GRAPHICAL MARIONETTE:
A MODERN-DAY PINOCCHIO

by

Delle Rae Maxwell

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ABSTRACT

Representing the form and movement of human beings naturally, expressively, and computationally is a challenging endeavor. While the skeletal framework can be conveniently described, conventional modelling techniques are generally inadequate for rendering the flexible and irregular surface features of the body. Detail that is sacrificed in articulating the geometry of a life-like character can be compensated for by realistically depicting the character's motion. It is theorized that the most effective method of capturing the subtle dynamics of human motion is to track that motion directly. With the goal of complete body-tracking in view, a prototype system for designing "graphical marionettes" animated by diverse inputs has been developed.

The evolution of body modelling as both an artistic and scientific concern are reviewed as precedents to current modelling systems. The development of data structures, animation programs, and some singular rendering techniques are discussed within the context of the project. Several difficulties in handling missing or occluded motion data are presented. Some interesting animation scenarios are envisioned as future applications of the system. Improvements to the present version are suggested in the concluding chapter.

Thesis Supervisor: Dr. Kenneth R. Sloan, Jr.
Title: Assistant Professor of Computer Graphics

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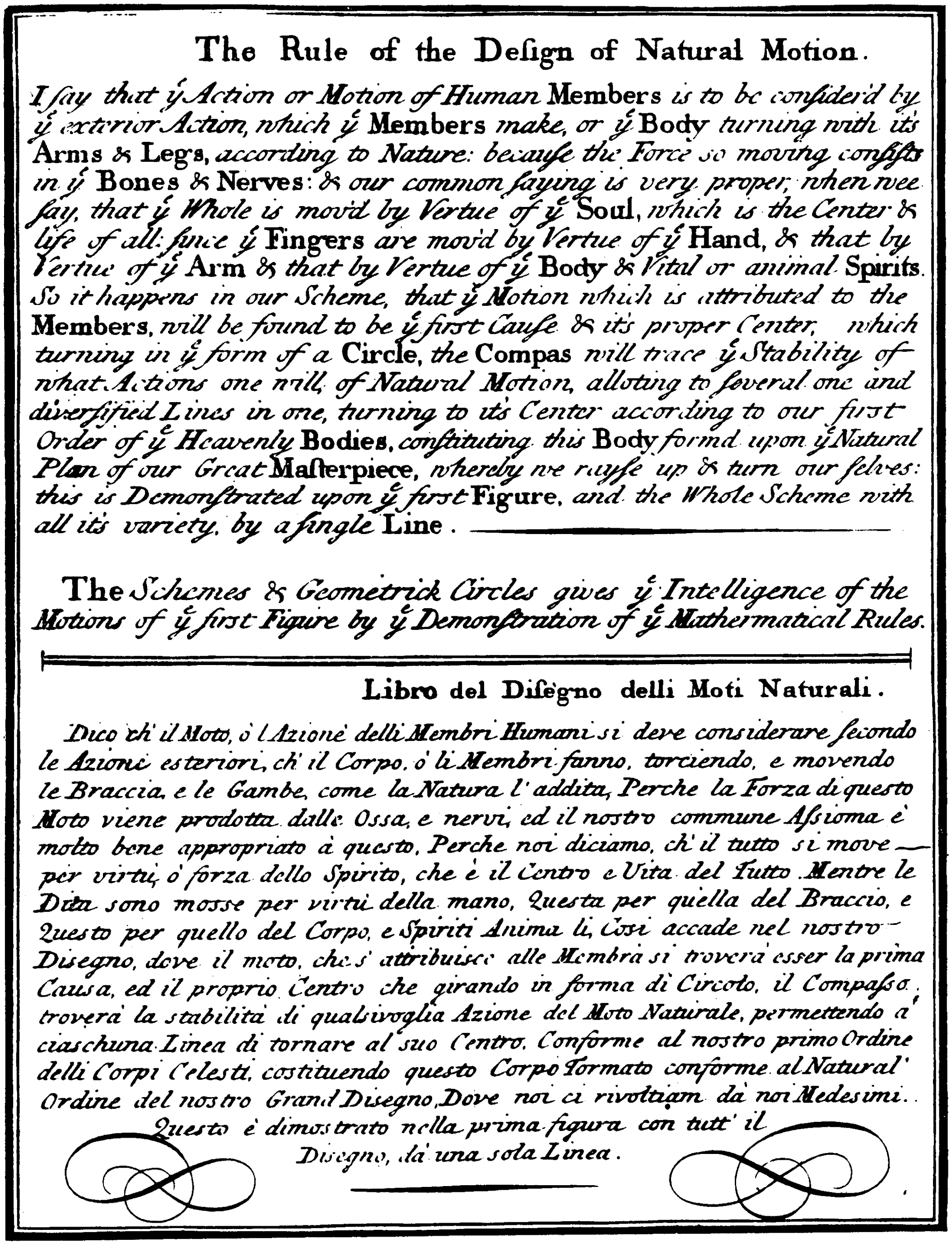


The Rule of the Deſign of Natural Motion.

I ſay that yᵉ Action or Motion of Human **Members** *is to be conſider'd by yᵉ exterior Action, which yᵉ* **Members** *make, or yᵉ* **Body** *turning with it's* **Arms & Legs,** *according to Nature: becauſe the Force so moving conſiſts in yᵉ* **Bones & Nerves:** *& our common ſaying is very proper, when wee ſay, that yᵉ Whole is mov'd by Vertue of yᵉ* **Soul,** *which is the Center & life of all: ſince yᵉ* **Fingers** *are mov'd by Vertue of yᵉ* **Hand,** *& that by Vertue of yᵉ* **Arm** *& that by Vertue of yᵉ* **Body** *& Vital or animal* **Spirits.** *So it happens in our Scheme, that yᵉ Motion which is attributed to the* **Members,** *will be found to be yᵉ first Cauſe & it's proper Center, which turning in yᵉ form of a* **Circle,** *the* **Compas** *will trace yᵉ Stability of what Actions one will, of Natural Motion, alloting to ſeveral one and diverſified Lines in one, turning to it's Center according to our first Order of yᵉ Heavenly* **Bodies,** *conſtituting this* **Body** *form'd upon yᵉ Natural Plan of our Great* **Maſterpiece,** *whereby we rayſe up & turn our ſelves: this is Demonſtrated upon yᵉ first* **Figure,** *and the Whole Scheme with all it's variety, by a ſingle* **Line.**

The *Schemes & Geometrick Circles gives yᵉ Intelligence of the Motions of yᵉ first Figure by yᵉ Demonſtration of yᵉ Mathermatical Rules.*

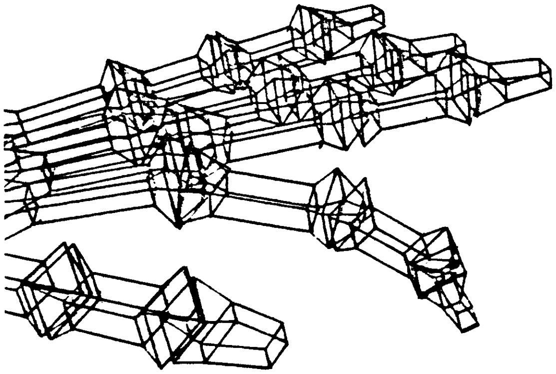
Libro del Diſegno delli Moti Naturali.

Dico ch' il Moto, ò l'Azione delli Membri Humani si deve considerare ſecondo le Azioni esteriori, ch' il Corpo, ò li Membri fanno, torciendo, e movendo le Braccia, e le Gambe, come la Natura l' addita, Perche la Forza di questo Moto viene prodotta dalle Ossa, e nervi, ed il nostro commune Aſsioma è molto bene appropriato à questo, Perche noi diciamo, ch' il tutto si move — per virtù, ò forza dello Spirito, che è il Centro e Vita del Tutto. Mentre le Dita sono mosse per virtù della mano, Questa per quella del Braccio, e Questo per quello del Corpo, e Spiriti Anima li, Così accade nel nostro — Disegno, dove il moto, che s' attribuisce alle Membra si troverà esser la prima Causa, ed il proprio Centro che girando in forma di Circolo, il Compaſso, troverà la stabilità di qualsivoglia Azione del Moto Naturale, permettendo à ciaschuna Linea di tornare al suo Centro, Conforme al nostro primo Ordine delli Corpi Celesti, costituendo questo Corpo Formato conforme al Natural' Ordine del nostro Grand Disegno, Dove noi ci rivoltiam da noi Medesimi.

Questo è dimostrato nella prima figura con tutt' il Disegno, da una sola Linea.

From the Codex Huygens [31]

"Skeletal Hand", Southern Illinois University



INTRODUCTION TO HUMAN MODELLING SYSTEMS

Three-dimensional computer animation provides the animator with a powerful set of tools, and the potential to portray the human form in ways unattainable by conventional two-dimensional animation techniques. Many human modelling animation systems are currently being developed, yet the problems of convincingly portraying the motion and appearance of the human form are far from being solved. With over 200 degrees of freedom, the human form is capable of such intricate motion that its specification and display presents considerable difficulty to both animators and animation systems designers. What has been gained in automating the tedious rote aspects of animation is usually lost in the difficulties of defining form and motion within a computational environment.

While the skeletal framework can be conveniently described, conventional techniques such as surface modelling and volumetric models are generally inadequate for rendering the flexible and irregular surface features of the body. In many cases the actual physical mien of the graphic figure is relegated a secondary status, due in part to the limits of modelling techniques, and in part to greater concern with motion representation. A primitive and unconvincing appearance is the usual result. Unfortunately, the process of creating a realistic counterpart is never quite as simple as is portrayed in popular lore. Figure 1 shows a still from the film "Metropolis".

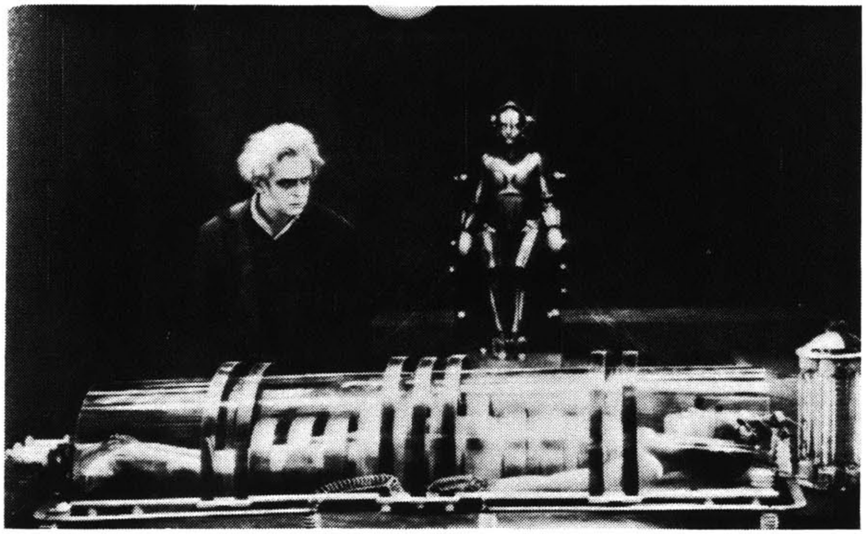


Figure 1 From Metropolis, Human-to-Robot Feature Mapping

Here, the features of the human woman are about to be mapped onto her robot "double", merely by the flip of a switch. As whimsical as this may seem, the idea of mapping from the real to the simulated underlies much of the research in human modelling systems.

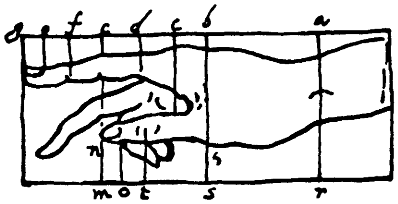
Numerous methodologies have been devised to record, analyze, and describe the figure in motion. Notation systems attempt to comprehensively define motion primitives [5]. Although motion can be abstracted as a series of rotations and translations of body segments, it is the recombination of these primitives as smooth natural motion that presents many obstacles. It is theorized that the most natural and effective means of accomplishing motion representation is to have a human "scriptor" directly act out the motions that will eventually be interpreted graphically. This method is termed "scripting-by-enactment" [6]. The animated output may be referred to as a "graphical marionette". Scripting-by-enactment is accomplished by tracking the actual motions of the human scriptor with position sensing hardware [17].

Running parallel with the drive to incorporate true- to-life human forms into computer graphics is the drive to incorporate true-to-life, i.e. natural, human actions into the use of computers and other machines. Where we began by communicating non-interactively with computers using an alpha-numeric format, we have progressed to highly interactive styles and expanded the I/O repertoire to include such means as touch-sensitive displays and voice recognition/ synthesis. The next logical step to enhancing the human-machine interface is to incorporate kinetic input, or input by gesture. This technique furthers the realization of the "fully responsive interface" [24], facilitating conversation between the animator and the computer, its various peripherals, and its graphic inhabitants.

What is then needed in such a system are easily defined body data structures, interchangeable drawing modules which convincingly characterize the figure, and quick feedback to the animator. The animator should be able to script motion in the most direct way possible. During system development, the animation progams must be testable at each stage. This thesis explores these issues of expressive appearance, user interface, and natural motion within an animation application.

With the goal of integration with the completed body-tracking hardware in view, a prototype system for designing "graphical marionettes" animated by diverse inputs has been developed. The body is abstracted as a data structure and maintained as a template file. Motion data contained in similar files can be mapped to the corresponding body segments and processed in a systematic fashion for each "frame" of animation. A method for representing the body as "clouds" of points is presented as a viable alternative to surface and solid volume modelling. In addition to being aesthetically engaging, its transparency obviates the need to perform costly computation such as hidden surface removal.

Chapter One provides a brief history of body and motion modelling, and gives a synopsis of related current research. Chapter Two presents an overview of the Graphical Marionette project; both its long-range and more immediate goals. Classification of the body segments and motions, the creation of body templates, methods for positioning the segments using rotational primitives, and rendering programs are examined in Chapter Three. Body-tracking techniques, a description of the hardware configuration, and the hardware-software interface are presented in Chapter Four. Chapter Five chronicles the development of the animation system in preparation for the actual tracking data. Some of the problems with underconstrained systems are mentioned. Chapter Six summarizes the project and its concerns, and suggests some possible future directions. Appendix A is intended as an abbreviated user's manual to the current programs, and Appendix B contains a table of joint rotation limits.



Leonardo

HISTORY, BACKGROUND, AND CURRENT ISSUES

Replicants

The concept of modelling human figures is by no means novel; one can refer back to the myths of Pygmalion and Galatea, or to the "animated statues" of Daedalus.

> Man … has used all possible ingenuity to cause inanimate matter to perform the functions of living beings: whether it be human or animal, playing musical instruments, eating, or whatever else was stirring people's imagination … [30].

The eighteenth century fascination with the construction of automata gave rise to such tales as E.T. A. Hoffmann's "The Sandman", in which the seemingly human Olimpia captivates the young hero. This century has witnessed the advent of the robot and android character in numerous films and books. Not all of these creations belong to the realm of science fiction;

robots, for example, have begun to be an integral part of the manufacturing workforce. Accurate graphical replication of the human figure in motion comprises an important branch of research in computer science and related disciplines.

The depiction of motion has an equally long history.

