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A Human Body Modelling System for Motion Studies

Norman I. Badler
University of Pennsylvania, badler@seas.upenn.edu

Joseph O'Rourke

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Norman I. Badler

Joseph O'Rourke

Department of Computer and Information Science
Moore School of Electrical Engineering
University of Pennsylvania
Philadelphia, PA 19104

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A Human Body Modelling System
For Motion Studies

Norman I. Badler, Assistant Professor
Joseph O'Rourke, Research Assistant

Department of Computer and Information Science
Moore School of Electrical Engineering
University of Pennsylvania, Philadelphia, PA 19104

Abstract

The need to visualize and interpret human body movement data from experiments and simulations has led to the development of a new, computerized, three-dimensional representation for the human body. Based on a skeleton of joints and segments, the model is manipulated by specifying joint positions with respect to arbitrary frames of reference. The external form is modelled as the union of overlapping spheres which define the surface of each segment. The properties of the segment and sphere model include: an ability to utilize any connected portion of the body in order to examine selected movements without computing movements of undesired parts, a naming mechanism for describing parts within a segment, and a collision detection algorithm for finding contacts or illegal intersections of the body with itself or other objects. One of the most attractive features of this model is the simple hidden surface removal algorithm. Since spheres always project onto a plane as disks, a solid, shaded, realistically-formed raster display of the model can be efficiently generated by a simple overlaying of the disks from the backmost to the frontmost. A three-dimensional animated display on a line-drawing device is based on drawing circles. Examples of the three-dimensional figure as viewed on these different display media are presented. The flexibility of the representation is enhanced by a method for decomposing an object into spheres, given one or more of its cross-sections, so that the data input problem is significantly simplified, should other models be desired. Using data from existing simulation programs, movements of the model have been computed and displayed, yielding very satisfactory results. Various transportation related applications are proposed.

I. Introduction

There are numerous computer programs for the analysis or simulation of human movement in various vehicular environments (for example, 1, 2, 3, 4), but perhaps the only common feature of all these systems is that they produce movement data to manipulate some skeletal model of the human body. While conventional charts and graphs can be used to diagram movements of individual body parts, it is our view that only by observing the entire movement of the body can experimental results be integrated with simulation studies. Such a process requires that the program output be used to animate a realistically formed and jointed human body model. Animations are essential whenever the mass of data collected or generated is too great to assimilate piecemeal, or when the complexity of the movements under study leads to visualization difficulties in a two-dimensional graph. We are concerned with fully general three-dimensional motion of the body, and although data reduction is a desirable side effect of the animation process and our graphic displays are themselves two-dimensional, our primary goal is the efficient and effective generation of a realistic, three-dimensional animation to facilitate movement interpretation. Dissatisfaction with existing body models and stick figure displays led to our development of a new human model for the computer with certain distinct advantages in display realism, movement definition, collision detection and cost-effectiveness in a real-time animation playback environment.

Our original motivation to develop a human body model came not from product engineering considerations, but as a tool with which to investigate human movement itself. Working under National Science Foundation grants to examine techniques for the representation of movement information in a computer, we were led to interaction with professional movement analyists, recorders (notators), and performers. These people were primarily interested in a human body animation as a visualization of notated movement, in both a verification mode and a demonstration or tutorial mode (5). In either case, the constraints which arose from discussions on the form and movement of the body took the following forms:

- The three-dimensionality of the body, both in space and in substance, must be unquestionnable.
- The movements would have to be displayed in real-time for teaching purposes, although slower rates were acceptable for verification of notated movements.
- The model would be positioned with respect to any rectangular coordinate system and, in particular, any body part could be treated as a reference segment from which other movements are computed.
- Any connected subset of the body could be animated, that is, the movements could be observed in a "logical window" of body parts and not even computed for others out of the set.

- The presence of environment objects as well as other people must be allowed.
- Collision detection should be simple and should return concise information on the location of any interference or contacts.

The first and last conditions especially preclude the use of stick-figure models since the surfaces of the body are extremely important in movement interpretation and collision detection.

Besides these criteria we imposed our own graphical design consideration:

- The display generation process should be as device-independent as possible, yet support a variety of different graphic displays.

In particular, we were interested in output to video raster devices as well as line-drawing refresh CRT's. Moreover, the efficiency of the display algorithms should not be undermined by this flexibility. We feel that we have achieved this goal with our model; indeed it is the first proposed for a raster device that promises to be suitable for low cost graphic display hardware. Each of these points will be addressed in the following sections. After some discussion on existing or potential models based on various object representation schemes, we will describe our model and how it can be used, among other things, to generate different visual displays, name particular body parts and surfaces, and locate collisions. Various transportation applications are then discussed or proposed.

II. Modelling Schemes

Representing the form of the human body with computer data structures is not a simple task. A variety of models are in use and a slightly larger set of possible representation structures are presently available, but each has certain faults to balance its advantages. Our model fits this description, too, but we intend to show that whatever disadvantages it has are certainly less severe than those of the others.

We can categorize the schemes for modelling complex three-dimensional objects into two broad groups, then further divide these into specific representations based on different primitives:

I. Surface representations
    A. Planar polygon surface patches
    B. Curved surface patches
        (bicubic or other mathematical formulations)
II. Volumetric representations
    A. Polyhedral decomposition
    B. Object algebras
    C. Cylinders
    D. Ellipsoids
    E. Spheres

A surface representation is a partition by a number of primitive patches, that is, the surface must be covered completely and in a non-overlapping fashion. In a volumetric representation, on the other hand, the surface is approximated by the visible portions of primitive solid objects which may arbitrarily overlap and combine.

