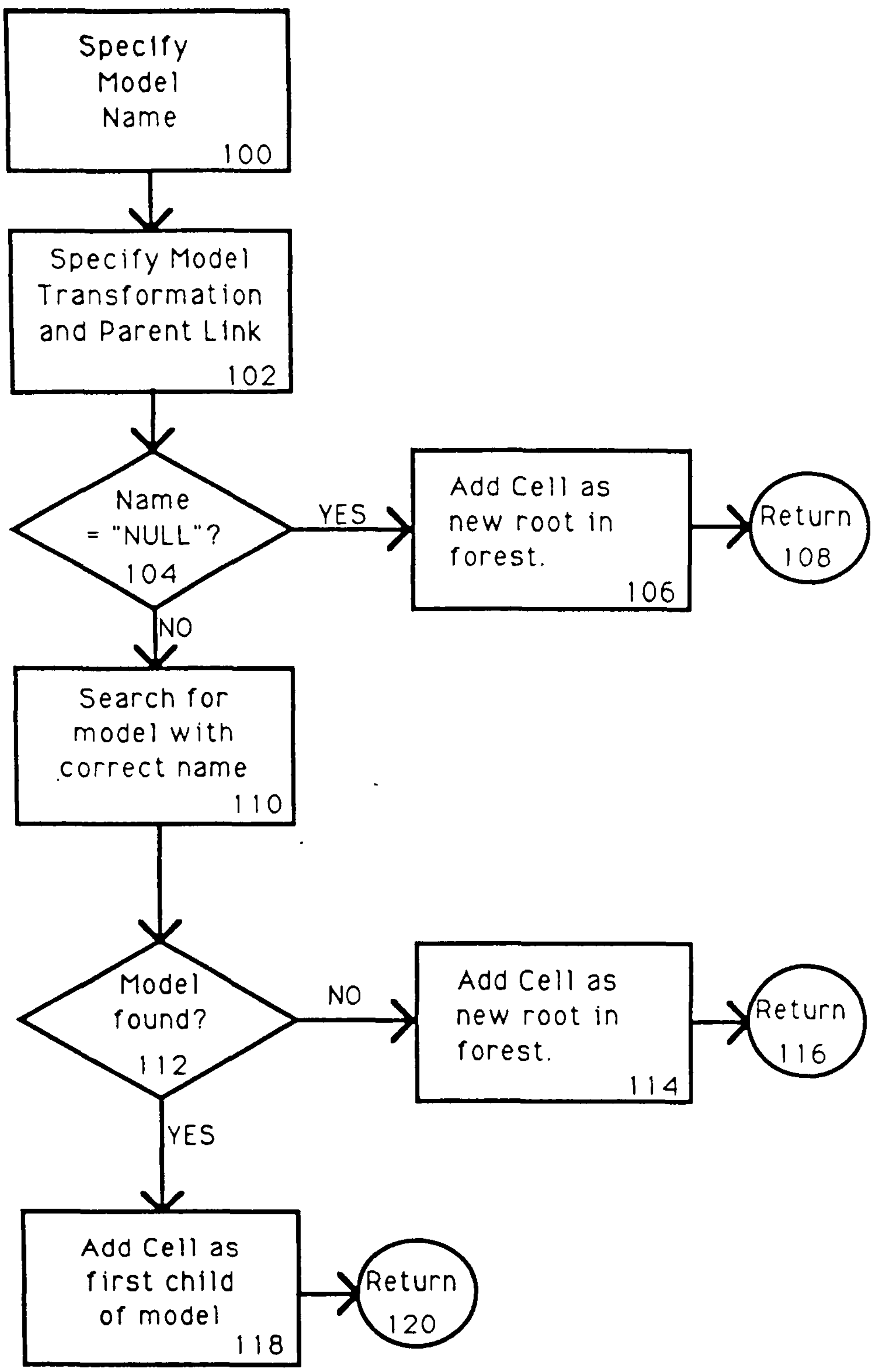
FIGURE 5B

| | | |
|---|---|---|
| 1 | -RMS-2 | |
| 2 | SHY | y |
| 3 | SHY | p |
| 4 | SHY | r |
| 5 | SHP | p |
| 6 | ELP | p |
| . | . | . |
| . | . | . |
| . | . | . |
| . | DONE | |