> The early Greeks were aware of the fact that that the illusion of motion could be created by first drawing a series of sequential pictures of motion positions on a wall. By running or riding rapidly past the pictures while gazing generally at them, the still pictures appeared to spring to life, depicting the motion originally conceived. [20]

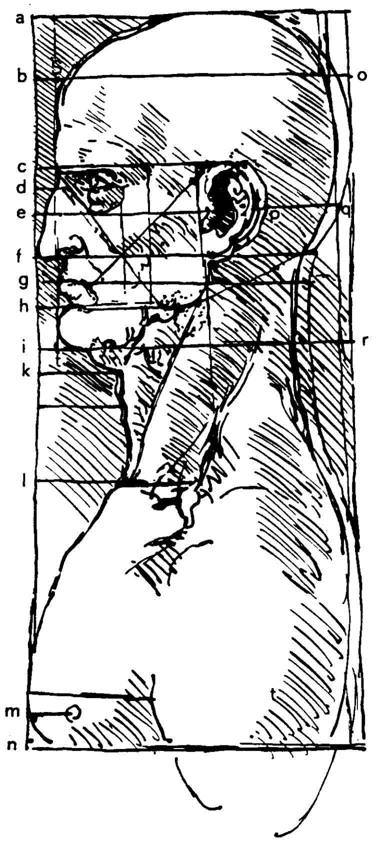
Now, of course, the animation procedure is reversed; one sits still and watches the images upon a screen flashing by.

The Measure of Man

Our predominantly mathematical interpretation of nature becomes evident when one considers the numerous endeavors to create systems of proportion and order devised to relate the human form to its environment. The Pythagorean-Platonic tradition in the study of geometry and proportion has wielded its influence in

Figure 2 Villard de Honnecourt, Notebook Page, c. 1235

the western world for over two thousand years, although its use as a basis for human proportion reached its zenith during the Middle Ages, Renaissance, and Classical periods. Different uses of this tradition were favored during different stylistic periods: the medieval artist tends to project an established geometrical norm into his imagery, as seen in Figure 2, while the Renaissance artist tends to "extract a metrical norm from the phenomena that surround him", [37] as shown in Figure 3 below.

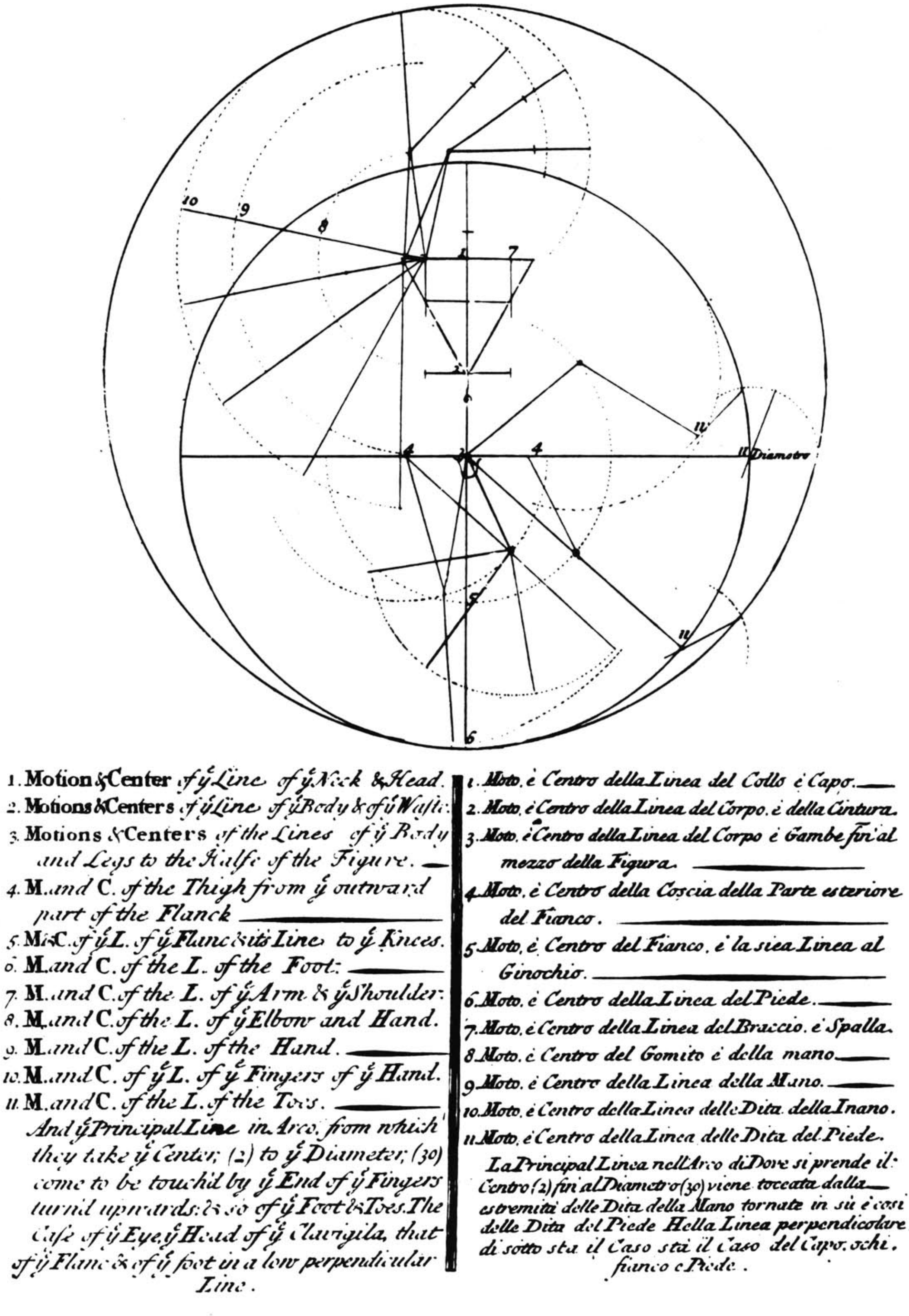


h.i $\frac{1}{6}$ del (*capo*)ʌvoltoʌ	*h i* is $\frac{1}{6}$ of the face
g.i $\frac{1}{5}$ del capo	*g i* is $\frac{1}{5}$ of the head
g.i $\frac{1}{4}$ del uolto	*g i* is $\frac{1}{4}$ of the face
f.i $\frac{1}{3}$ del uolto	*f i* is $\frac{1}{3}$ of the face
c.f $\frac{1}{3}$ del uolto	*c f* is $\frac{1}{3}$ of the face
b.c $\frac{1}{3}$ del uolto	*b c* is $\frac{1}{3}$ of the face
K l $\frac{1}{2}$ volto	*k l* is $\frac{1}{2}$ a face
h f e $\frac{1}{6}$ del uolto	*h f* is $\frac{1}{6}$ of the face

Figure 3 Leonardo Da Vinci, Proportions of Head and Face

During the 15th century, a rigorous approach to the accurate and expressive depiction of human proportion and motion is embodied in the vast oeuvre of Leonardo da Vinci, and in the numerous canons of proportion devised by Quattrocento artists. The drawings and notebooks from this period are evidence of the beginnings of descriptions of different types of motion, although the renderings remain in the static realm of painting, as can be seen in this page from the Codex Huygens in Figure 4. Leonardo's studies of kinetics and anatomical investigations of structure, from bones to muscle to flesh, exemplify this desire to both understand and powerfully portray human appearance, motion, and character [32].

Since the 18th century we have witnessed the breakdown of the use of only one objective set of proportions which guided the depiction of the human form. Individual proclivity has been of far greater influence than an all-embracing system in the fine arts. Yet, a new set of proportions based perhaps more on the efficiency and economics of standardization have come into use, primarily in the fields of architecture and industrial design. One such study, Humanscale [14], compiled by Henry Dreyfuss Associates, is comprised of anthropometric data gathered from males, females, and children from White, Black, and Japanese racial groups. Height, weight, body segment circumferences and center of gravity locations, and limits of segment motion are



1. **Motion & Center** *of yᵉ Line of yᵉ Neck & Head.*	*1. Moto. è Centro della Linea del Collo è Capo.*
2. **Motions & Centers** *of yᵉ Line of yᵉ Body & of yᵉ Waste:*	*2. Moto. è Centro della Linea del Corpo. è della Cintura.*
3. **Motions & Centers** *of the Lines of yᵉ Body and Legs to the Halfe of the Figure.*	*3. Moto. è Centro della Linea del Corpo è Gambe fin'al mezzo della Figura.*
4. **M.** *and* **C.** *of the Thigh from yᵉ outward part of the Flanck*	*4. Moto. è Centro della Coscia della Parte esteriore del Fianco.*
5. **M.&C.** *of yᵉ L. of yᵉ Flanc & its Line to yᵉ Knees.*	*5. Moto. è Centro del Fianco. è la siea Linea al Ginochio.*
6. **M.** *and* **C.** *of the L. of the Foot:*	*6. Moto. è Centro della Linea del Piede.*
7. **M.** *and* **C.** *of the L. of yᵉ Arm & yᵉ Shoulder:*	*7. Moto. è Centro della Linea del Braccio. è Spalla.*
8. **M.** *and* **C.** *of the L. of yᵉ Elbow and Hand.*	*8. Moto. è Centro del Gomito è della mano*
9. **M.** *and* **C.** *of the L. of the Hand.*	*9. Moto. è Centro della Linea della Mano.*
10. **M.** *and* **C.** *of yᵉ L. of yᵉ Fingers of yᵉ Hand.*	*10. Moto. è Centro della Linea delle Dita. della Inano.*
11. **M.** *and* **C.** *of the L. of the Toes.*	*11. Moto. è Centro della Linea delle Dita del Piede.*
And yᵉ Principal Line in Arco, from which they take yᵉ Center; (2) to yᵉ Diameter; (30) come to be touch'd by yᵉ End of yᵉ Fingers turn'd upwards: & so of yᵉ Foot & Toes. The Case of yᵉ Eye, yᵉ Head of yᵉ Clavigila, that of yᵉ Flanc & of yᵉ foot in a low perpendicular Line.	*La Principal Linea nell'Arco di Dove si prende il: Centro (2) fin al Diametro (30) viene toccata dalla estremità delle Dita della Mano tornate in sù è così delle Dita del Piede Hella Linea perpendicolare. di sotto sta il Caso stà il Caso del Capo. ochi. fianco e Piede.*

Figure 4 Codex Huygens, Human Motion Study

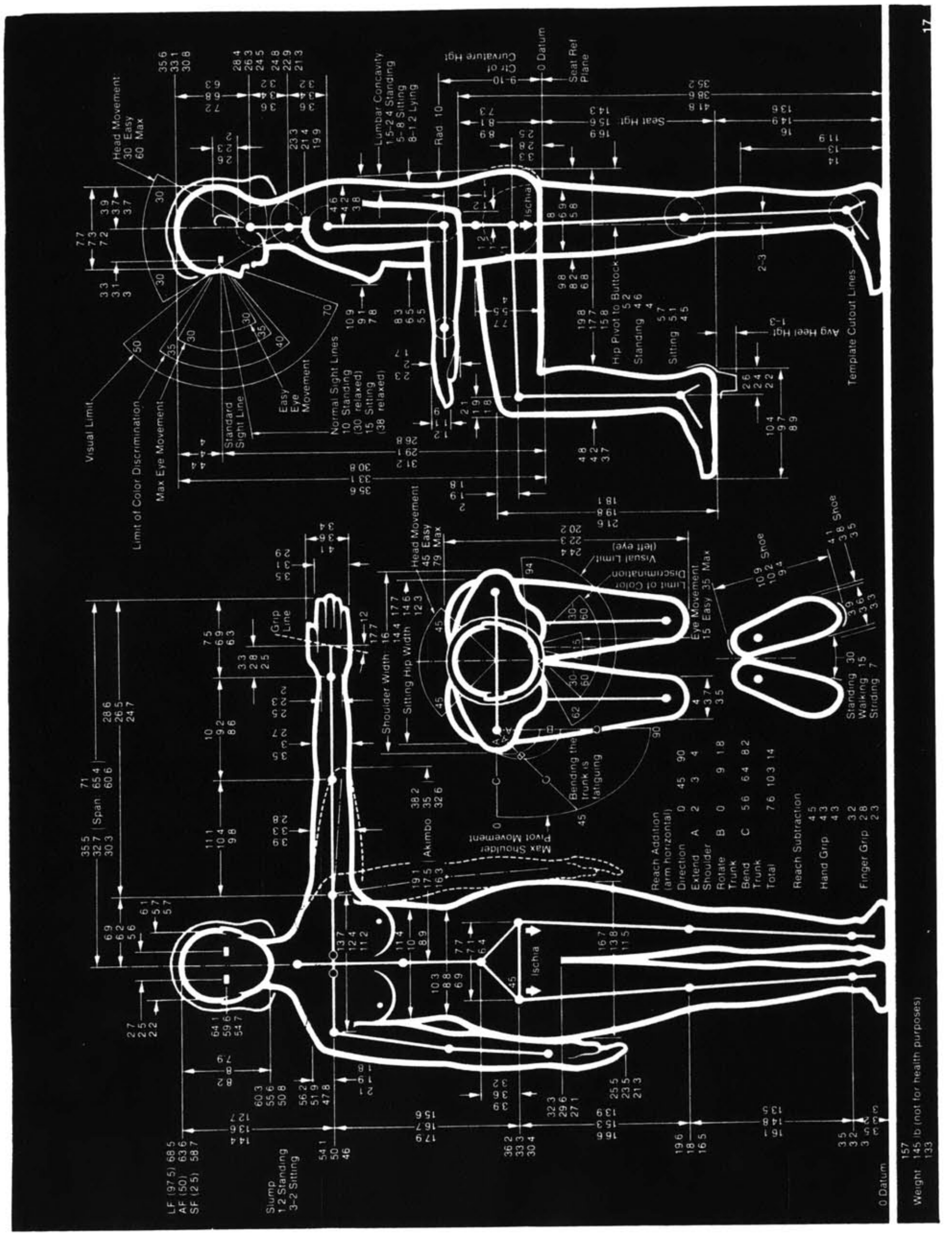


Figure 5 Henry Dreyfuss Associates, "Humanscale"

some of the factors considered. The measurements gathered are summarized and analyzed, yielding a statistical description for 95 percent of the people, that is, those between the 2.5 and 97. 5 percentiles. The "average" is the 50th percentile, which indicates that the percentage of people at or below that certain measurement is at 50. A page from Humanscale is shown in Figure 5. This survey has provided the database for Sammie, a human modelling system designed for "general anthropometric analysis and design applications". [15] The figure's proportions may be altered by varying the percentiles, as well as change the somatotype of the figure.

Yet even this seemingly extensive collection of data on the human figure is not adequate to fully describe the innumerable variations in proportion. "There IS no standard size human!" is the observation of Norman Badler [1], made in reference to the employment of such a database in their own extensive body modelling system at the University of Pennsylvania. Perhaps a solution to the problem of seeking an all-inclusive standardization is to consider the usage in each instance. Research in human biomechanics requires more precise measurement, even the measurement of one particular person, as compared to the generation of a human figure for animation, which may be characterized by a certain degree of exaggeration.

Motion Study as a Scientific Discipline

Artistic interpretation of the meaning of motion is only one aspect of the study of movement. An observer in the medical field may be analysing movement patterns to understand the difference between normal and abnormal motion. An Olympic coach may wish to closely observe the motion of an athlete, in order to improve his or her performance. Designers of systems such as Sammie need to observe the motions of a simulated figure within a prospective work environment. All of these applications require in varying degrees involvement in disciplines such as kinesiology or biomechanics.