A planar polygonal description is used in two human models by Fetter (6, 7), one having 300 vertices, the other, 3000. Subsets of the body have been digitized for animation by Parke (8, 9). The advantages of planar polygons are their ability to model small detail and the ease of display of the edge network by line-drawing devices. Outweighing these factors, however, are the facts that a very large number of such polygons would be required to model the human body, hidden line removal or surface shading is expensive and perhaps most importantly, joint movements deform the surface in unrealistic ways. For example, in a film of finger flexion in a polygon-surface hand (10), the fingers become thinner as they bend. No provision is made in the graphical data structure to modify the planar vertices as the movements are executed, and specification of the appropriately interpolated transformations which might provide each vertex with a realistic movement would be non-trivial.

Representing curved surfaces by a partition into bicubic or other mathematical curve patches (11, 12, 13) solves some of the problems posed by polygonal patches. The number of patches can be drastically reduced and the surfaces are inherently smooth, avoiding the intensity smoothing which gives polyhedra the appearance of uniform curvature (14, 15). The hidden surface removal is, however, no easier (16); if none is desired, then a grid network must be displayed instead. This is potentially taxing on the line-drawing display as well as the human observer who must interpret the image. The joint deformation problem is potentially solvable, since the patches will adjust to changes in their boundary curves, but certain representations could produce singularities or strange shapes if deformed past certain limits (12). We know of no existing human model based on such curved patches.

The failures of surface partitioning schemes are partially rectified by using a volumetric representation. Ryan (17) constructs a model based on six-sided polyhedra (usually rectangular prisms). Object algebras such as described by Braid (18) or the Magi Corporation (19) include in the primitive set curved solids such as cylinders, ellipsoids, and spheres, although by their generality do not lend themselves to computationally simple display techniques.

Models are in use which are based on cylindrical volumes: Evans in the Combiman model (20) and Potter and Wilmert in the Calspan model (21). Cylinders are a natural component in an object such as the body where many axes already exist, although "blobby" parts such as the head or hand may be hard to model. A rather small number of cylinders is therefore sufficient. The real difficulty begins, however, when the cylinder caps are smoothed at the joints. The Calspan model takes special pains to achieve rounded corners, but the best results are nevertheless obtained only from side or front views. Hidden parts of the cylinders are not removed either.

The cylinder end problem can be solved by abandoning cylinders for ellipsoids. Herbison-Evans (22) uses such a model to produce animated cartoons of human figures. He shows that hidden parts of the ellipsoid can be removed with a modest amount of computation since ellipsoids orthogonally project into ellipses. That advantage, however, precludes using a perspective projection which is often an important depth cue. Not all body parts are well approximated by ellipsoids either, and surface shading would also be costly.

The projection problem is solved if a primitive is used whose form is unchanged from any view or perspective. The only primitive meeting this criterion is the sphere since its projection is always a circle or disk. If the body is decomposed into overlapping spheres, non-cylindrical parts can be modelled as easily as cylindrical ones. Directionality is rightfully a property of sets of spherical primitives and is not imposed by the representation itself. Although the number of spheres required to represent the body is greater than the number of cylinders usually used, there are compensating savings in display computation and hidden surface removal. Joint deformation and smoothing problems also disappear. Since this is our proposal for a new body model, the next section will describe its properties in detail.

III. The Spherical Model

Because of the difficulties of the other modelling methods, we are presenting the human body as a collection of interpenetrating spheres (23). Besides avoiding or solving most of the problems inherent to the other schemes, high quality graphics are obtained for very little cost.

The skeletal structure of the body is used as a framework for the set of spheres so that the problems associated with pure surface representations are avoided. In fact, if a sphere is placed exactly at a joint of the body, then the two adjoining body segments join smoothly regardless of their relative orientation. Unlike cylindrical approximations, the sphere model can be easily refined to any desired degree, and because spheres have no inherent directionality, they are better than cylinders for modelling shapes such as the head (Fig. 1).

When a sphere is projected into the two-dimensional viewing plane it always appears as a disk or circle. In an orthogonal projection the radii remain fixed, while in a (linear) perspective projection the radii decrease in inverse proportion to the depth. In no case is the circular boundary affected. Efficient methods for drawing disks or circles appear in (24) and (25).

The most exciting aspect of the spherical representation is that it lends itself to cheap hidden surface removal and shading on a raster display. After transformation into the viewing coordinate system, hidden surface removal is obtained by sorting the spheres (on the basis of the frontmost point) from furthest to closest, then displaying them as solid disks in that back-to-front order. Those spheres which are hidden are overwritten in the raster memory or frame buffer by the spheres in front of them. (A related technique for polygons is given in (26).) By changing the grey value of the disk according to the depth, making closer spheres lighter and distant spheres darker, depth curve and shading effects can be generated. As long as the body decomposition is fine enough, adjacent spheres will be close in depth and therefore have nearly the same grey value, producing an effect of almost smooth shading (Fig. 2). The surface of each sphere is not shaded, only rendered uniformly.