FIGURE 5C

| | | |
|---|---|---|
| 1 | ELBOW CAM | (Name of model) |
| 2 | 0.0 0.0 0.0 | (position) |
| 3 | 0.0 0.0 0.0 | (tilt, pan, roll) |
| 4 | 1.0 | (degree of zoom) |
| 5 | ELBOW PITCH | (model dependency) |
| 6 | WRIST CAM | (name of next model |
| 7 | 0.0 0.0 1.0 | |
| 8 | 0.0 0.0 0.0 | |
| 9 | 1.0 | |
| 10 | WRIST ROLL | |
| 11 | ICAM | |
| 12 | 32.5 12.7 017.59 | |
| 13 | 20.0 0.0 0.0 | |
| 14 | 2.0 | |
| 15 | NULL | |

FIGURE 6



Specify Model Name
100
Specify Model Transformation and Parent Link
102
Name = "NULL"?
104
YES
Add Cell as new root in forest.
106
Return
108
NO
Search for model with correct name
110
Model found?
112
NO
Add Cell as new root in forest.
114
Return
116
YES
Add Cell as first child of model
118
Return
120


Figure 7A

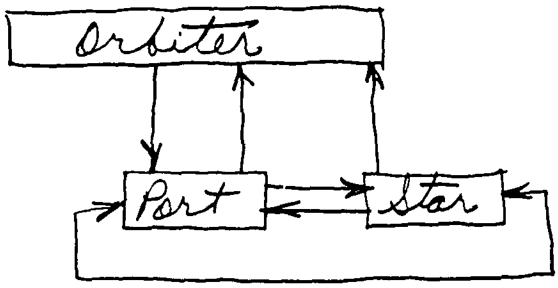


FIGURE 7B

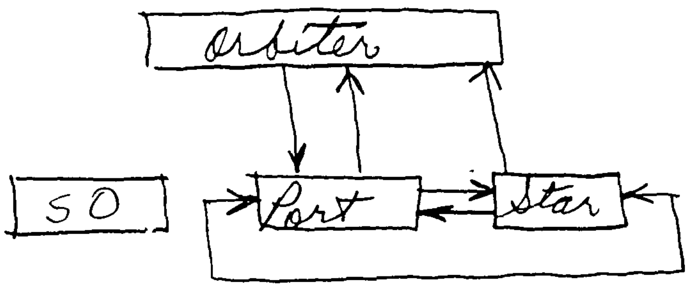


FIGURE 7C

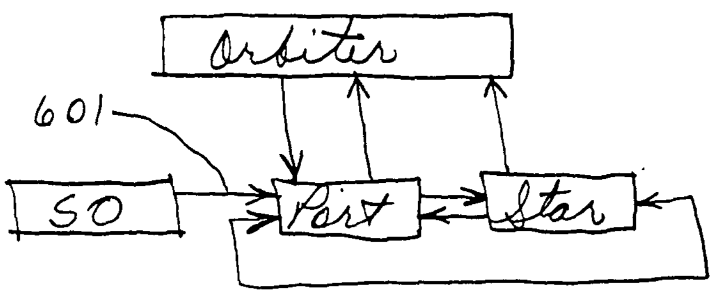


FIGURE 7D

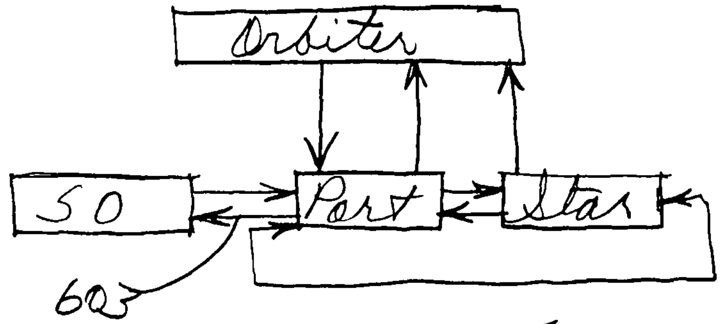



FIGURE 7E

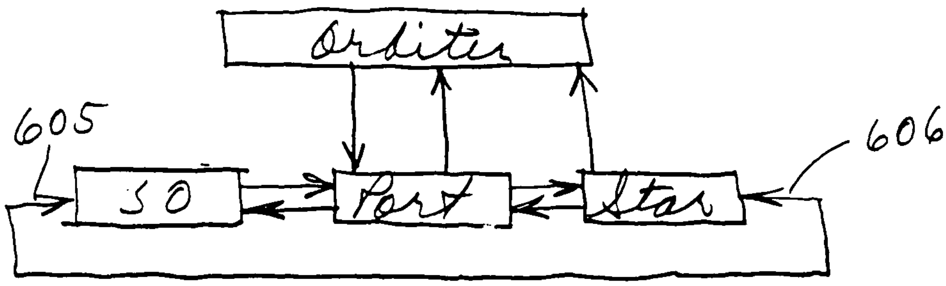



FIGURE 7F

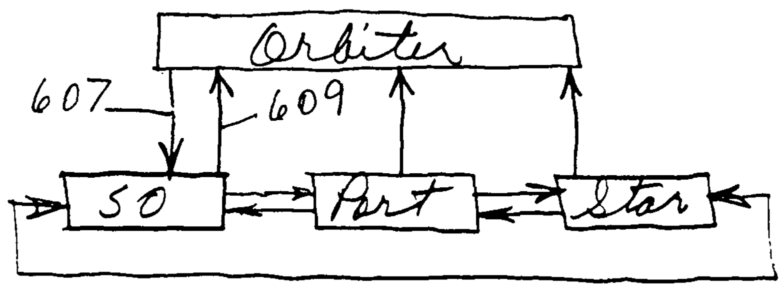



FIGURE 7G

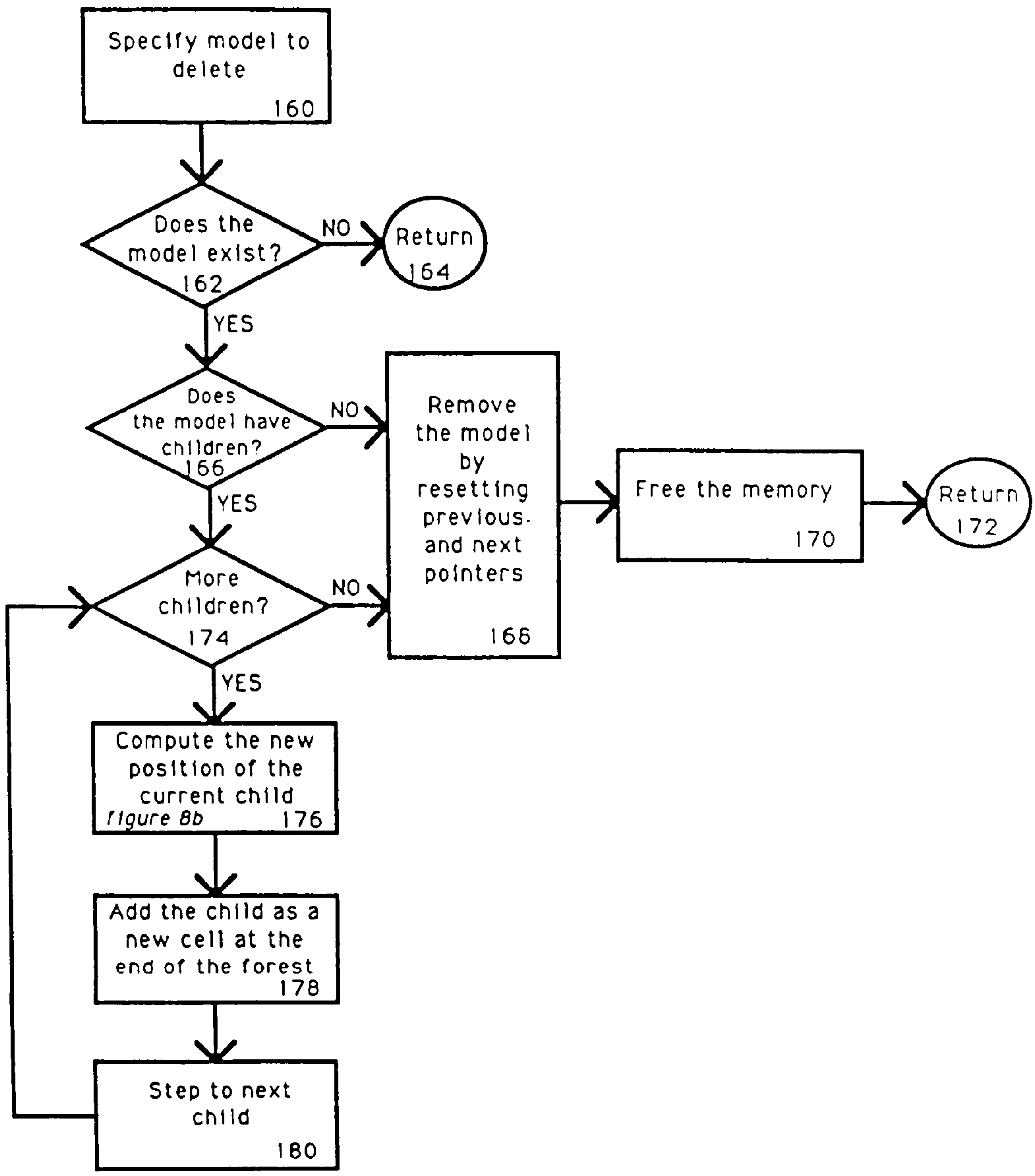

Specify model to delete
160
Does the model exist?
162
NO
Return
164
YES
Does the model have children?
166
NO
Remove the model by resetting previous. and next pointers
168
Free the memory
170
Return
172
YES
More children?
174
NO
YES
Compute the new position of the current child
figure 8b
176
Add the child as a new cell at the end of the forest
178
Step to next child
180