Motion, the change of position of an object within some frame of reference, is obviously a term encompassing a lot of terrritory. In science, even more than in art, systems of ordering and classification are essential to the expansion of knowledge in each particular field. In regards to motion study, both the qualities and quantities must be considered. Qualities of motion, exemplified by such terms as contained, gentle, brusque, and the like are useful in identifying motion. (These qualities are also the most difficult to describe and reproduce algorithmically !) The quantitative description, based on measurement, is the concern of kinetics and kinematics, both being a part of the science of mechanics. With the kinematic approach, motion is described without reference to mass or cause, referring primarily to its measurement. Kinetics, or dynamics as it is sometimes known, treats also the causes of motion, which may be external or internal forces. The anatomy of the body, its skeletal and musculature structure, must also be studied in order to determine how motion occurs.

A great deal of knowledge may be gained through observation and measurement of the body in motion. Photography and the subsequent motion picture allowed for the viewing of the figure in motion, observable one frame at a time. Stroboscopic images, made famous by Edgerton and Killian show several instantaneous postions on one negative of a stationary camera, illuminated by a stroboscopic flash at some controlled frequency. This produces an image which is sometimes hard to analyze if certain parts of the body are obscured by the path of the limbs. The technique of electromyography (EMG) can be employed to measure the extent of actual muscle contraction with surface or needle electrodes placed near to the motor unit controlling a certain muscle. The results may be recorded on graph paper, or an oscilloscope. A tool often used in gait analysis is the force plate. Placed on the floor, it measures vertical and horizontal forces exerted upon its plane. Electrogoniometers can record joint angle changes in limb segments over time. Such data can also be used to drive animated output, as is mentioned later in the discussion of related human modelling research. Other motion tracking devices will be covered in greater detail in Chapter Four. As may be imagined, such techniques produce extensive amounts of data which would be difficult to classify and analyze without the aid of a computer. With this aid, not only can motion be analyzed in a controlled environment, but motion and a graphical model can be synthesized.

Human Motion Simulation

Recent developments in related computer fields such as artificial intelligence, graphics, robotics, and animation enable us to more closely approximate human movement and gesture than ever before. Numerous movement representation methods have been devised, both "notation systems designed for recording movement, and animation systems designed for the display of movement" [2]. The aim of these systems ranges from entertainment, characterized by a degree of artistic license in the animation, to more detailed research applications; simulations with the goal of modelling "exactly...a process, theory or system" [28], drawing upon and augmenting the knowledge of other related previously mentioned discplines such as biomechanics and kinesiology. Simulation systems generally can be classified as kinematic or dynamic; the dynamic simulation significantly increases the amount of computation.

The Fundamental Tasks

Regardless of application, the fundamental problems of representing human motion remain the same: specifying the movements, and creating a graphical image based on a physical model. The motion may be directed by descriptive or analytic inputs, as exemplified, respectively, by analog position sensors or symbolic inputs (as in the Labanotation dance notation system [19] See also Figure 6). Processing the input data, at the simplest level, requires conversion to movement primitives which in turn are used to animate the database model. These primitives are primarily rotation, and to a lesser extent, translation. The figure can be abstracted as a network of linked segments driven by such motion.

The database, or description of the figure, provides at least segment or joint names, connectivity information, and segment lengths. Stick figures provide a basis from which to work, but more realism is achieved through wire frame or solid models. A more natural-looking, but more complex figure may model surface "skin" over the linear segments using a large number of polygons, or surface patches. Such surface modelling techniques are not entirely satisfactory, as problems such as deformations of the surfaces near moving joints occur. [5] Computational cost is high in trying to rectify these problems. Other approaches, such as volume models (cylinders, ellipsoids, or spheres) are also being explored as alternatives to these methods. This may seem familiar: perhaps it is appropriate at this point to refer to the 13th century illustration seen previously in Figure 2. At the other end of the scale of "realism" are NYIT's whirling geometric solids suggestive of a dancing figure, exemplifying the creative use of such animation systems.

Nevertheless, a common goal, realistic portrayal of human form and motion, constitutes a focal point for diverse research. Brief descriptions of current systems under development are presented as examples of some of the techniques mentioned above.

Related Research at Other Laboratories

The University of Pennsylvania group, directed by Badler, [1,2,3,4,5] is conducting human movement research based primarily in these areas: computer graphics used for motion synthesis, computer vision, Labanotation [19] for movement notation, language analysis, and robotics [2]. One of the applications of this system is the simulation of the "activities of several people in a workstation environment" [2]. Directions, facings, revolutions, contacts, and shapes, concepts culled from the Labanotation system, are used as positional and directional movement primitives. In order to represent the dynamic qualities of movement, i.e., how one moves (slow, quick, forceful), other notation systems are being investigated which can be incorporated with the concepts of Labanotation. Describing these dynamic qualities using natural language would require using motion verbs and their modifiers developed within a special purpose task specification language. This method extends this research into ancillary fields such as language analysis, thereby increasing the scope and complexity of the research. The graphical representation is modelled using spheres, which are mapped onto the display as circles and ellipses, making for a somewhat lumpy looking, albeit versatile character known as the Bubble Person. The emphasis in this system is more on the representation and synthesis of movement, and the development of task specification languages, than on the physiognomy of the figure.

At Ohio State University, Zeltzer and the Computer Graphics Research Group are modelling human and animal forms as skeletons, simulating the bone and joint structures before tackling the problem of muscle and flesh [38,39,40,41]. Articulated, realistically modelled skeletal figures combined with motor control programs have been used to create convincing walking sequences over flat terrain. This system is not based on a movement description notation such as the Labanotation [19] used by Badler, et al [1,2,3,4,5], as they doubt its extendability to other (non-human or imaginary) figures. Their method is likened to the GRAMPS [27] system, with its "facilities for defining articulated objects" [41]. Joint movement primitives, "bends", are called in two ways. The first is by keyboard commands, entering rotation amounts for each joint. Alternatively, an animator may choose to describe "tasks" to a task manager, which calls motor control programs, which then in turn activate local motor programs. These local motor programs, or LMPs, act upon the skeleton database by changing joint rotation values, and thus represent bend primitives. Work is being done to control the LMPs during cycles of motion by the implementation of finite-state machines. (The abstraction of the body and its motion as a set of machines is a concept that Leonardo da Vinci discussed in his own work!) An eventual goal here, as well as at the University of Pennsylvania, is further development of systems which accept natural language scripting as input [41].

Yet another approach to human animation, under development by Calvert, Chapman, and Patla at Simon

Fraser University applies both symbolic (Labanotation-based) and analog (electrogonimeter) inputs to motion control [10,11]. In this case, the graphics display can be driven by both simultaneously. The notation pattern can be built to produce an animation duplicating that obtained from the analog data. Modifications can be made after observing the actual movement to check for subtleties which may have been overlooked by the electrogoniometer's input. Three potential applications are being investigated. The system can first function as a tool assisting in dance notation and its visualization. Second are its clinical usages, primarily in studying motion abnormalities. Lastly, the macrolanguage developed for the human animations is also is used in robot manipulator control [11]. Previous difficulties in the synchronization of the two inputs [10] appear to have been resolved in later versions [11]. Its implementation as a kinematic simulation limits the types of motion that can be performed, but this is viewed as a reasonable compromise in terms of practicality.

The Design of Natural Motion

Choreography of motion, whether in determining primitive moves, planning a walk cycle, or synchronizing multiple figures, has a predecessor in

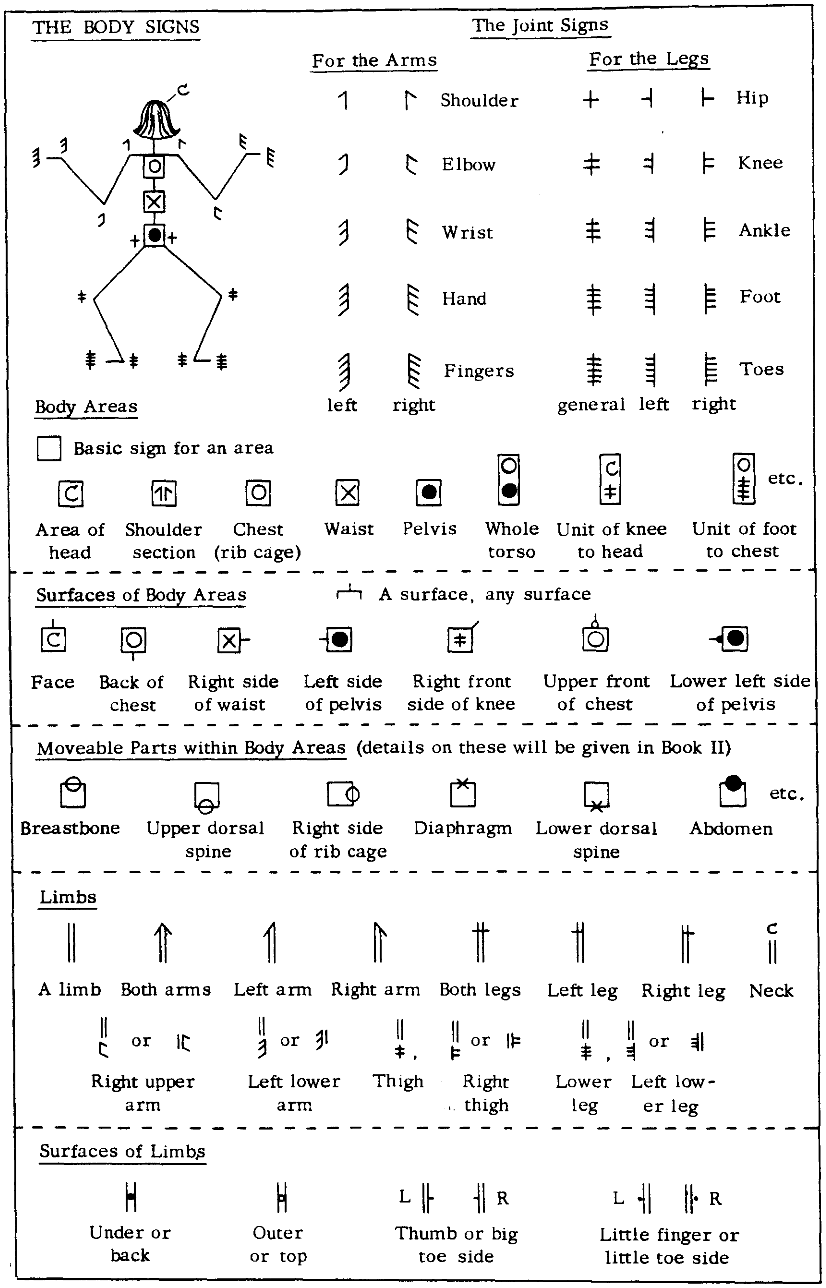
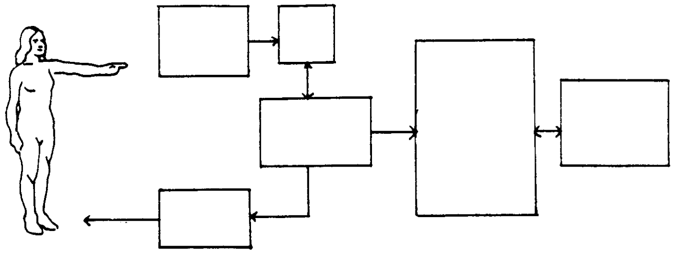


Figure 6 Labanotation Symbols

the field of dance. Some of the motion modelling systems in use today have adapted Labanotation, a system devised in 1928 by Rudolf Laban to record and analyse motion in dance. With its comprehensive categorization of direction, system of reference, rotations, timimg, and so on, it has been relatively straightforward to represent computationally. A page from the glossary of symbols is shown in Figure 5. The specification of HOW a motion is to be performed is not something that this system accounts for, and must be augmented by some other method. Ironically, dancers themselves tend not to employ this system, because of the large numbers of symbols which must be memorized.

A goal of many simulation systems is the use of natural language for simple top-level dynamic motion specification. With a flourish of the hand, commanding "waltz over there across the floor!" is certainly more natural and straightforward than relating trajectory descriptions composed of joint angles, velocities and accelerations to joint torques, which eventually are used to graphically realize that trajectory. However, this kind of simplicity at the animator's level presupposes a complex "hidden" system drawing upon knowlege gained from artificial intelligence and robotics research as well as from language analysis. Without prior knowledge about about dance, rhythm, grace and implied direction, how easily can the concept of "waltz" and even "across" be described? Is there a point at which the verbal description fails to communicate the desired action?

The manipulation of a graphic entity appearing to move autonomously and smoothly, capturing the subtleties of human gesture, remains a significant issue and challenge. In response to this challenge, we maintain that the most direct way to move a graphic figure is by "showing" it how, as a choreographer might instruct a dancer.



CONSTRUCTING THE GRAPHICAL MARIONETTE SYSTEM

The Scope of the Project

We have chosen to circumvent the complexity of a true dynamic simulation in favor of a more manageable yet unique combination of hardware and programming tools to animate our marionettes. The anticipated gain in the production of natural appearing motion and in the scripting of multiple figures outweighs the need to obtain a more precise kinetic description. The Graphical Marionette project focuses on the themes of designing body models, scripting-by-enactment of the bodily motions of the marionette, the elaboration of facial expressions from multiple inputs, and the refinement of natural motion [6]. The immediate concern is with the first two themes, and in this thesis, the former of the two.

Capturing the subtle dynamics of human motion via scripting-by-enactment will be accomplished through body tracking. The hardware being developed for this project will parameterize human motion in real time and make this data available to the other system components in the host computer. To produce such a system, concurrent work on building tracking hardware [17] and this modelling software must occur. More importantly, the two must interface properly. Figure 6 shows the overall system architecture.

Two cameras will be used to sense the positions of an array of LEDs attached to a garment worn by the scriptor. These signals are sent to the Op-Eye as "frames", a set of 15 or more discrete points, where they are amplified and digitized, then output to the AppleII. The AppleII also serves as the master controller of the tracking hardware. After further low-level processing, the data is shipped to the host via an RS-232 serial interface, and stored as a data file.