For the raster display the costliest step of the algorithm is the sphere sort for the hidden surface display. On a frame-by-frame animation, however, the sort order will change very little and so a sort (for example, sift sort) which utilizes this object coherance will have less work to do. All the other steps in the production of the display have a linear dependence on the number of spheres, n, whereas the sort cost is generally $n \log_2 n$. In addition, a fast disk generation algorithm allows the disks to be displayed a scan line at a time with a minimum of computation (24).

An alternative display technique, but which involves more computations, is an adaptation of Watkins' hidden surface algorithm (27). The display is produced a scan line at a time by computing only the frontmost, visible portions of the spheres intersecting the current horizontal cutting plane. A modification of this technique has been programmed in an attempt to generate outline drawings of the body model (28) for a vector drawing display. The idea is to use the structure of the body to decide when a sphere boundary should be ignored or treated as a visible edge. Thus an arm positioned across the front of the body should appear in outline and properly occluding the body edges, yet visibly connected to the body (Fig. 3). More work needs to be done on this algorithm to improve output quality; its cost, however, probably precludes it from use in real-time animation anyway.

For a vector drawing display the sort step can be skipped since now each sphere is drawn as a circle. In spite of the fact that no hidden surfaces are removed, depth cueing on the circle intensities and animation combine to produce an excellent three-dimensional effect. Since circle drawing generates a sizable number of graphic commands, a display with a built-in hardware circle generator is preferred. One such graphic display, the Vector General 3400 (29), not only provides such a circle generator, but also allows the circles to be positioned in any depth plane and intensity controlled automatically.

As with most surface or volume representations, the most difficult step is data entry. We have discovered an algorithm for the decomposition of curved surface objects into overlapping spheres (28). Starting with any number of cross-sectional outlines of a portion of the object, the algorithm provides a set of spheres to fit the surface (as described by the outlines) within some tolerance. The maximum and minimum sizes for the spheres can also be specified. The algorithm has been used to construct part of our human body model and could be employed to produce other models with different body frames. Models for children, and even other animals, could be developed as well.

IV. The Body Model

In order to position the model for a display a segment structure is used as a "skeleton." This consists of a number of body segments connected by joints where each segment is conceptually a three-dimensional mass of arbitrary shape and extension and each joint is the point where two segments connect. Sliding joints, such as in the human shoulder, are not permitted since the joint must remain fixed relative to each of the adjacent segments. Each joint may connect only two segments, but a single segment may have connections through any number of joints. The current model uses 20 segments and 19 joints without articulating fingers and toes (Tables 1 and 2). The model may be easily extended, however, since all structural parameters are in generalizable arrays. The stage or ground is considered a segment so that the model may be related to the environment.

The segments are organized into a tree structure with segments as nodes and joints as edges. One segment is designated as the <u>reference segment</u> and becomes the root of the tree. If the standard choice of the ground as the reference segment is made, then the tree structure will be as shown in Fig. 4. An important feature of this organization is the ability to deal with a connected subset of the tree. By specifying a subset of the set of segments as a logical window (as opposed to the viewing window of the actual display) the user can restrict the model in order to examine some particular body area. Only segments within the logical window or which lie along a path from the reference segment to some segment within the logical window are retained. For example, Fig. 5 shows the included segments if the logical window is specified as $\{$LLA, LF$\}$ and the reference segment is left at STG.

The shape and size of each segment is described independently of the other segments. For each segment we associated a local coordinate system, which is rigidly embedded within the segment and which moves together with it. The origin of a local coordinate system is at the center of gravity of its segment and coordinate systems are all oriented so that with the human standing upright and feet flat, toes forward, hands at sides and palms toward thighs, the z-axis points upward, the x-axis points forward, and the y-axis points to the left.

Using these local coordinate systems, the shape of the segment and the joint locations can be determined. Each joint is completely specified by giving its coordinates the coordinate systems of the adjacent segments. The external surface shape of a segment is the union of surfaces of overlapping spheres which are defined by their center coordinates and radii in the local segment coordinate system. Adjacent segments cannot physically address the same spheres, but the spheres from one segment may arbitrarily overlap those from another.

With each local coordinate system we can associate a table specifying the directions for back, front, top, bottom, right, and left for the segment itself. Thus for the segment RHN (right hand) "back" is -y, "top" is -z, and "left" is x. This allows any point on the surface of the segment to be "named" by a local direction independent of the segment's orientation in space. Such a feature is very useful for describing points of collision or contact in the model.

In addition to local direction naming, a sphere can be optionally named as a specific subpart of a segment (perhaps restricted to a certain direction). Thus we could label the spheres at each joint to name that joint if, for example, they were detected as a contact during a collision. Other spheres could name exterior features such as nose, ear, heel, or fingernail. In each case we might want to indicate the central directionality of each feature in a table: for example, the sphere for a fingernail would be associated with the "back" direction of its segment.

When a new position is desired, the angles at each joint and the position in space of the reference segment are specified. Because all the segments are part of a tree with the reference segment as the root, this information unambiguously determines the position and orientation in space of each body segment. To actually compute the global coordinates of the spheres, which are only defined in their local segment coordinate systems, transformations are chained along the paths of the tree. To facilitate this process homogeneous coordinates are used. Translations (from segment center of gravity to joint) are represented as 4 x 4 matrices so that transformation chaining can be achieved by matrix multiplication. The result of chaining transformations out to a segment is a single 4 x 4 matrix which when multiplied by the local coordinates of a point in the segment will yield the global coordinates. Once a position for the body is established, the transformation for a segment can be used for all the spheres defined for that segment.