Figure 8A

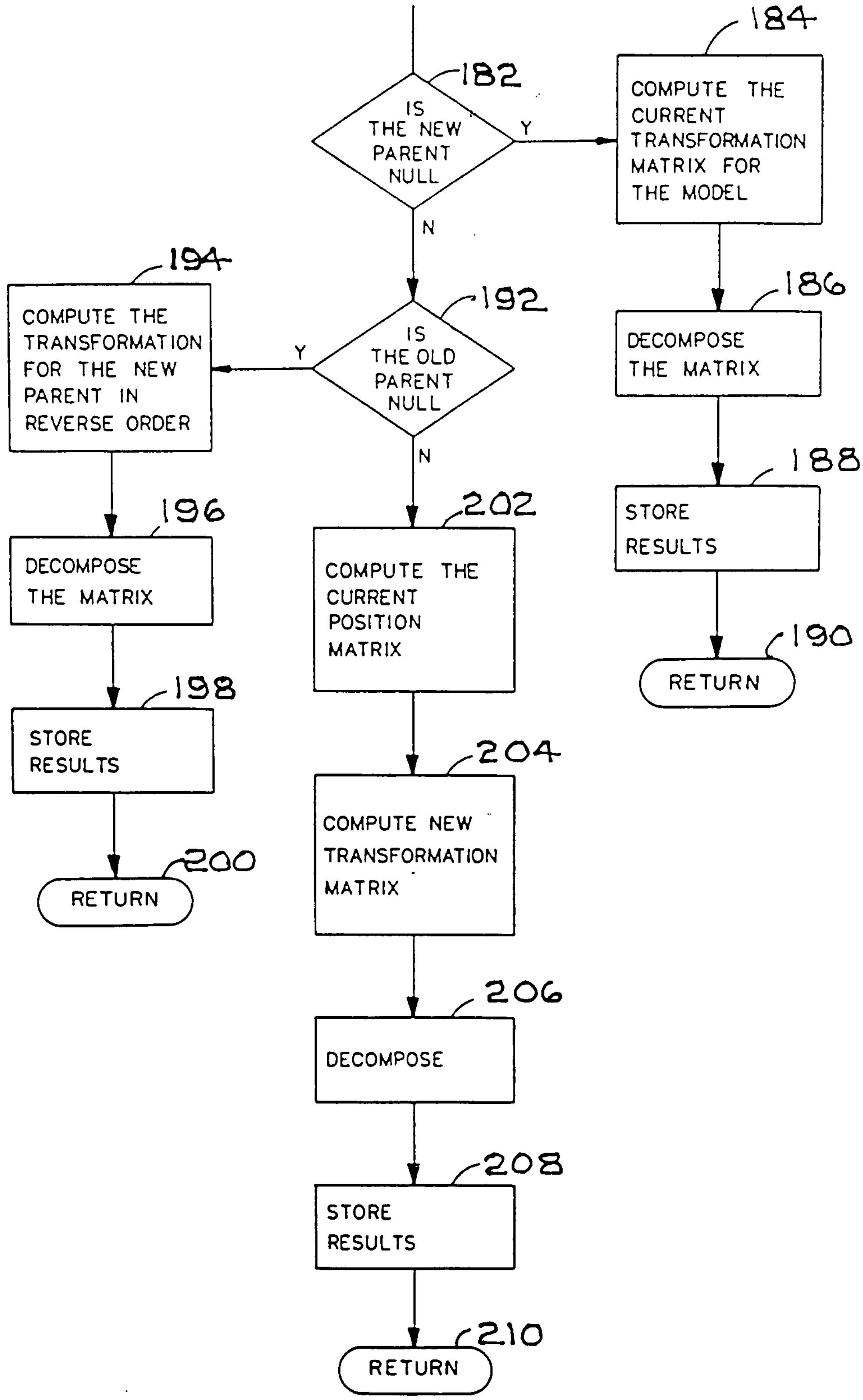
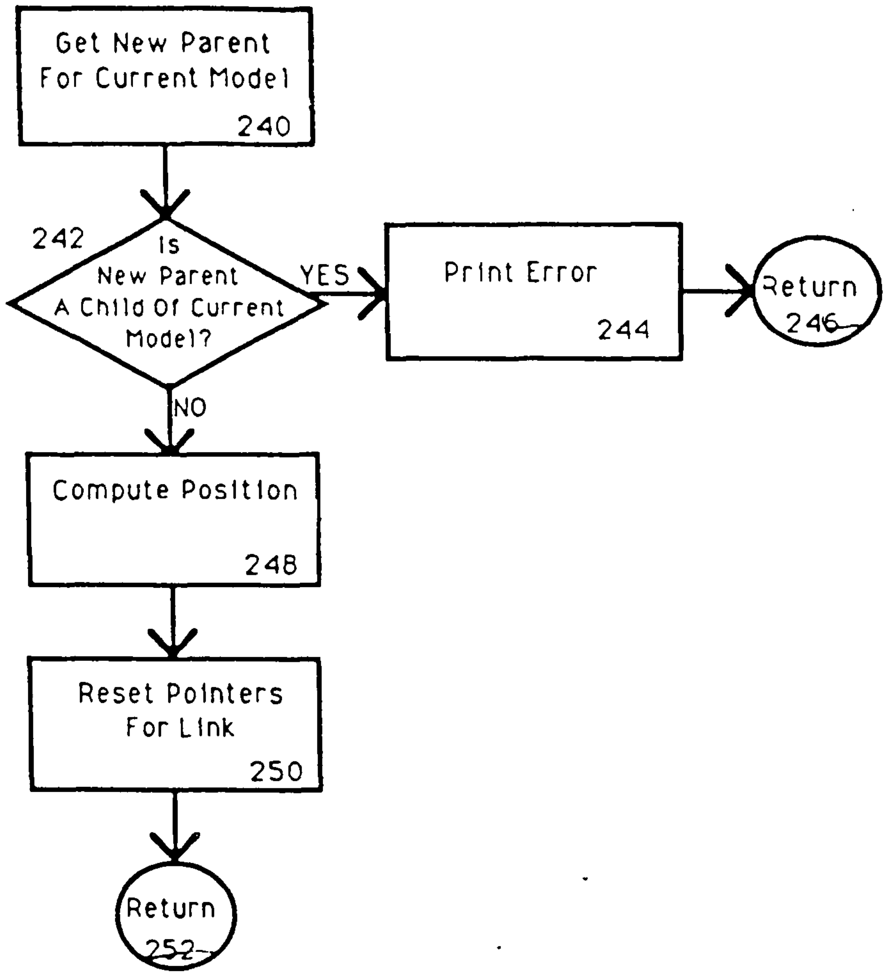

182
IS THE NEW PARENT NULL
Y
N
184
COMPUTE THE CURRENT TRANSFORMATION MATRIX FOR THE MODEL
186
DECOMPOSE THE MATRIX
188
STORE RESULTS
190
RETURN
192
IS THE OLD PARENT NULL
Y
N
194
COMPUTE THE TRANSFORMATION FOR THE NEW PARENT IN REVERSE ORDER
196
DECOMPOSE THE MATRIX
198
STORE RESULTS
200
RETURN
202
COMPUTE THE CURRENT POSITION MATRIX
204
COMPUTE NEW TRANSFORMATION MATRIX
206
DECOMPOSE
208
STORE RESULTS
210
RETURN

FIGURE 8B



Get New Parent For Current Model
240
242
Is New Parent A Child Of Current Model?
YES
NO
Print Error
244
Return
246
Compute Position
248
Reset Pointers For Link
250
Return
252


Figure 9