Mapping of the positional data from the coordinate space of the tracking device to the body data structure must be done before passing the data to the animation programs. Conversion to rotational information must also occur. A display processing module (the animation programs) accepts input data used to update current locations of the figure. For each frame, this module is passed rotational data for each segment, as well as viewing data, the body database, and commands for

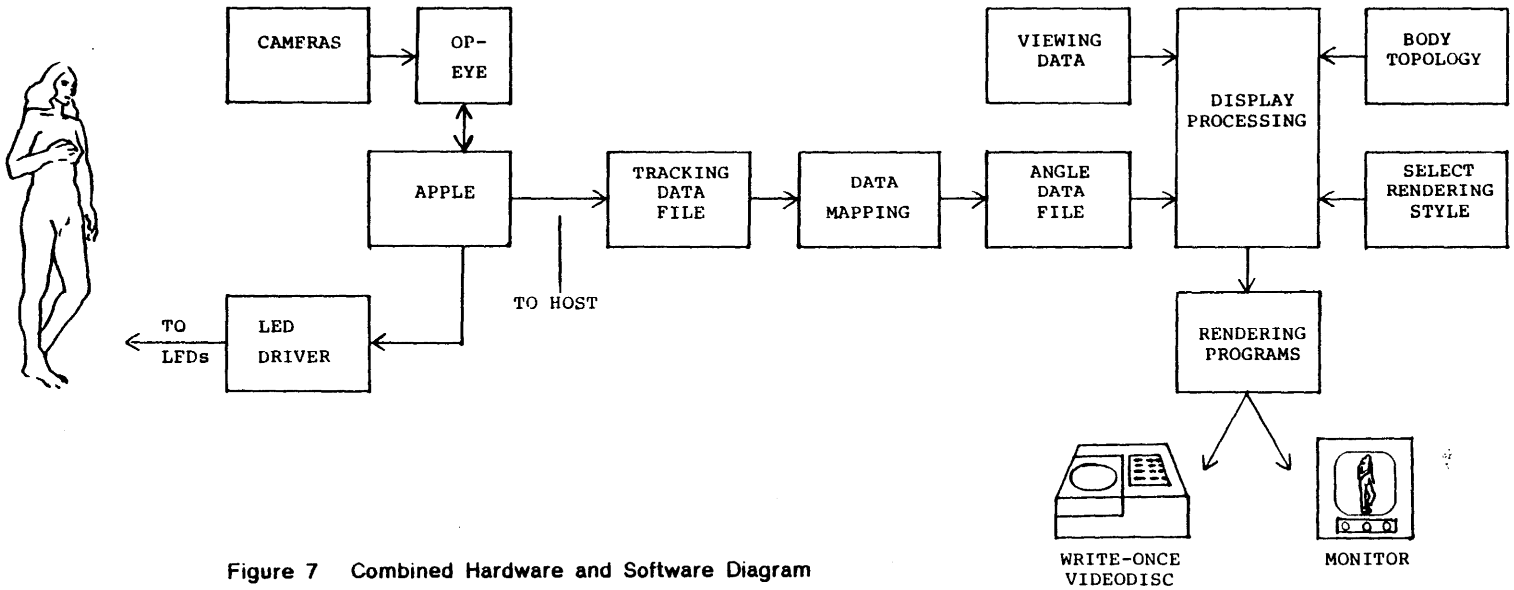
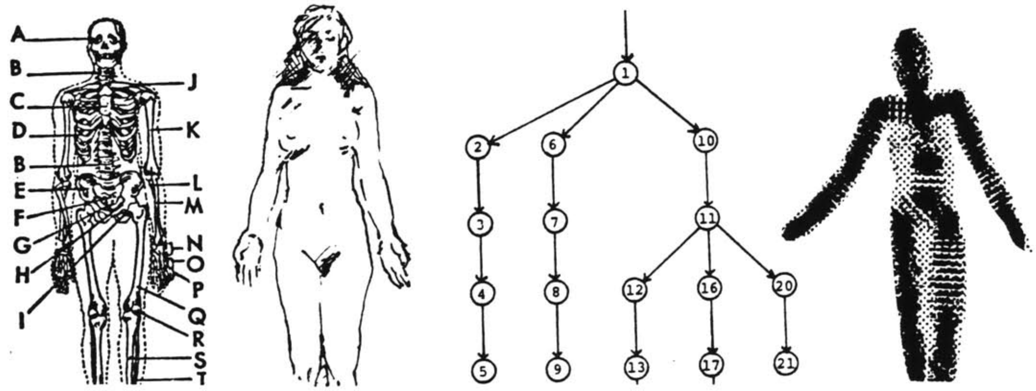


Figure 7 Combined Hardware and Software Diagram

specifying rendering style and control of peripheral devices such as the write-once videodisc, for immediate playback. Appropriate rendering programs utilize the final screen coordinate output to produce each frame of animation on a color raster display.

The "scripting space" is defined by the fields of view of the cameras and will be located in the MIT Architecture Machine Group's "Media Room". This room is about sixteen feet long, eleven feet wide and eight feet high. The far wall is a back-projection screen illuminated by a projector situated in an adjoining room. For visual feedback, the scriptor may make use of any combination of a CRT terminal, a graphics monitor, the projection screen, a "head-mounted display" [9], and a 3-D display [26]. The latter two devices were created at the Architecture Machine Group.

Discussed in Chapter Three are the processes of abstracting the body's structure and motion so that it may be represented computationally. The "body template" data structure, the composition of rotation and translation matrices, and the rendering programs are also described. Chapter Four is an overview of body-tracking and the proposed system hardware. The animation, to be driven ultimately by the tracking data, has been implemented in several preliminary stages, which are described in Chapter Five. The initial method, joint angle input, can be done independently of the body tracking, and provides a means of testing for errors. Animation sequences can be created by "keyframing", a traditional two-dimensional animation method adapted to three dimensions. The next stage is the use of simulated walk sequence data. This data is created on the AppleII, transferred to the the host, and mapped to the body model as the tracked data will be mapped. Thus, it is useful in development and preliminary debugging of the various system components. During the early development of body tracking the number of limbs that can be tracked will be limited. The problem of determining limb position from partial data arises. A typical example would be finding the elbow position given that for the wrist and the shoulder. Occlusion of one body part by another creates the same difficulty. By checking anatomical constraints and checking past history of a motion sequence, interpolation of positions within a legal range can be done. The concluding section of Chapter Six discusses some interesting animation scenarios made possible by scripting-by-enactment.



MODELLING THE BODY

A Further Measure of Man

The human body, for modelling purposes, can be regarded as a sequence of limbs, or segments connected by joints, whose movement results from rotatory motion about those joints. Albeit an oversimplification of a human being, this model is based on on bone structure, as seen in Figure 8a, and provides a connected "skeleton" upon which to build.

For programming purposes, the figure can be thought of in terms of rigid bodies, although this is not the case in the actual body. In the actual body, four segments could be considered to be rigid bodies; the two arms and two thighs (humerus and femur bones), as they contain only one bone each. The forearms and legs each contain two bones, enabling different types of motion. Foot and hand segments contain 26 and 27 bones, respectively, the head-neck or vertebral column

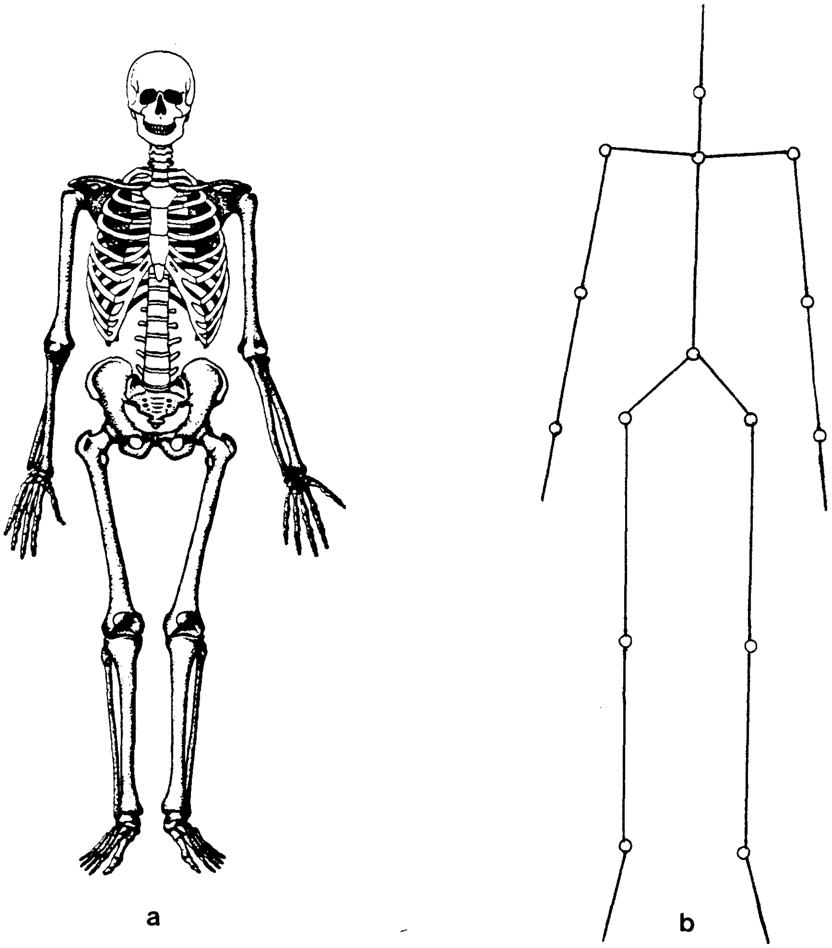


Figure 8 Skeleton and Stick Figure

consists of 24 vertebrae, a sacrum and a coccyx. A wide variety of movements, twists, and deformations possible through such an extensive array of bones make a true body model extremely difficult to attain; one must compromise by constructing the model as a series of individual small rigid bodies.

This stick figure shown in Figure 8b models the primary segments and joints in the body: pairs of feet, lower legs, thighs, hips, shoulders, upper arms, lower arms, and hands, and singly, the trunk, neck, and head. This level of representation is enough to approximate motion, yet not sufficent to show such subtleties as hand gesture employing the fingers. Separate "close-ups" are necessary to show such detail. Further abstraction of the body's architecture is required to devise an efficient data structure representing relationships among the data.

The body may be divided into eight simple components or SEGMENTS when considering motion classification [20]. They are identified easily from both the standpoints of anatomy and motion. Six come in pairs; the feet, hands, lower legs, thighs, upper arms, and the lower arms. The remaining two, the trunk and the head-neck are treated as single segments when identifying motion. When actually building a model, the trunk and head-neck may be defined by several segments, depending on the degree of articulation desired.

Establishing a Reference System

In order to establish a system of classification or movement notation one must establish a reference system, analagous to the world coordinate system in 3d graphics. There are two body postions which are referred to as the standard or default positions within this reference system. One is called the ANATOMICAL POSITION, the other the FUNDAMENTAL STANDING POSITION and are illustrated in Figure 9.

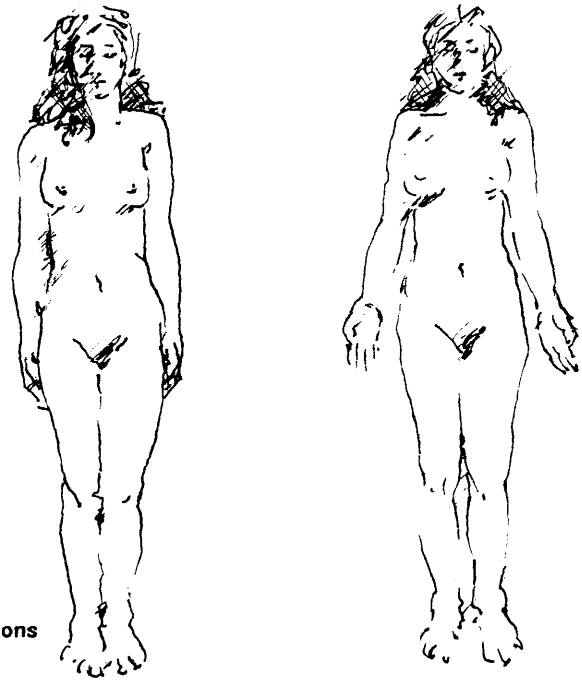


Figure 9 Anatomical and Fundamental Positions

The anatomical position is described as that of the body standing erect, feet together and pointing forward, and the arms at the sides with the palms facing forward.

The fundamental position differs only in that the hands are held with the palms facing the sides of the thighs. Establishing a primary position is useful in calibrating the relationships of the different body coordinate systems. Note that the following are kinesiological terms given with their counterparts in the marionette's coordinate system. These next descriptions assume that the body is standing in the anatomical position, for the purpose of simplifying the discussion. They are shown in Figure 10.

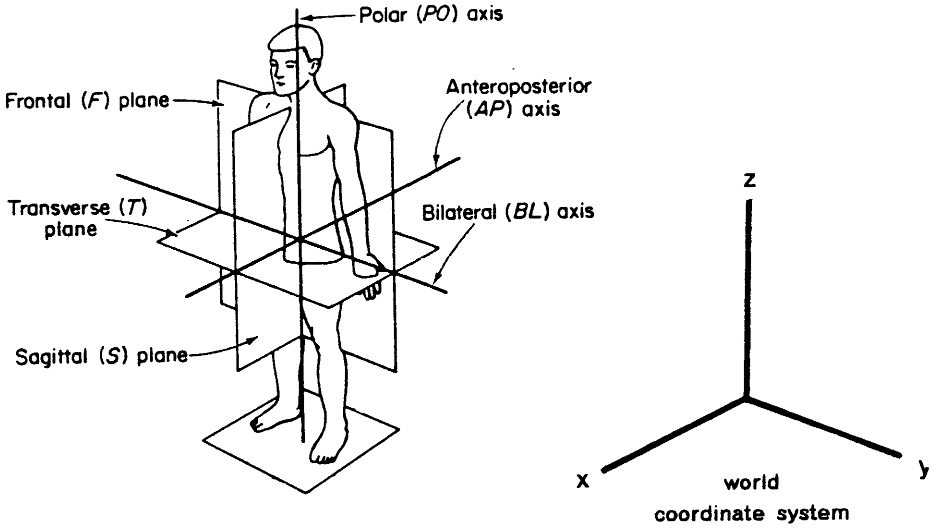


Figure 10 Body Motion Reference Systems

The POLAR AXIS of the body as a whole is the vertical orientation. This axis would pass through the head, down through the body center, to the surface upon which the body is standing. Other vertically oriented segments' longitudinal axes run parallel to this polar axis. The planes of these rotations are said to be parallel to the TRANSVERSE PLANE of the body as a whole. This axis corresponds to the Z-AXIS in my world coodinate system.

The BILATERAL AXIS is that which runs horizontal relative to the supporting surface, and passing sideways through the body. Imagine an axis drawn through the left hip, center hip, then the right hip, perpendicular to the polar axis. Horizontally oriented joint axes run parallel to this axis. The planes of motion about these axes are considered to be parallel to the body's SAGITTAL PLANE. This axis corresponds to the Y-AXIS in my world coordinate system.

The ANTEROPOSTERIOR AXIS is, like the bilateral axis, horizontal, but runs from front to back through the body. The horizontally oriented lengthwise axes of the feet lie parallel to this axis. Rotation about these axes are considered parallel to the body's FRONTAL PLANE. The X-AXIS is the world coordinate analogue of this axis. Most joint axes of the body in the standard position are oriented horizontally, parallel to the whole body's bilateral axis.

Now consider the body in motion. Most movements are not so easily described as the simple orientations of the anatomical position. For example, the elbow flexion may occur parallel to any of the three planes. Visualize the simple act of eating, of lifting a forkful of food from plate to mouth. The shoulder, elbow, wrist, and finger joints and related segments move into positions which are far from being parallel to the standard orientations. To further describe this orientation in space, each segment has one or more AXIS of ROTATION, exclusive to itself, as a part of the general body database. Six variables specify position (x,y,z) and orientation (ϕ, θ, ψ) of a segment in space; it is therefore said to have six degrees of freedom (DOF). The position and orientation of each segment in relation to its neighboring segments' orientations combine to create the innumerable complex motions of the human figure.

Motion Classification Terminology

There are six basic segment movement classes: FLEXION, EXTENSION, ABDUCTION, ADDUCTION, ROTATION, and CIRCUMDUCTION. All but circumduction depend on rotatory motion, in one of two ways. We can consider the body segment as the "axis of rotation" in some cases (as in a twisting motion), and in others it to be rotating about an axis at one of its two ends, with the plane of rotation traced through space by the segment itself. In both cases the axis of rotation is perpendicular to the plane of rotation, but not limited to one position in space. Two of the previous terms are commonly used to describe almost all of these classes of motion; FLEXION covers about all bending motion, and ROTATION is used to describe most segment orientations. Movements such as flexion and extension nearly always refer to the joint involved rather than the segment, whereas rotation terminology refers to the segment(s) involved.

From Body to Binary Tree: The Data Structure

The sequence of rigid segments connected by joints can be treated as a tree structure to describe the body's connectivity. A convenient method for expressing hierarchical structures such as the body, a tree allows for a systematic processing of all the body parts.