The only exception to the application of the final transformation to the whole segment occurs if the segment itself is twisted along some axis as happens in the lower legs, forearms, and torso. In that case the sphere centers are transformed by a rotation proportional to the distance of their centers along the axis, that is, one end is not rotated about the axis at all, while the other end is rotated the full amount. Of course, the effect will be visible only when the segment is not perfectly circular in cross-section along the axis.

When successive positions of the body must be computed, as in an animation, some computation is avoided if the orientation of some joint is unchanged. The associated segment-to-segment transformation does not change either, so when chaining from the reference segment outward, the transformations need to be recomputed only after the first changed joint orientation is encountered. From that joint onward, the remainder of the tree path must be updated.

V. Collision Detection

One problem which is nontrivial in most object representations is the detection and localization of collisions or contact between parts. Moreover, some collisions are "legal" in the sense that two adjacent segments will intersect to a varying degree about the common joint. These problems can be easily solved within the proposed model.

First, consider collisions between the model and itself. For adjacent segments we can define joint stops to give numerical limits of relative orientation about a joint. For convenience this can be taken to be a cone, but more complex dependencies could be used. Illegal collision of adjacent segments therefore only requires a simple angle check, or at worst a function evaluation for a complex joint stop function.

The power of the segment and sphere model solves the remaining cases. Let I be the intersection function defined for two spheres S(i) and S(j):

$$I(S(i),S(j)) = ||\overline{c}(i) - \overline{c}(j)|| - (r(i) + r(j))$$

where $\overline{c}(i)$, $r(i)$ and $\overline{c}(j)$, $r(j)$ are the center coordinates and radii of S(i) and S(j), respectively, and $||\ldots||$ denotes the distance function in three dimensions. Clearly, I is a symmetric function. Notice that I is just the (signed) distance between

S(i) and S(j) along the line connecting their centers, and:

$I(S(i),S(j)) = 0 \leftrightarrows S(i)$ and $S(j)$ are tangent

$I(S(i),S(j)) > 0 \leftrightarrows S(i)$ and $S(j)$ are disjoint

$I(S(i),S(j)) < 0 \leftrightarrows S(i)$ and $S(j)$ share a nonzero volume.

The collision detection algorithm follows easily. Let L(i) denote the minimum enclosing sphere for body segment i. (This can be stored in the data structure unless parts are allowed to stretch.)

1. For each pair of segments i and j such that i and j are not adjacent to one another, if $I(L(i), L(j)) < 0$ then go to 2, else get next pair of segments.
2. For each sphere $S_i(K)$ in segment i, if $I(S_i(k), L(j)) < 0$ then go to 3, else get next sphere.
3. For each sphere $S_j(m)$ in segment j, if $I(S_i(k), S_j(m) < 0$ then $S_i(k)$ and $S_j(m)$ intersect, else get next sphere.

In step 1, we check if the segments i and j can possibly overlap, and if so, in step 2 we check which spheres of segment i actually overlap the minimum enclosing sphere of segment j. Those that do are checked against the sphere set of segment j. Notice that once the pair (i,j) is checked, the symmetry of I assures us that (j,i) need not be. It is perhaps prudent to renumber the segments such that the number of spheres in segment i is less than the number in segment j if $i < j$.

The output of this algorithm is a list of sphere intersections which might be used as feedback to the simulation program. Alternatively, using the direction naming or subpart naming tables discussed in the previous section, collisions or contacts (differentiated by the value of I) can also be quickly named.

It is a straightforward process to extend collision detection to one model against another spherically represented object or body. What is perhaps more surprising is that the process can be extended to check sphere intersections with object surfaces described by planar polygons. The details will not be given here, but the idea is that sphere to plane distances are easy to compute. Should a sphere intersect a plane the problem reduces to testing a circle against a polygon. If the sphere intersects the minimum enclosing circle of the polygon, further tests determine whether the circle intersects any edge. If so, then we are done; if not then the circle either lies totally within or totally outside the polygon. If outside, the original sphere does not intersect; if inside, the sphere does intersect. The resulting list of sphere-polygon intersections or contacts can now be used to provide part names or to modify the controlling simulation program. Figure 6 shows the human model seated in an airplane cockpit defined by polygons in order to illustrate that the two representations can be effectively merged when the polygon approximated environment is relatively stable.

One of the reasons why we are especially concerned with naming colliding or contacting areas is that we expect eventually to produce a verbal description of the movement of the model. The feasibility of this process has been demonstrated (<u>30</u>, <u>31</u>) and the results imply that contact detection is a very important aspect of verbal descriptions.

V. Applications

Because our model's development has been based on the study of human movement for its own sake, we are concurrently designing and implementing a simulation (32) which will convert motion descriptions in a movement notation system (Labanotation, (33)) into animation commands. There are, however, a few output applications which we are pursuing and others that are certainly feasible.

As Figure 6 shows, we expect to integrate our model with a cockpit design program (17). Of course, the cockpit could be replaced by any planar-approximated environment such as a vehicle interior, whether for operator or passenger. Body models are used to evaluate control accessibility (reach), collision possibilities, and other human factor design criteria such as comfort, visibility, and roominess.

Another application which generates voluminous movement data is crash simulation. Figure 7 shows a sequence of four positions in a simulated car crash (head-to-head crash at an oblique angle; occupant restrained by a lap belt only). The angles for these positions were generated by the Calspan crash victim simulator (4), a computer program for predicting occupant motions. Besides the visualization of the predicted movement, the use of a video display offers the possibility of eventually producing a simultaneous, superimposed display of the predicted and actual experimental motion.