A tree is a nonlinear data structure which can be viewed as a particular type of graph; a graph being a representation of a system of connections or relationships between a number of things. A GRAPH, G, consists of a nonempty set V (the set of VERTICES), a set E which is the set of EDGES, and a mapping from the set of edges E to a set of pairs of elements of V [34]. There is at most one edge joining any pair of vertices. A tree structure indicates a branching relationship between its vertices, or NODES. Knuth defines a TREE

> as a finite set T of one or more nodes such that

a) There is one specially designated node called the ROOT of the tree, root(T); and

b) The remaining nodes (excluding the root) are partitioned into m >= 0 disjoint sets T1,...,Tm, and each of these sets in turn is a tree. The trees T1,...,Tm are called the SUBTREES of the root. [21]

The LEVEL of a node is given as being its distance from the root. Every node that is reachable from a node N, is said to be a descendant of N. The nodes that are reachable from that node N, through a single edge, are called N's SONS. N can thus be referred to as their FATHER. BROTHER nodes are those which are sons of the same father. A node with no sons is called a TERMINAL NODE or a LEAF. A tree TRAVERSAL or "tree walk" is a procedure by which each node is visited in some systematic fashion. The general tree structure can be represented equivalently as a BINARY TREE. Knuth defines a binary tree as "a finite set of nodes which either is empty, or consists of a root and two disjoint binary trees called the left and right subtrees of the root." [21] This correspondence allows for a more convenient computational representation of any tree, and can be defined algorithmically. In contrast to the way in which real trees grow, this structure is visualized with the branches growing downwards from the root. By studying the diagrams in Figure 11, one can see the relationships of the components within a tree structure, as well as that between a general and a binary tree.

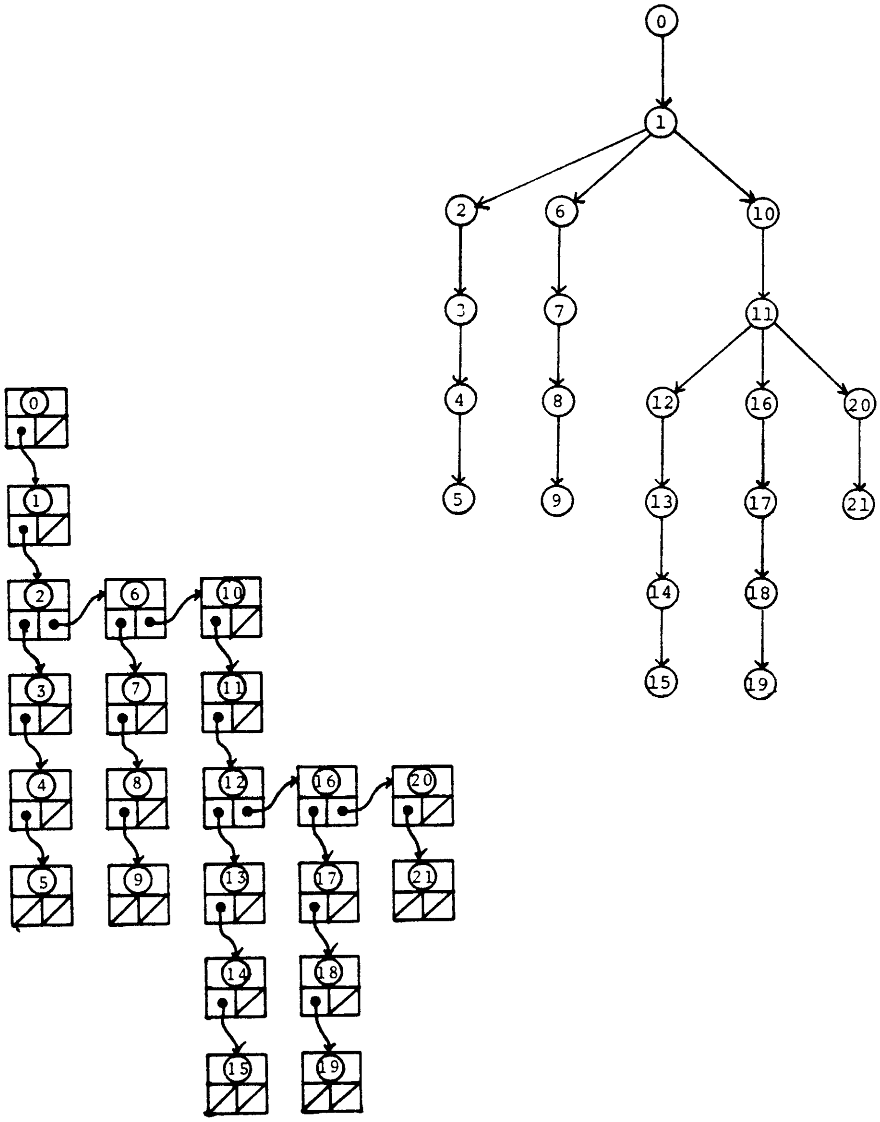


Figure 11 General and Corresponding Binary Tree Structures

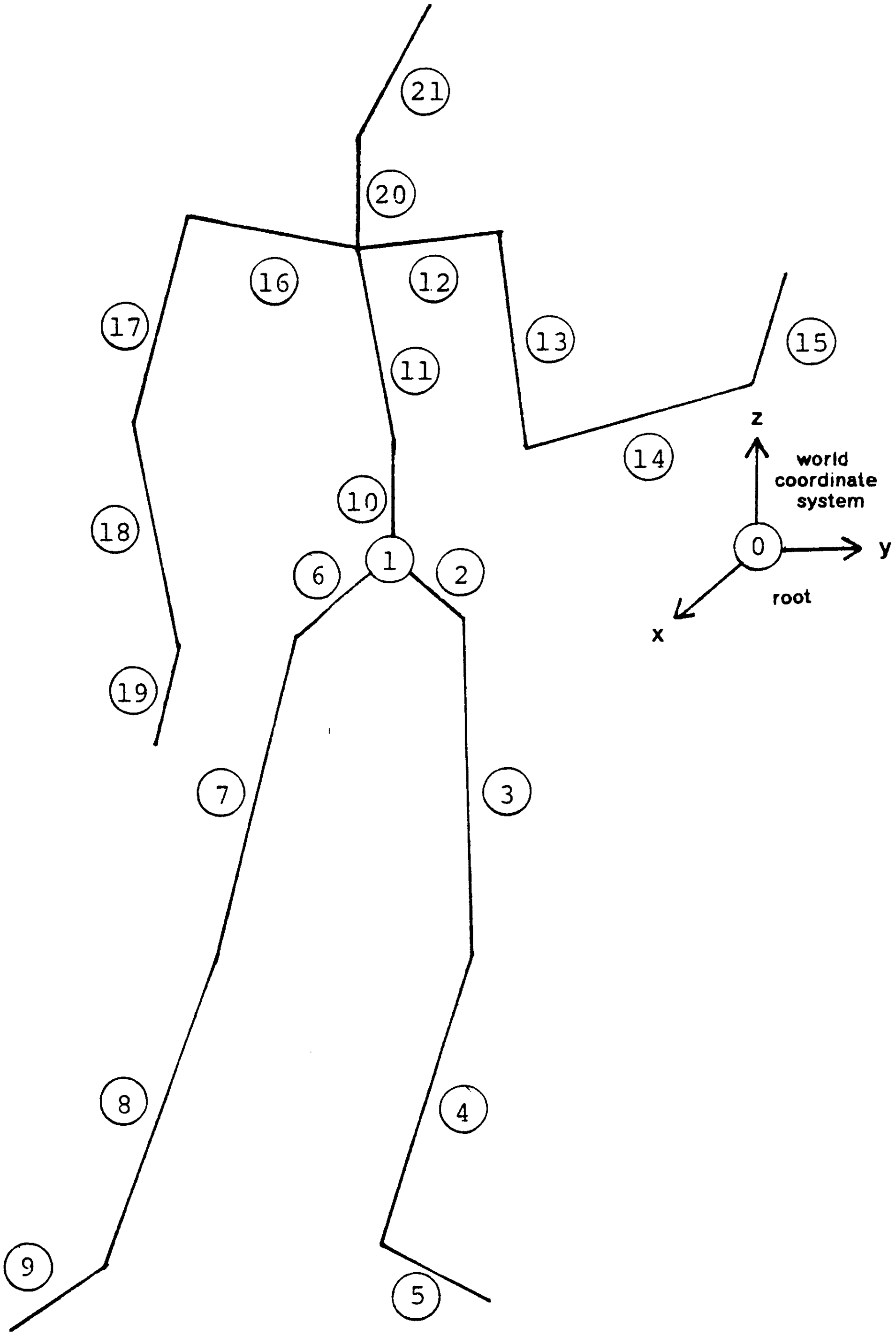


Figure 12 Node Numbering Conventions for Body

The numbering of the nodes in all of the body data structures refer to the body segment names, rather than the joint names. This is consistent with the motion classification convention of rotation referring to the segment(s) involved. This numbering begins with the root node(0), which functions as a connection between the world coordinate system and the center hip(1), and continues as shown in Figure 12. When definining the body's connectivity, the son and brother node are also given. A "0" son or brother number indicates a leaf node has been reached (i.e. the left and right subtrees are null). The father's number is assigned at run time.

Traversing the "body tree" requires a STACK, a linear list permitting the addition and deletion of an element at one end. The addition process is called PUSH, while the deletion is POP. The elements can be removed only in the opposite order than the order in which they were added; the bottom of the stack would therefore be first element added, and the top the last element added. A stack pointer keeps track of the top element in the stack, and is incremented by one each time a new element is added. To begin:

a) Initialize. Set stack pointer to 0, node to root node number.

b) Check if the current node has a brother. If there is one, push the brother onto stack and increment the stack pointer by one.

c) Check if the current node has a son. If so, the son now becomes the current node. Return to step b and repeat until there are no more sons, then proceed to step d.

d) Check the stack pointer to see if there are any brothers waiting in the stack. If so, pop the brother that is indexed by the pointer. This becomes the current node.
Decrement the stack pointer by one, then return to step b.

When all of the son and brother nodes have been visited, the walk is complete.

Components of the Body Data Base

The information for each body segment is summarized as follows:

node number
name
current x-rotation
current y-rotation
current z-rotation
segment length
circumference
current 4x4 matrix(LTM)

son

brother

father

flag (bit(1))

Minimum and maximum rotation limits for each joint may also be contained in this structure, but are not essential at this point.

This data, although maintained as a single structure at run time, is composed of a number of smaller, related structures. Son and brother information completely and flexibly specify the connectivity of the body. Each segment has an associated 4x4 matrix, controlling the motion of that segment and its descendants, functioning much as the in an actual limb would. The flag signals rotation occurring at this joint so a new matrix will be composed. The terms PROXIMAL and DISTAL are often used to describe positions as "near" or "distant" from the point of origin. Maximum and minimum extent of rotation (current x,y,z) and translation (segment length), as well as other anatomical constraints, may also be stored in the data structure and used for error checking and interpolation. The segment circumference information is used later by the rendering programs. Rotations in x, y, and z represent the rotational transformation that the current segment must go through such that its distal joint is contained in the z-axis of the father's own local transformaton matrix (LTM).

The first rotation provides a twist around the previous segment, the remaining two rotations line up the distal joint with the z-axis. The segments' orientations combine to create the innumerable complex motions of the human figure. The LTM of a node represents the history of all previous joint rotations and segment translations plus the current rotations. Composing of the LTM will be described shortly. The function of the x, y, and z rotations are best understood in that context.

Each segment exists in a coordinate system embedded in its proximal end at 0,0,0. The z-axis always points along the segment's longitudinal axis to its distal end, which is also the proximal end of the next segment. The distance between them is thus (0, 0, length). When the body is standing in the anatomical position, the positive x-axis points forward, and the y-axis points in the direction that maintains a right-handed coordinate system. In the case where the z-axis points forward, as in the feet, the x-axis points upward in relation to the whole body.

Composing the Transformation Matrix

The orientation of the distal joint of each segment, saved as angles in the body data structure, is described in relation to the father's coordinate system after the latter has been translated along the father's segment length. There must exist a composed world-to-proximal-joint coordinate transformation that causes the distal joint to be placed in the proper relative orientation for subsequent rotation. Hence, prior to actual operation on the current segment, the current transformation matrix contains information about all the relative rotations and translations of the node's antecedents. To compose each local coordinate system transformation matrix, independent of any other segment, the operations are concatenated in this order:

```
M[node]     = identity_mat[node]
M'[node]    = M[node] * rotx_mat[node]
M''[node]   = M'[node] * roty_mat[node]
M'''[node] = M''[node] * rotz_mat[node]
M''''[node]= M'''[node] *  z_trans_mat[father]
```

```
In short: M''''[node] = rotx[node] * roty[node]
          * rotz[node] * ztrans[father]
```

The world-to-proximal-joint transform is composed in this order:

```
LTM[node] = M''''[node] * LTM[father]
```

Matrix operations done in this order signify that a coordinate system is being transformed, as opposed to a point or set of points. The sequence can be thought of as actually being performed from the last component, backwards. The LTM is now updated by the current angles and becomes the transformation matrix to be used by the next node, that is, the son. In short, the sequence for each segment is:

a) Orient to the father's coordinate system, with proximal joint on the father's z-axis.
b) Translate the father's coordinate system to the proximal joint.
c) Rotate about the z-axis.
d) Rotate about the y-axis.
e) Rotate about the x-axis.
f) Update to the new coordinate system.
g) Draw the segment, using its limblength and other associated data, in the new coordinate system.

Note that even though this allows us to visualize each segment in its own coordinate system, the points remain in the world coordinate system. Also, a rotation of any given joint will affect the motion of all of its descendants; if you move the shoulder, the arm and hand are moved as well. Thus, a rotation of any given joint will affect the motion of all of its descendants (sons) -- if you move the shoulder, you move the arm and hand as well. Segment/node [0] connects the entire body to the world coordinate system.

Segment/node [1] is the center node of the entire body. Both segments have a limblength of 0.

Rendering Programs

The initial body types are three: a stick figure, a "cloud" figure composed of points distributed about the longitudinal axes within ellipsoidal volumes, and a handless and footless stick figure. The latter was made specifically for the walk simulation program described in Chapter Five. All of these provide simple, quick visual feedback to the animator. Subsequent "fleshed-out" models can be constructed from this initial database after the animation has been scripted and previewed.

Unfortunately, modelling the features of the body is not a trivial task. Two techniques commonly used, surface modelling and volume models both have certain drawbacks, as mentioned in Chapter One. Some experiments were done with volume models before arriving at the current "cloud person". The ellipsoid, out of all the simple volumes, appeared to be the shape which best represented most of the parts of the human form, but still appeared overstylized. By generating points randomly within that volume, the ellipsoid shape can be degraded enough so as to appear more like a limb, that is, more irregular.

The first model used parametric representations of an ellipse and a circle to generate the points about the longitudinal axis [33]. "Circles of points" were drawn at even intervals from the distal to proximal end of each segment. A random number determined the radial distance of the point between 0 (on the longitudinal axis) and the maximum radius determined for that point on the ellipse. Although efficient (a minimal number of sine and cosine calculations), the circles of points looked like horizontal slices through the body. (See Figure 13)

In order to minimize this effect, the distance along the z-axis, the distance about the z-axis in degrees, and the radius were all multiplied by a random number between 0 and 1. The result can be seen in Figure 14 . The distribution of points may be adjusted so that denser clustering along the longitudinal axis gives the appearance of solid "bones". Color can also be regulated by the same distribution function; the "bones" can be white, while the outer points may be of some other darker color. The advantages of using randomly distributed points are mainly in the avoidance of both the hidden surface removal computation normally used for solids and the problem of holes or "singularities" occurring at sharply bent joints.

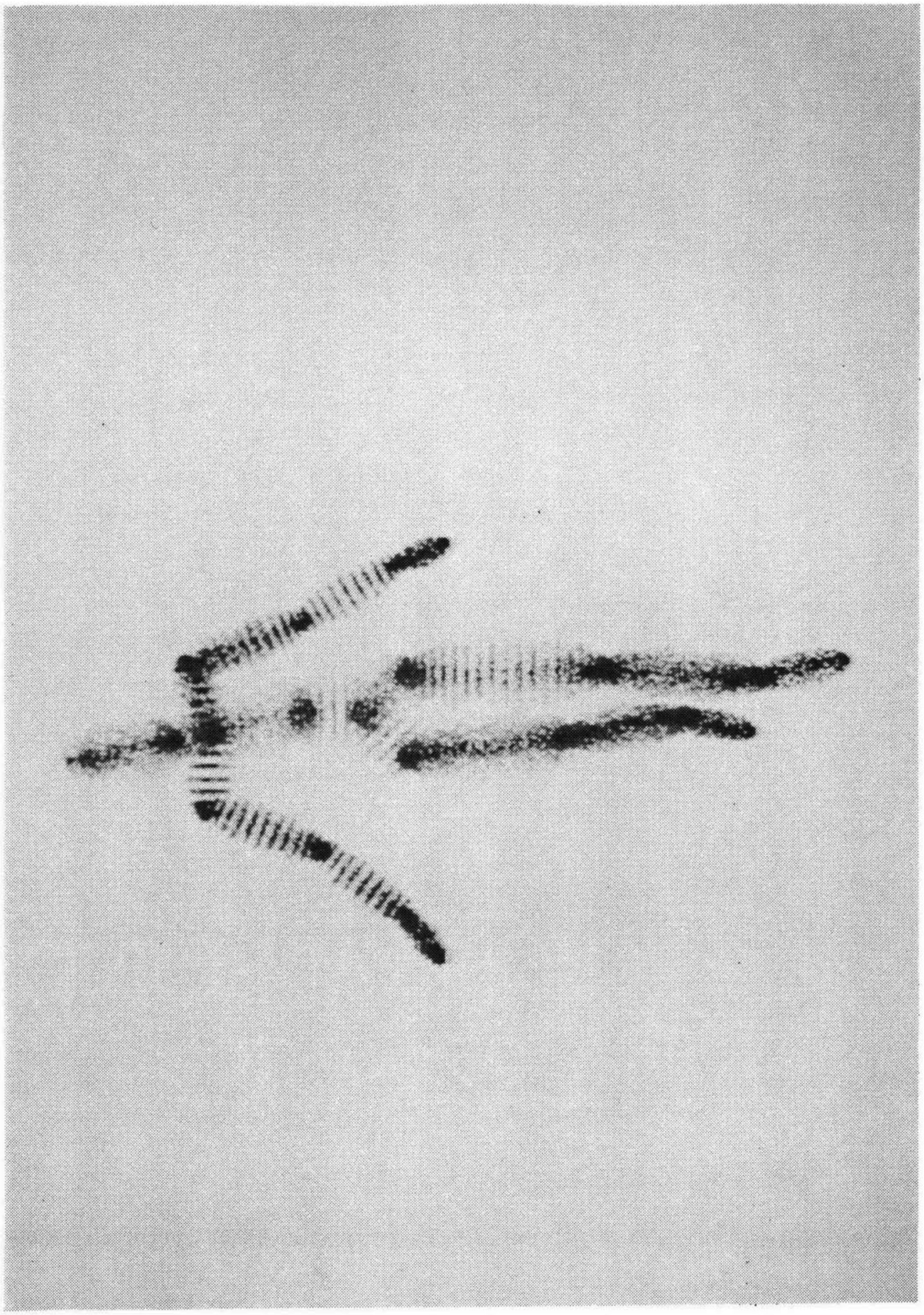


Figure 13 "Cloud Person" with One Random Variable

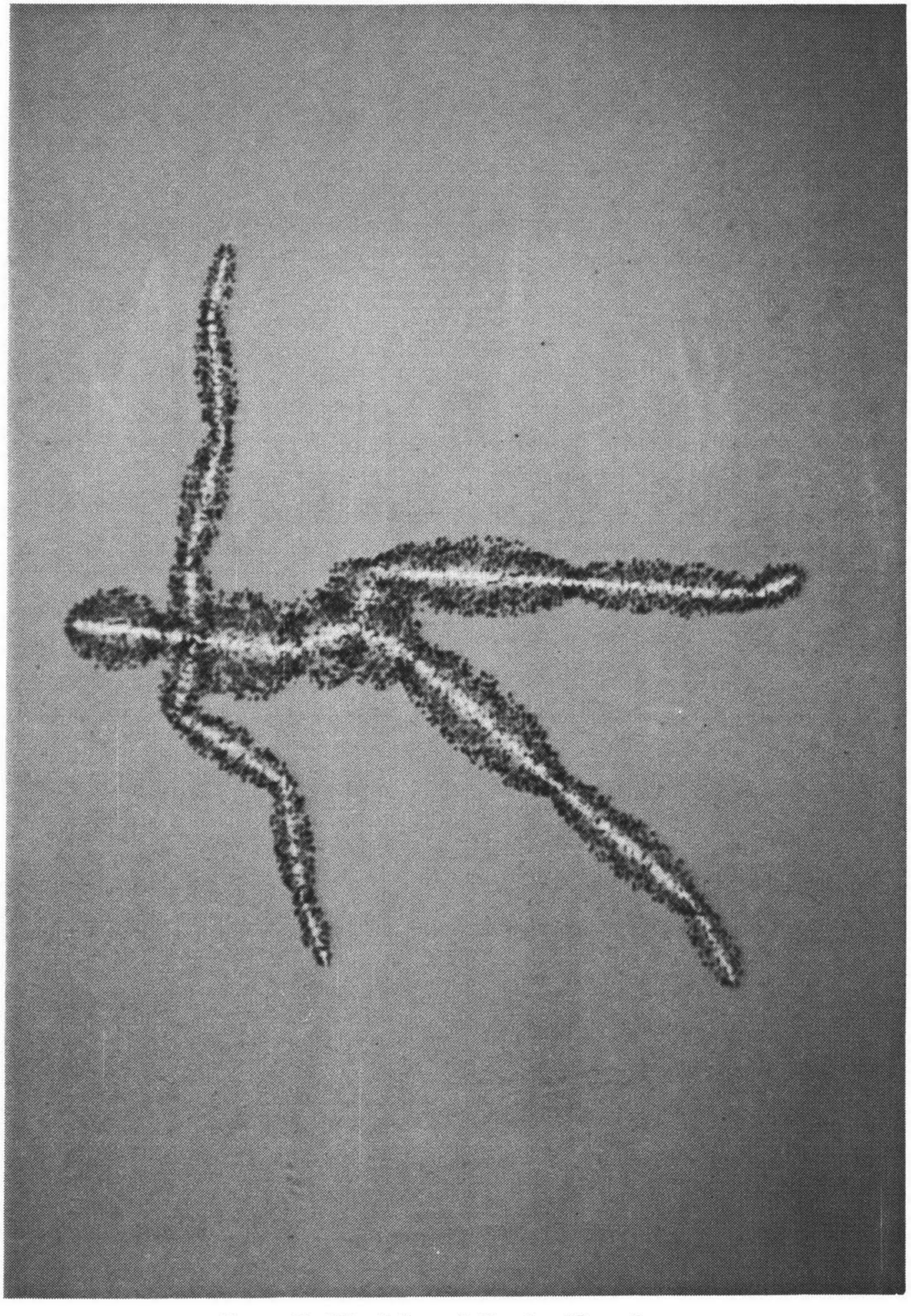


Figure 14 "Cloud Person" Showing "Bones"

The lengths of the body segments were obtained from the Humanscale [14] survey, being the link measurements of a fifty percentile female. These dimensions only are useful as a general rule of thumb; in rendering the body in diferent styles, one must adjust the measurements. For example, to display a stick figure of pleasing proportion, the shoulders must be moved higher, the hips made wider, and the neck shortened. This will help to account for the missing bulk of muscles and flesh. For the cloud model, on the other hand, the lengths of the feet, hands, and head must be shortened to accomodate the extension of the ellipsoid past the end of the segment. Segment circumference, controlling the ellipsoid radius, must also be adjusted until an aesthetic proportion is achieved. The measurements for the body in the walk simulation were obtained by algorithm generating segments proportional to the torso, as is explained in Chapter Five.

By passing the current LTM (concatenated with the view matrix), the limblength, and radius, to the rendering routine, various drawing programs can be invoked at will. More information on the body dimensions can be added to the database, and more complex rendering programs can be devised. The creative programmer can go further and build things that are a bit odd. For example, this Bauhaus Theatre character in Figure 15 could be modelled by primitive solids.

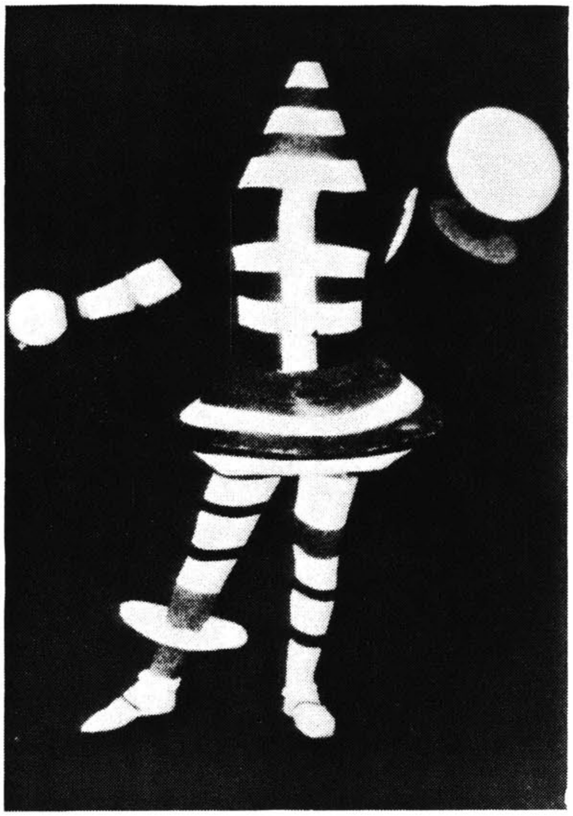
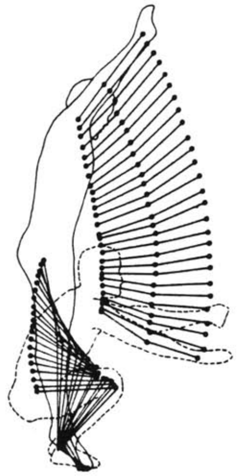


Figure 15 Bauhaus Theatre Performer

The procedure for generating animated images can be summarized briefly. The body is abstracted as a data structure, and maintained as a template accessed by the animation program. A similar data structure contains movement data for each body segment. A sequence of these individual frames may be combined to form a script. The animation can be viewed in perspective from any viewpoint. Newman and Sproull's "Principles of Interactive Computer Graphics" is the source of this algorithm [25]. In addition, a viewport, a rectangular area on the screen bounding the drawn image may be chosen. The image is scaled correctly to the dimensions of this viewport, and clipped if necessary. Rendering programs are written as separate and interchangeable modules. A stick figure, and several variations on a volume model can be chosen. These programs are written to be compatible with any body model that has been created as a template. The development of the animation programs is described in greater detail in Chapter Five.



From Plagenhoef [28]

BODY-TRACKING

Background

Machine analysis of human motion has been studied in several ways. Pattern recognition of video or film is potentially the most powerful in terms of the richness of the data available and the ease in acquiring it. However, precisely because of the abundance of information and also because of limits on present technology, it is an extremely complicated problem in machine vision which is not presently suited to tracking of unconstrained body motion.

Moving Light Displays (MLDs) are a simplified representation of motion for pattern recognition and have traditionally been used for studies in motion perception [35]. The object or objects whose motion is to be studied is represented as a set of points or lights distributed on its (their) surface(s). These lights then constitute a mapping from object space to image space and can be analyzed for motion as the image varies over time. In the context of scripting-by-enactment, the human subject, or scriptor, would wear a set of continuously illuminated lights located at strategic points. This amounts to parallel acquisition of data which is presented as successive sets of dots, each set representing a "snapshot" or frame of the object in question. The problem in this case would be to assign meaning to each dot within each frame. In other words, correspondance must be established between each dot of the captured image and points on the surface of the object. This is a complicated yet tractable endeavor but when two separate perspectives and triangulation for depth information are required then problems with speed, occlusion of lights and the added correspondance factor all become severe [31]. It then becomes unreasonable to track in three-dimensions gross body movements with a flexible, array-of-lights setup in real time at low cost.

Several products that illustrate other approaches are available commercially, including the Polhemus, the Coda-3, and the Selspot. The Polhemus system [7] consists of a transmitting device, a sensing device, and support software. The sensing device, attached to a cord and worn by the subject, is a plastic cube into which three mutually orthogonal coils are epoxied. The transmitter radiates a nutating dipole field by which the sensing cube is able to yeild six degrees-of-freedom positional information. This type of tracking has been tested on a smaller scale in a software simulation of a Unimation Puma robot arm. The graphic robot can be "taught" to move by a human trainer using a Polhemus cube system in our Media Room [23]. Cubes like this, with their cords, are unwieldy for total body tracking, not to mention the fact that on the order of thirty transmitting/ sensing sequences would have to be multiplexed.

The Coda-3 is a device, not yet available in the U.S., that provides remote and non-contacting means of monitoring the movement of up to eight so-called landmarks. It uses optical scanning to sweep three fan-shaped beams of light across the field of view and then senses the reflections from the landmarks. It is a good, if costly, solution to the problem but the limit of eight position indicators is too restrictive for body-tracking as an animation tool.

In the Selspot system [12,22], the subject wears a set of LEDs emitting in the infrared range which are pulsed in sequence. Typically, thirty LEDs may be worn. A camera which is sensitive primarily to these LEDs and synchronized to them senses their projected position by means of a two-axis lateral effect diode. Depth is determined by triangulation from the output of two cameras. This method of movement monitoring corresponds to serial acquisition of the data and also poses the most likely solution to body-tracking for driving a graphical marionette. The Selspot is, however, too restrictive in terms of the placement of the LEDs and too expensive.

The application is tracking of gross body movements for driving a body model. The Selspot approach is a good place to start but is inappropriate for several reasons. It is typically used in situations, such as determining muscle forces, where great precision is required. Lower resolution and lower accuracy are tolerable in the present context and even necessary to reduce costs and simplify processing requirements. On the other hand, greater flexibility is required in LED placement. The Selspot uses arrays of LEDs which are strapped to the body segment. The scriptor of the graphical marionette should be able to don a comfortable, ready-to-wear garment. The point is to enhance the human-machine interface, not complicate it. Many more LEDs will have to be used to compensate for the non-rigidity of the garment. This fact can be used to advantage since many LEDs in the vicinity of one body point may pulsed simultaneously, thus constituting a "virtual point" and providing a brighter light source. Unlike Selspot, domain specific knowledge, i.e. body geometry and dynamics, may also be used for error checking and interpolation.

The body-tracker should be automated, i.e. it should require no operator intervention. It should produce a set of position points (x,y,z) in real time and provide visual feedback for the scriptor. It should also be as unobtrusive as possible to the scriptor and aim for portability in the sense of being adaptable for use on a personal computer.