Not only would the observer be able to integrate and compare both movements, but the veracity of the simulation program itself could be checked.

Because a reasonable input method exists for decomposing an object into overlapping spheres, it is possible to produce displays of human figures besides the one we have been using. Children and even animal models could be generated, as well as bodies with various physical features, normal or abnormal. The latter could be used to examine vehicle design for the handicapped. It is even possible to "digitize" a particular person so as to customize the vehicle environment to that body.

VII. Conclusions

The conceptual simplicity of the spherical decomposition of the human body provides many advantages to the user in hidden surface removal, collision detection, part naming, and device independent display. We are particularly hopeful that the raster-based display will provide, for the first time, the possibility of saving computer simulation data on video tape or cassettes so that animation playback can be done offline without tying up large computers or expensive display devices. The vector drawing device would be used primarily for preview or online animation.

Such a configuration is being developed at the Moore School of Electrical Engineering at the University of Pennsylvania. Our raster display is a Ramtek GX-100B with 240 x 320 spatial resolution and 256 grey levels or 4096 colors. It will be possible to animate short sequences by playback directly from moving head disk storage attached to a PDP-11/60. We hope to utilize television systems for recording in the future. Also attached to the PDP-11/60 is a Vector General 3404 refresh graphics display. There is enough local processing power within this device to completely encode the human model structure and spheres, while using the hardware transformation capabilities to perform the joint movements. Ideally, only joint displacement commands need be sent from the computer to the VC3404 display in order to animate the human model on the screen.

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Number	Segment Name	Mnemonic
1	stage	STG
2	lower torso	LT
3	central torso	CT
4	upper torso	UT
5	neck	N
6	head	H
7	left shoulder mass	LSM
8	right shoulder mass	RSM
9	left upper arm	LUA
10	right upper arm	RUA
11	left lower arm	LLA
12	right lower arm	RLA
13	left hand	LHN
14	right hand	RHN
15	left upper leg	LUL
16	right upper leg	RUL
17	left lower leg	LLL
18	right lower leg	RLL
19	left foot	LF
20	right foot	RF

Table 1. Segment names and mnemonics.

Number	Joint Name	Mnemonic
1	pelvis	PV
2	waist	W
3	solar plexus	SP
4	neck pivot	NP
5	head pivot	HP
6	left clavicular joint	LC
7	right clavicular joint	RC
8	left shoulder	LS
9	right shoulder	RS
10	left elbow	LE
11	right elbow	RE
12	left wrist	LW
13	right wrist	RW
14	left hip	LH
15	right hip	RH
16	left knee	LK
17	right knee	RK
18	left ankle	LA
19	right ankle	RA

Table 2. Joint names and mnemonics.