Developing the Body-Tracking Hardware

The heart of the body tracking system is a two-axis lateral effect diode made by United Detector Technologies (UDT). This optical sensor detects the position of a spot of light on its surface. Two-dimensional position information is then obtained via four electrode connections at the edges of the detector. The signals from these connections are fed to an interface module, called the Op-Eye (UDT), where they are amplified and digitized to 12 bits. The output is compatible with an AppleII which then sends the data to a Perkin Elmer 3230 after a certain amount of low-level processing. The camera system uses ordinary optics and does not require precise focus since the detector senses the "centroid" of the light spot on its surface. Motion is constrained to the intersecting fields of view of two cameras. Both the tracked LEDs and the photo-detector operate in the infrared range so the system is relatively unaffected by ambient light.

The prototype garment being developed is like a lab coat. A suit will be devised or pants will be added to enable tracking of the entire body. LEDs will be distributed across the surface of the prototype garment and fastened by piercing their leads through the fabric and wire-wrapping the leads on the inside of the garment. Wiring for the LEDs will thus be on the inside and will be protected by a lining. Placement of the LEDs will be on points corresponding to joints and other bony prominences.

Control circuitry must be as portable as possible so as not to encumber the wearer. No umbilical cord would be necessary given an initialization sequence for each "body-cycle". One is planned for now, however, so that the sequencing of the LEDs can be done in a flexible asynchronous manner, so that problems with loss of synch can be avoided, and so that a standard power supply can be used. Since each LED will be pulsed individually, the LED wiring inside the garment is forced to be in parallel. To minimize this wiring, a decoding scheme can be employed. In this case, the LEDs are divided into subgroups with the LEDs belonging to each subgroup connected in parallel. Each subgroup corresponds to a major subdivision of the human body, like a leg-hip section, for instance. The master controller is implemented with the AppleII and thus is a separate unit located away from the scriptor.

The center frequency of the LEDs is such that it matches the peak response of the cameras and such that ambient light does not interfere. If necessary, optical filters may be used to eliminate incandescent sources. The diodes must operate with large included angle between half-intensity points in order for the camera to be able to detect them when they are at various orientations in space. For a radiation angle of 120 degrees, at least three LEDs must be used to represent a joint such as an elbow. More LEDs are actually needed since extra information helps offset the difficulties encountered by using a loose-fitting garment. More LEDs also yield a higher signal to noise ratio at the detector. In this context, the spatial averaging response of the detector is a feature which is exploited. Since all the LEDs associated with one joint are pulsed simultaneously, they do not, by themselves, represent increased bandwidth. The Op-Eye is capable of sampling at up to 5 KHz but the speed of the overall system is much greatly reduced by the present throughput limitations of the host (960 char/sec).

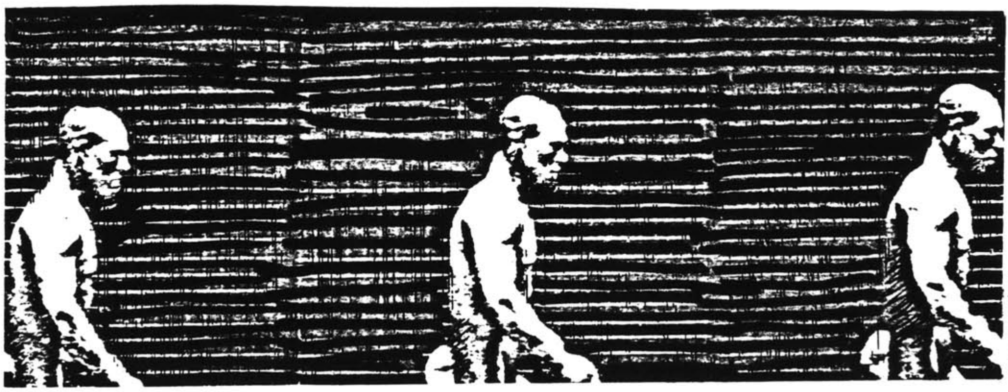
The diodes must radiate with adequate intensity to be detected by the cameras. They will be operated with a very short duty factor, enabling them to handle a large amount of instantaneous current. The Op-Eye's sensing photodiode has a minimum detectable intensity at its surface of 0.1 microwatts per square centimeter which translates to a required minimum LED power in the vicinity of 4 mW [16], considering optical parameters and scripting space dimensions. The diodes used can radiate on the order of 100 mW in derated situations.

Interfacing Hardware and Software

Upon transfer to the host, the data should first be used as entries into a lookup table to correct for non-linearities due to each camera. A calibration routine using a fixed grid of light sources is required to initialize the lookup table. The raw data are then low-pass filtered. The resulting x-y coordinates from each camera and corresponding to a particular LED are to be used along with focal length information to reconstruct by triangulation the position of the LED in object coordinates. Occluded points may be inserted by interpolation or neglected when feasible. All (x,y,z) coordinates may be checked for errors on the basis of past history and anatomical constraints [18].

The final points are conditioned for the animation program and then passed to it. The points must be mapped into a data structure compatible with the body template, which are combined in the animation program in the BODY_DATA structure. The (x,y,z) points in world coordinates are used to compute the orientation (in degrees) of each segment in its own coordinate system.

The goal is to process an entire body's worth of LEDs every thirtieth of a second, although the real bottleneck is likely to be the animation program. At this time, stick figures require approximately one second per two frames to render, and a cloud model requires from one to two minutes per frame, depending upon the number of points needed for the model. Optimization of the rendering routines can be accomplished at a future date.



Muybridge

EVOLUTION OF THE ANIMATION SYSTEM

Understanding how to generate motion even at the simplest level is prerequisite to building such a tracking and animation system. In light of this, the animation programs have progressed from simple input of of joint angles to a kinematic simulation of a walk cycle.

Keyframing

KEYFRAMING is a traditional animation technique which has also been adapted to computer animation. The animator draws the figure to be animated as it is to appear in frame A, then draws it as it is to appear in frame B. The process of INBETWEENING or INTERPOLATION determines the positions of the figure in frames A+1 to B-1. This method was used to test for correct body data structure connectivity and transformation matrix order.

Keyframe positions may be created and edited, then stored in named data files. One of the editing programs allows the animator to open any keyframe file, change the angles at any node, draw it, and continue until a satisfactory position has been reached. At that time, it is written out. A SCRIPT can then be made up of individual keyframes and the number of inbetweens to be generated. One may view an animated sequence by running a scripting program which does simple linear in-betweening based on the (x,y,z) rotation values at each joint. A synopsis of this process for a sample move is given below. If you are trying to generate values for the head angle between frames 1 and 5, and the values for frames 1 and 5 were 0 and 12 respectively, then you can say the following:

a) There are (finish-start-1) = 3 frames to inbetween.

b) The total motion for this segment is (head[5]-head[1]) = 12.

c) The motion for each step from one frame to the next is
(head[5]-head[1])/(finish-start) = 12/4 = 3.

d) For the n-th frame after the first frame, the position is:
head[1] + n * ((head[5]-head[1])/(finish-start)).

e) The problem with this is that any error in the increment (head[5]-head[1]) is multiplied by larger and larger values of n. Alternately;

f) Compute and save the difference (head[5]-head[1]), and compute the position as head[1] + (head[5]-head[1])*(n/(finish-start)).

g) n/(finish-start) can be thought of as the percentage of the way between the start and finish positions this frame (start+n) is in time.

Sequences showing both the stick figure and the cloud person have been recorded on the write_once disc and slides. For testing purposes, keyframing is adequate, and provides the animator with visual feedback. However, there are several drawbacks to this method. It generates motion which is too uniform to look natural; human motion consists of numerous parallel and uneven movements. It is possible to use some other method than linear interpolation to define a space curve, such as B-splines, but timing is still problematic. Also, trying to move the figure by joint angle input for 22 nodes is slow and non-intuitive for an animator. The effects of multiple rotations in 3-space are hard to predict unless one is thoroughly familiar with this method. Figure 16 shows the result of a keyframe script.

A Walk Simulation

For the purposes of system development and testing, an algorithm that generates synthetic walkers was

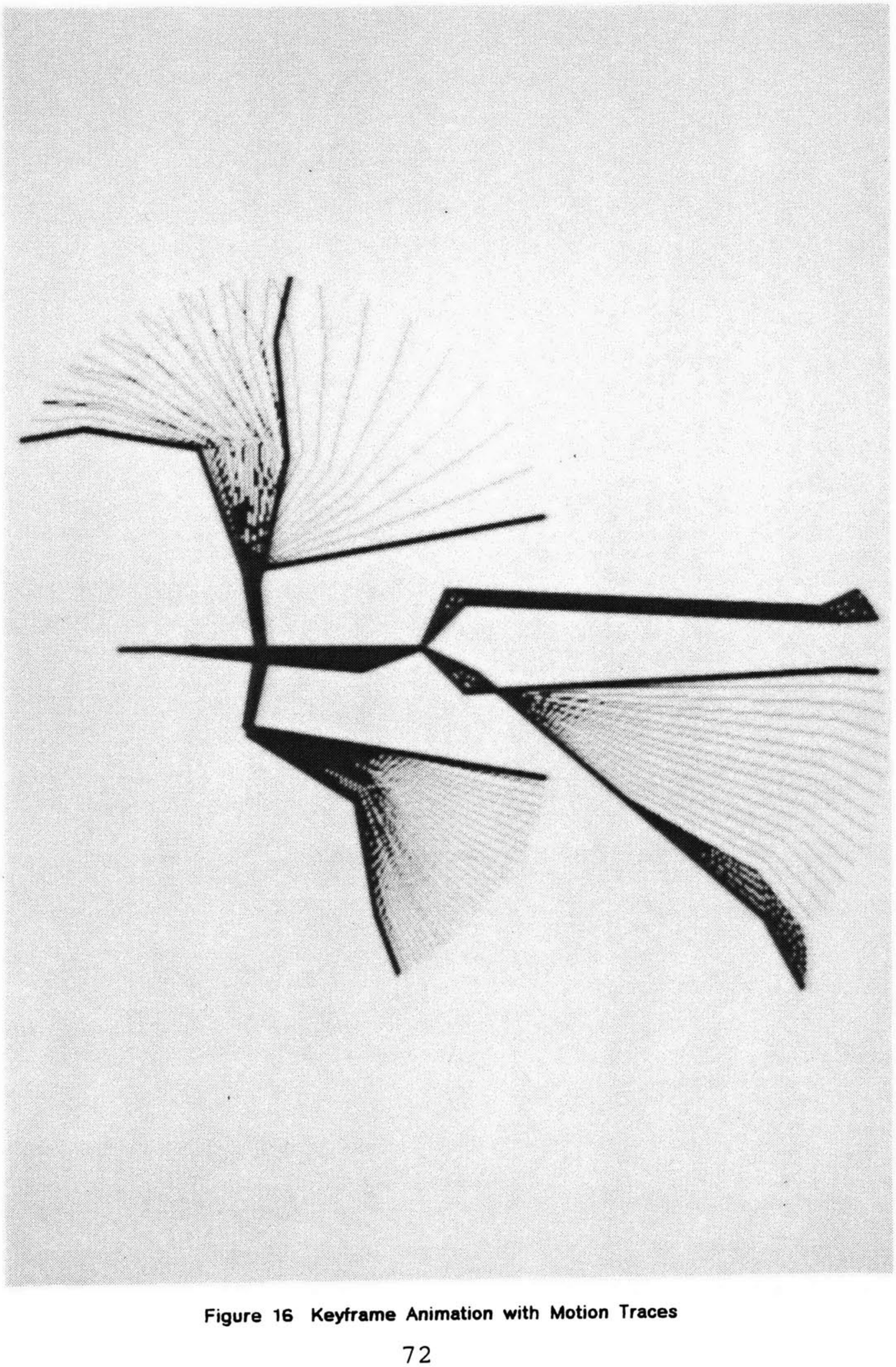


Figure 16 Keyframe Animation with Motion Traces

implemented. [17] This Apple Basic routine, called "SIM", eliminates the tracking hardware as a system variable and aids in the development and debugging of the RS-232 driver, the mapping of tracking data to the body model, and other software modules such as triangulation and filtering. The program was adapted from one by Rashid [31], written in SAIL (Stanford Artificial Intelligence Language), which, in turn, was adapted from an algorithm created by Cutting [13] and his colleagues. Many measurements of natural gait were made and used to design algorithms appropriate for gait synthesis.

The algorithm is kinematic, as opposed to dynamic, descriptive as opposed to analytic. Three step cycles, or six steps, are simulated for a total of 120 frames. Points are generated in three dimensions, thirteen per frame, based on elliptical motions of the hips and shoulders, and pendular motions of the limbs. Many trigonometric calculations are made each frame to determine the position of the points, which represent the head, shoulders, elbows, wrists, hips, knees, and ankles. The body, as thirteen points, moves on a straight path in the world coordinate system, with its vertical axis parallel to the y-axis. Motion and dimension may be adjusted with the following parameters:

a) torso length
b) hip excursion

c) shoulder excursion

d) step size

e) speed

All the limb lengths are keyed to the torso length, i.e., changing the torso simply scales the body. The hip and shoulder excursions affect the appearance of the figure, particularly on the basis of gender. Varying the step size and speed alters the quality of the motion. The body's forward lean increases with speed, as do the extent of arm and leg swing.

The present implementation is different from Cutting's in that no account is made of the occlusion of lights as the figure moves. The SIM program models the figure as transparent.

As created by the algorithm, the frames occur at even angular intervals of the swinging limbs, not even intervals of time. The synthetic gait data is generated off-line and played back with an assembly language program optimized for speed.

SIM creates a file of world coordinate data out of 120 frames; the data is then shipped out through the serial interface to the host computer. Although the SIM program was written in Basic to run on the Apple, it could just as well have been implemented on the host, with the resulting data sent back to the Apple which would then, in turn, simulate the original process of sending out the data itself, the point being to approximate the flow of the data as it would occur during normal operation of the body-tracker.

The SIM data file is used, in one application, to animate the tree-structured body model. It eliminates the need for keyframing and inbetweening, and is a good approximation of where the lights will be placed on the LED suit.

Three initial incompatibilities exist. In the first place, both the SIM and body-tracking data correspond to virtual points, or joints, while the body model uses nodes with segments that have non-zero length. Secondly, data from the body-tracker are in the form of cartesian coordinates, yet the tree structure uses angular data. One is a problem in mapping structure, the other in mapping data. Lastly, the dimensions of the two world coordinate spaces are dissimilar.

The first issue is resolved by creating a one-to-one correspondance between joints from SIM and segments from the body model. A potential for confusion lies in the fact that every segment is bounded by two joints, but if each segment is paired with its distal joint, as illustrated in Figure 17, then the mapping becomes unique and one-to-one.