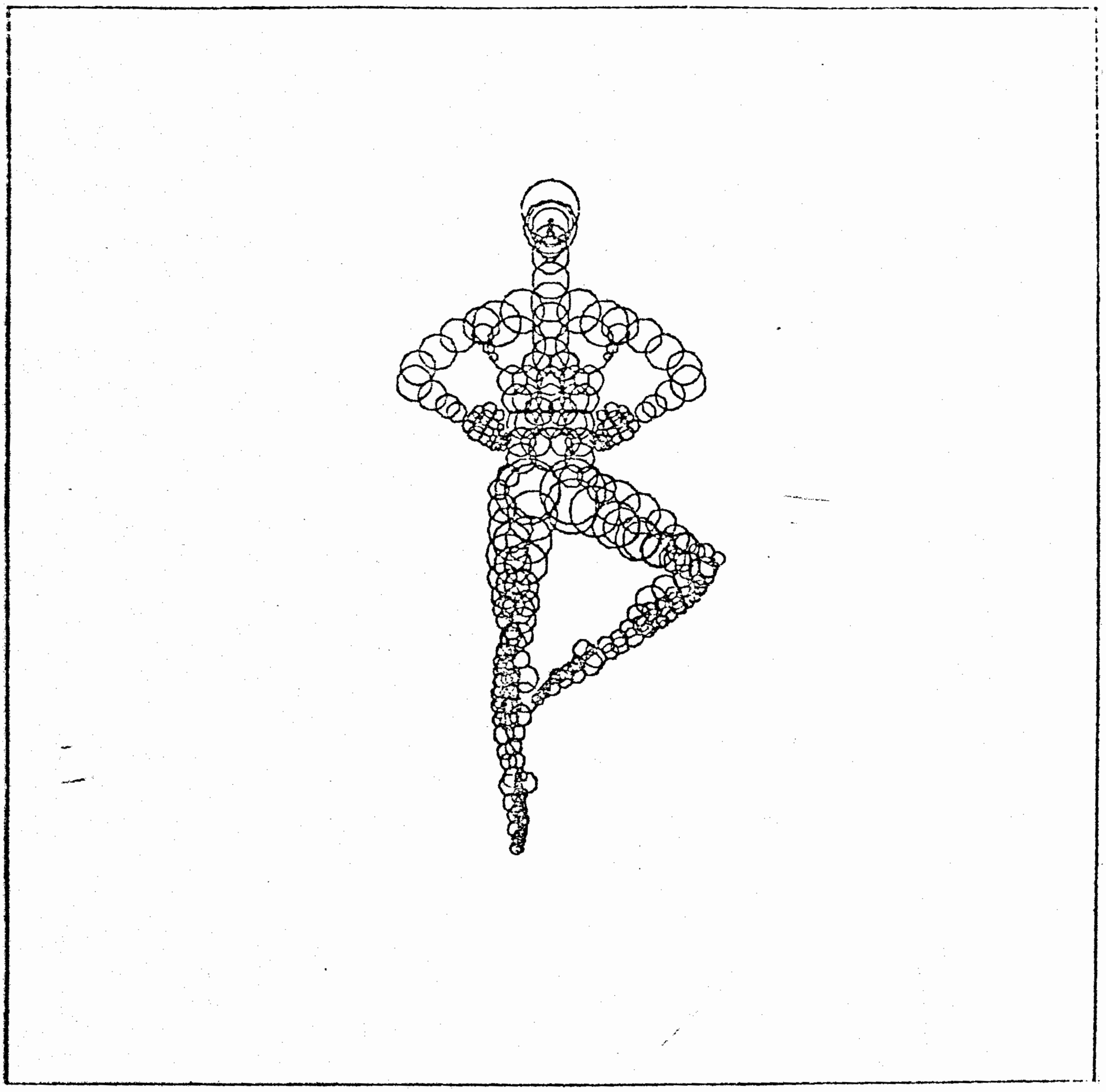

Figure 1. Human model displayed with circles.

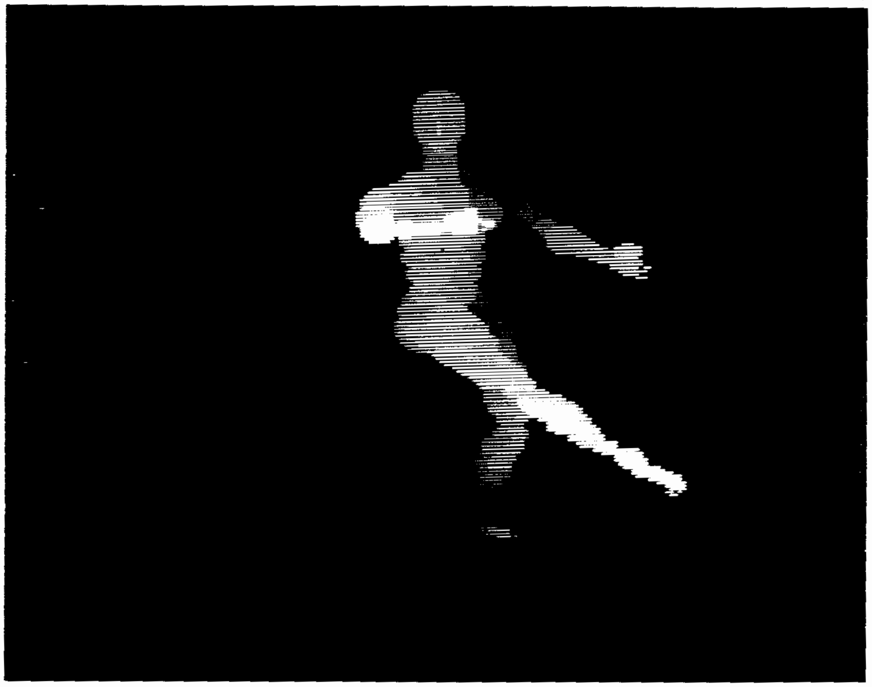

Figure 2. Human model displayed with disks.

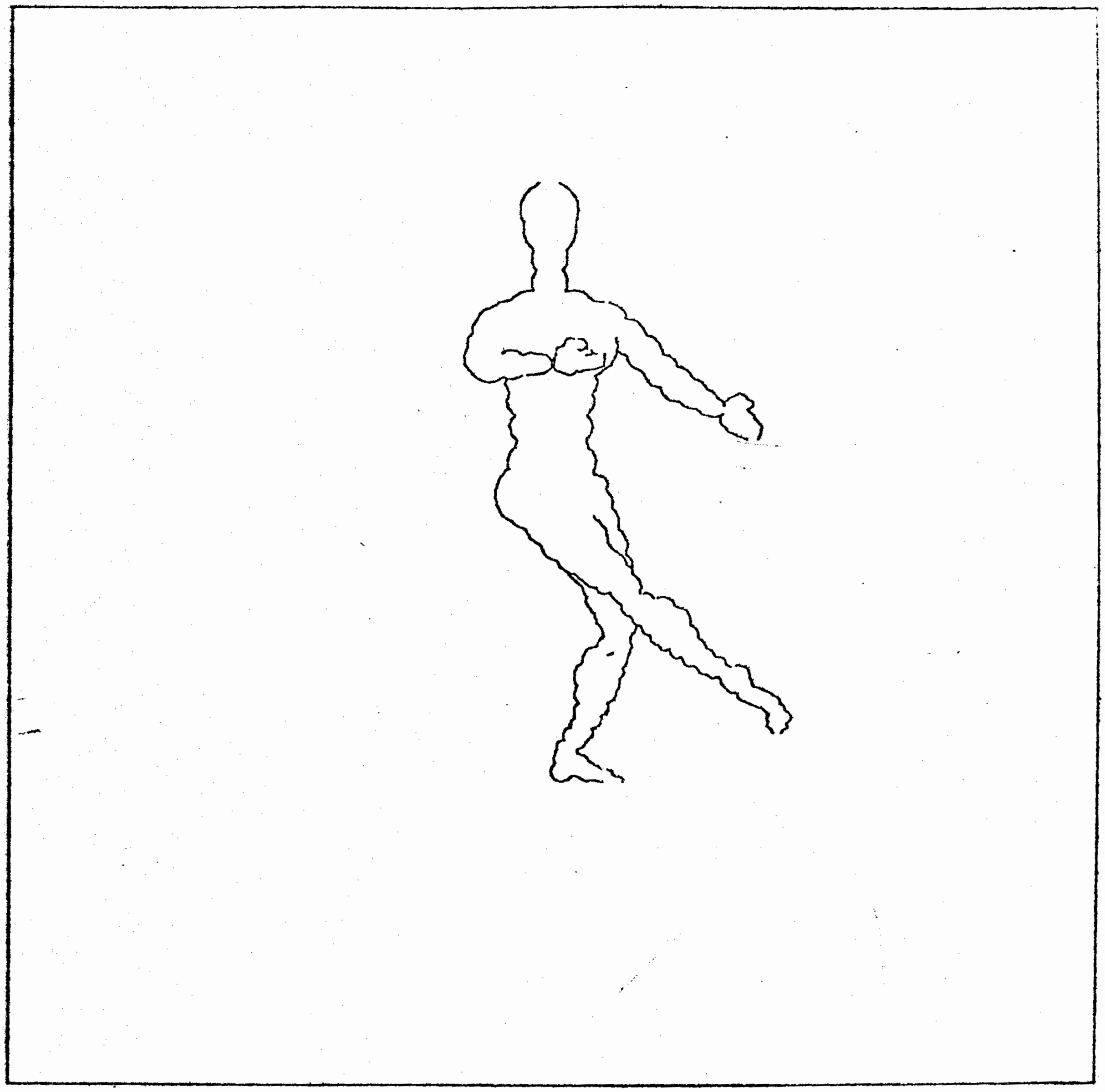

Figure 3. Human model in outline.

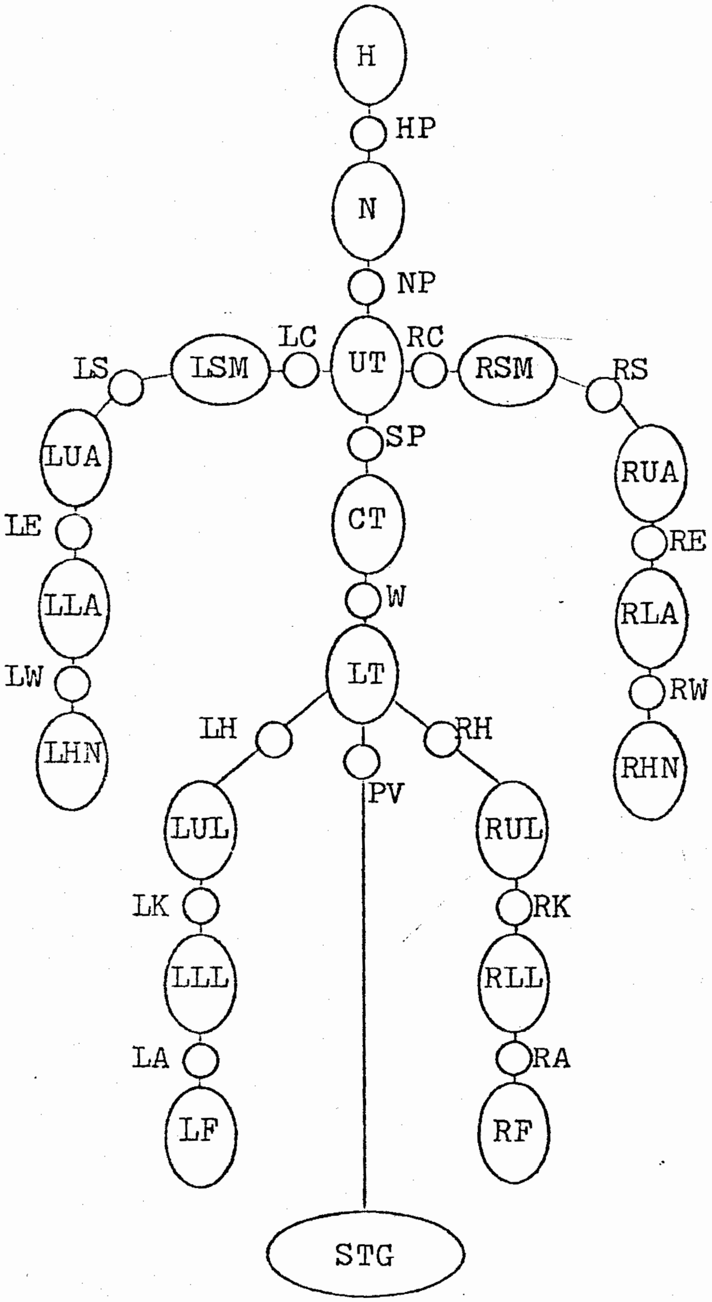

Figure 4. Tree structure of segments and joints.

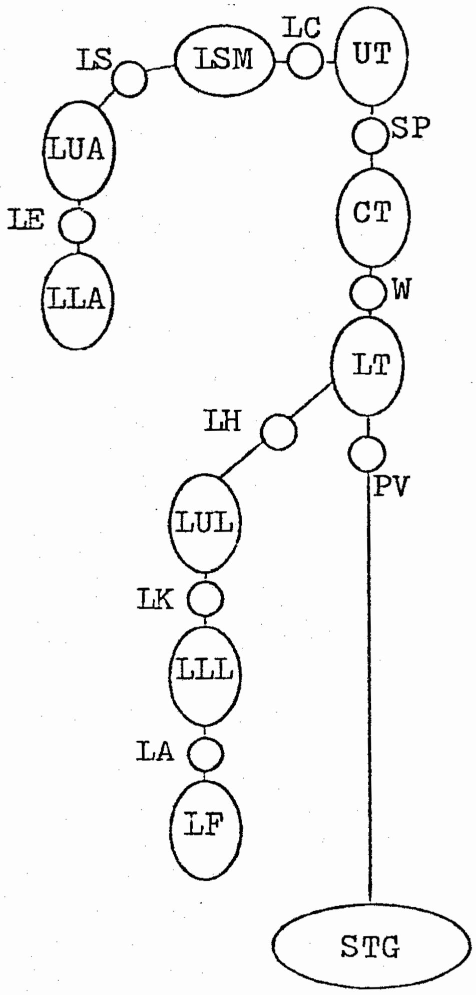

Figure 5. Tree structure of segments and joints with {LLA, LF} logical window and STG reference segment.

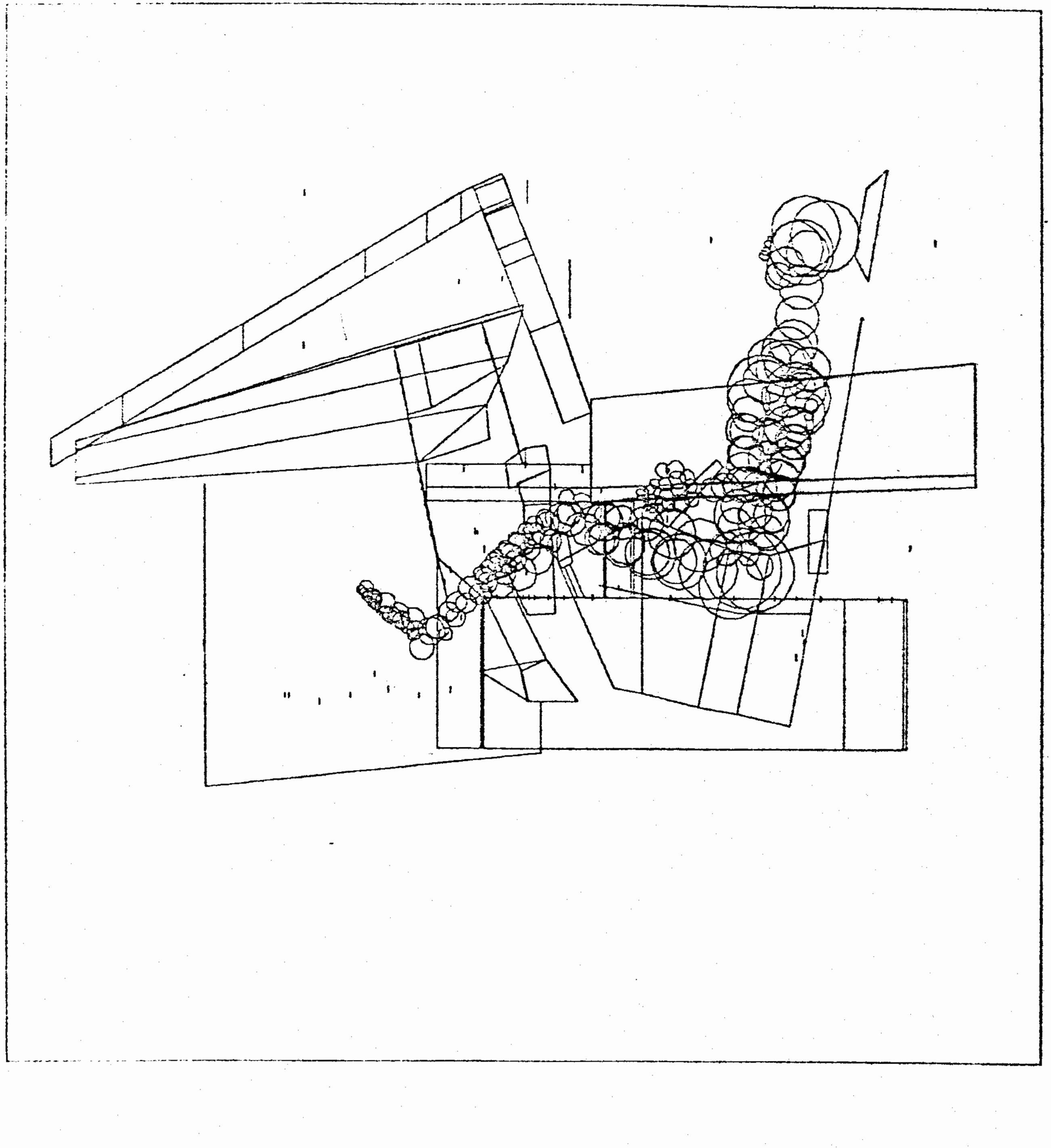

Figure 6. Human model in planar polygon cockpit environment.