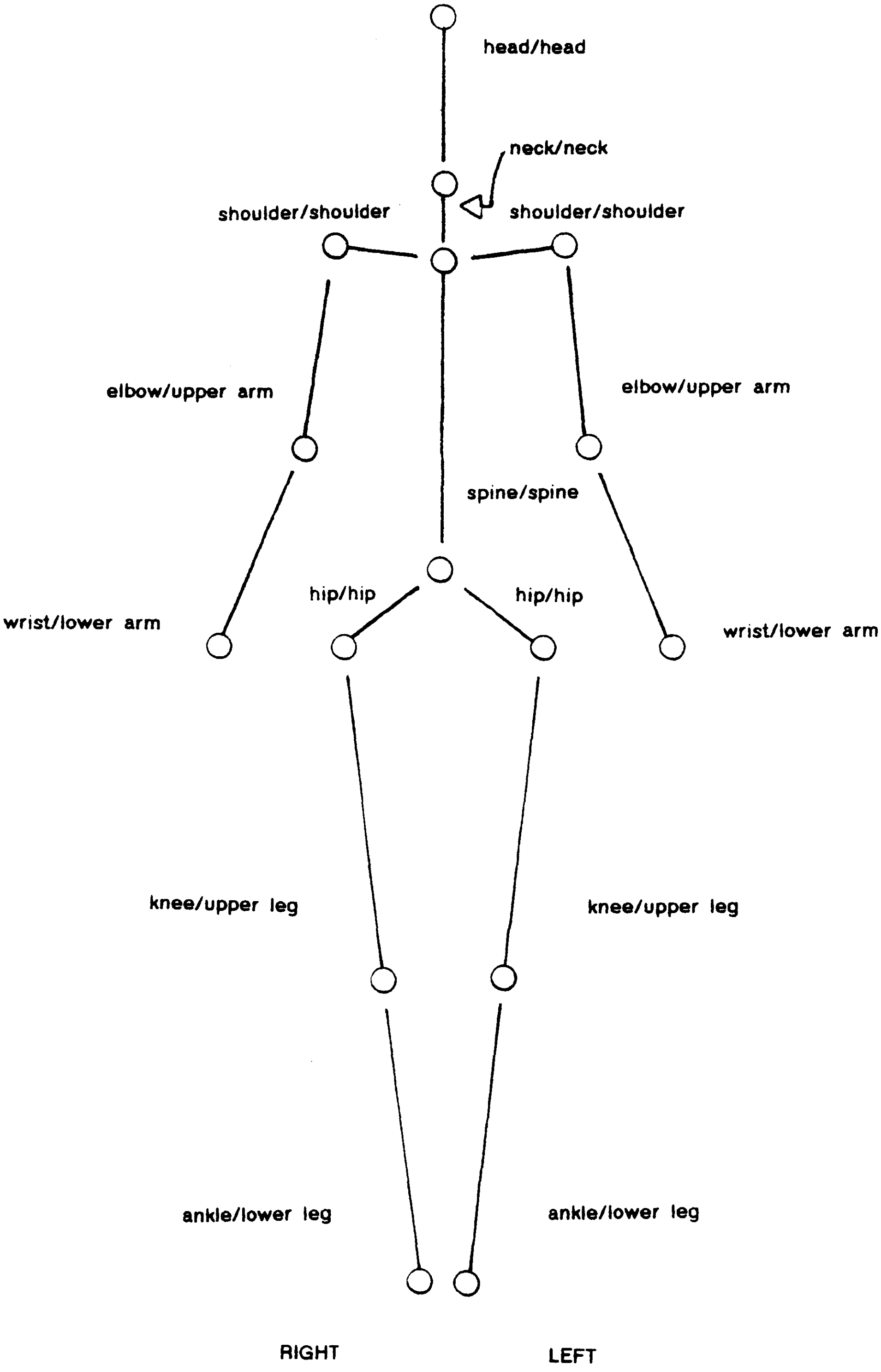


Figure 17 Correspondence of Two Data Strutures

In the second case, it is necessary to "walk the tree" in order to maintain compatibility with the existing programs; angles calculated relative to the previous segments are required. The current state of each coordinate system must be saved for subsequent use. Scaling from the SIM coordinate system to the marionette coordinate system alleviates the third problem.

After transfer from the AppleII, the coordinate data exists as a text file. It is first read in, transformed so as to be oriented correctly in the new coordinate system, and then scaled to be consistent with the dimensions of the modelling system. For each frame, the top and base of the spine are determined as averages of the shoulders and hips, respectively, and then a "center shoulder" and a "center hip" are created by parametrizing along the spine. This will give the stick figure a more realistic appearance, as if it has a clavicle and pelvis. Next, the order of points is unscrambled and made consistent with the node numbering in the body charcteristics template creation program. Also, the center hip location in world coordinates is saved for later use, and the points are translated so that the center hip is at the origin. Finally, the limb lengths in the template program are set according to the lengths established in SIM and from saved parameter data used to create the center shoulder and hip.

The simulated data is now ready for tree traversal, and for conversion to angular template data. This is accomplished by walking the tree in the same order as for drawing, but the matrix operations are performed in reverse order and with opposite sign (inverse translation and rotation matirces involve a change of sign). We are transforming points this time, not coordinate systems. The composition of an inverse LTM, LTM-1, may be expressed as follows:

```
LTM-1[node]=LTM-1[father] * ztrans-1[father] *
            rotz-1[node] * roty-1[node] * rotx-1[node]
```

The rotation operators are determined by first multiplying the homogenous distal point corresponding to the current node by the inverse LTM of the father, then translating it by the negative of the father's limb length along z. This puts the associated proximal joint at the origin and orients the distal point properly with respect to the axes, as shown in Figure 18. The angles are then calculated from the resulting x,y,z values according to the following algorithm:

```
hypoteneuse_1 = square_root(x2 + z2);
if hypoteneuse_1 = 0
     then y_rotation = 0;
     else y_rotation = arctan(x,z);
```

```
hypoteneuse_2 = square_root(x2 + y2 + z2);
if hypoteneuse_2 = 0
     then x_rotation = 0;
     else x_rotation = arctan(y,hypoteneuse_1);
```

The inverse tangent function used here takes two arguments and returns a value between -pi and +pi, so it preserves quadrant information. The x and y rotations are calculated such that the distal joint will lie on the z-axis, so the rotation about the z-axis can therefore be set to zero, as a matter of convention.

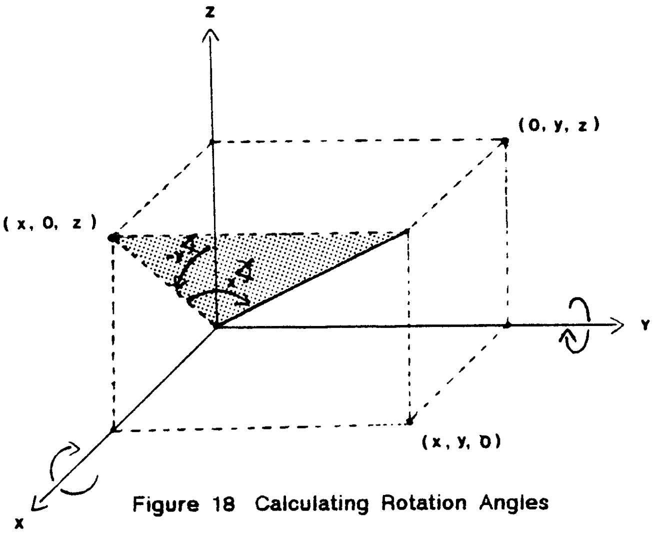


Figure 18 Calculating Rotation Angles

It is important, during these calculations, to ensure that hypoteneuse_2 is reasonbly close in value to the current segment's limb length, or else the angle data will propagate incorrectly through the inverse LTMs. The angles must be calculated in the above order to be consistent with the rest of the code.

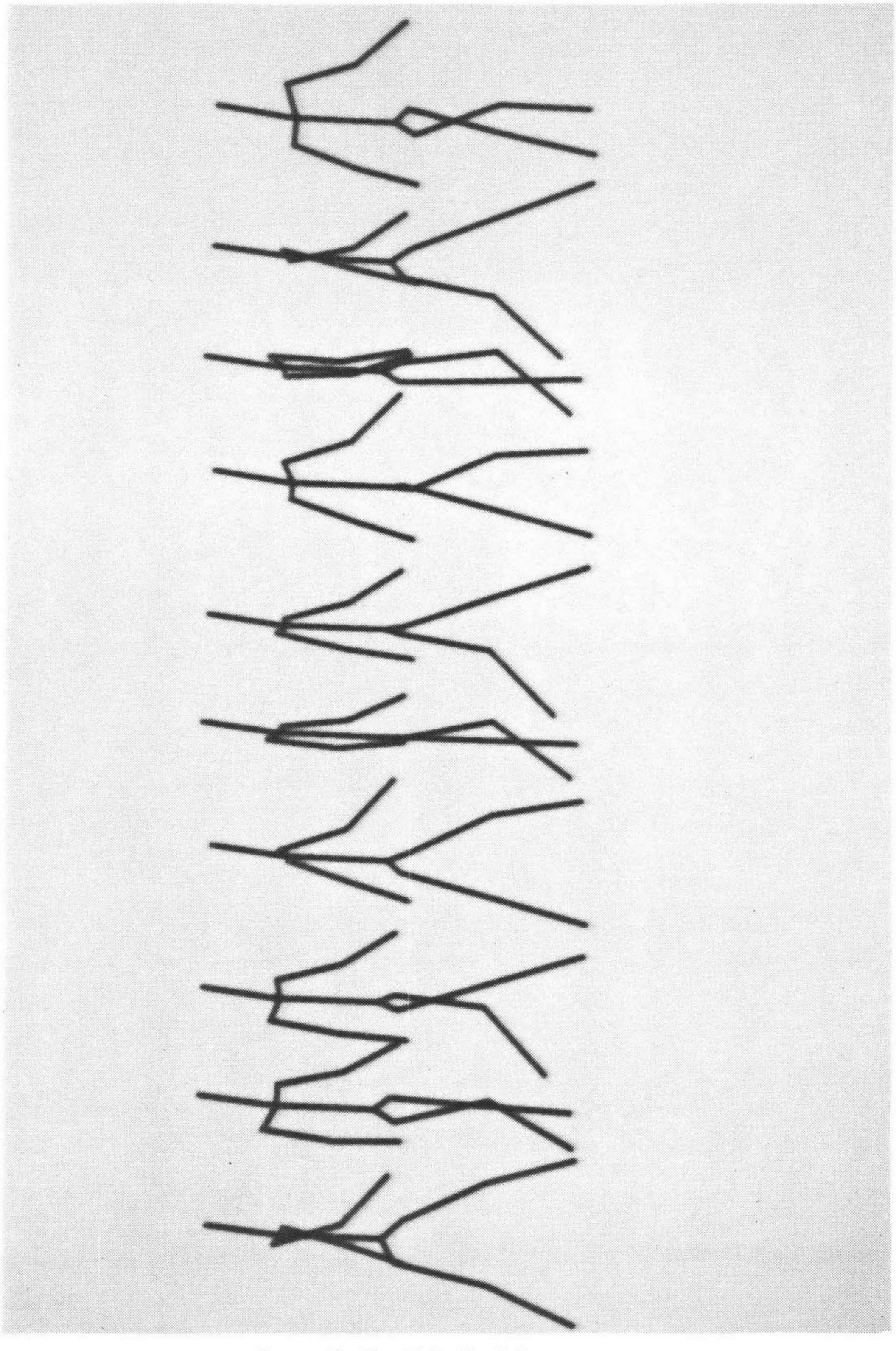


Figure 19 The Walk Simulation

An image illustrating stick figure motion is shown in Figure 19. As can be seen, the orientation of the limbs is more kinesiologically correct than that created by hand, and thus appears more lifelike.

Underconstrained Systems

If a system has more degrees of freedom than the number of imposed constraints, then it is said to be "underconstrained". When considering the motion of the human form, several difficulties arise in specifying completely the positions of the body segments.

During the initial stages of body-tracking development, a limited number of LEDs will be operational. Here arises the problem of missing data for certain joints. Even given a fully developed system, one encounters the problem when one body part may pass behind another, thereby occluding the LEDs completely for a period of time.

Consider the problem of finding the position of the elbow (B), given the location of the shoulder joint (A), and the wrist (C). Here the wrist and shoulder would be constrained by the given positions, and the elbow represents the extra degree of freedom.

Another variation would be missing data at (C).

This is shown by the body model used in the walk simulation, where the stick figure lacks hands and feet. Without the position of the distal end of the final segment, the orientation of the proximal joint can't be determined.

Many segments, such as the lower arm, are capable of "twist" about its' own z-axis. The limits of such twist are defined anatomically, as listed in Appendix B. Defining the direction of the segment during motion presents a problem because of the ambiguity of orientation. Body-tracking will not necessarily alleviate the difficulty, especially if the LEDs are placed symmetrically about a segment. Badler [3] proposes a "standard orientation" function, based on observations about certain orientations at given positions being more natural than others; indeed, given rotation limits, some orientations are anatomically impossible. The standard or default orientation is defined at each possible position of the limbs. When a segment is moved into a new position, the resulting orientation is computed (the orientation generally depends on the path used to reach the given position). This is compared to the standard orientation and adjusted if necessary.

The solution to these problems is beyond the scope of this thesis, but will constitute an important topic for future research. Some data available currently in the database provides a starting point for tackling this problem. The limits of rotation for each segment are maintained in the body data structure, and segment lengths are fixed. Given the locations of two joints, A and C, finding B is a matter of choosing a best solution from two loci of points formed by the segments' possible paths. The path of a locus of admissible points forms a circle, or part thereof, depending upon the angular limits on rotation.

In the case of temporarily occluded points, it may be more useful to also use the history of the preceding trajectory to determine a range of admissible positions.

Development of the tools for "scripting-by-enactment" has progressed in stages. Program modules were tested individually, then combined to to create a compatible interface. The system is now capable of animating figures using simulated data in the same way that the actual tracking data will be handled. Continued parallel development of hardware and software will help to solve the complex problems of portraying the human figure in motion.

Then, following eternal norms,
You move through multitudinous forms
To reach at last the state of man.

Goethe, FAUST Part Two

SUMMATION

Extensions and Improvements

The "cloud person" is seen as a viable method of portraying the human from, especially in view of a few adjustments that will enable the marionette to gain some semblance of character. The first will be to illuminate the figure given a light source. The next step is to "sculpt" more detailed features which can be accentuated by this new capability to portray light and shadow. The most interesting case in point is the head. A further control of the radial distance from the longitudinal axis, corresponding to such real distances on the head, could effectively model features such as the eyes, nose, and mouth. Even such sparse information will be enough to create recognizable images.

Less visible yet useful improvements are now planned. The interactive screen editor used to create and preview keyframes is being extended so that body data structures may be edited quickly. Changes such as body segment lengths and circumferences can be changed and verified using a similar editor. Currently under consideration is a generalization of the body data structures. The new hierarchy of class (humans, spiders), variations within that class (male,female), and motion data files and scripts related to each class will automatically prevent data files of the wrong size and type to be initiated in an animation program. This idea is based on the hierarchies familiar to us from biology studies; phylum, class, order, family, genus, and species. All of the sub-categories can refer to the class structure to reference names and node numbers, thus eliminating duplication.

Future Animation Scenarios

During the scripting process, the stick figure will serve as feedback to the animator. Once satisfied with a motion sequence, the animator may save this script for a later playback with a marionette "fleshed-out" as a solid figure. An extension of the scripting-by-enactment technique will be its application to scenes requiring more than one marionette performing in a sequence, or perhaps within a certain virtual environment - that is, "scripting-in-context" [6].

In this scenario there could be two figures walking about and conversing in an imagined space. The scriptor performs the actions of the first marionette while wearing 3-D head-mounted optics [9] which enables him/her to view this previously created and stored "virtual space", as well as the actual environment. This motion sequence, now stored, may be played back and viewed again with the head-mounted display. The scriptor similarly takes the part of the second or nth actor, in synchrony with the prior figure in that "space". This allows the scriptor to move about within the same space as the animated figures, so that the scripting occurs in both these 3-space contexts.

Future work will investigate the specification of emotion and expression for the face. Providing direct and effective interfaces for image manipulation will be a primary concern. In close-up views we wish to control eye position, head attitude, and expression change. Eye movement can be controlled in several ways; eye tracking, finger touch on a touch-sensitive display, or by joystick. Scriptor inputs from manipulation of a joystick along two axes or from other means can adjust the degree of distortion in the image. The caricature generator of Susan Brennan is a precursor to this work [8].

In attempting to accurately simulate human movement in relation to our physical environment, complex modelling systems have been devised. For the purpose of animation, such completeness is perhaps less important than the model's characterization and appearance, and ease in animation. Our focus here is on those concerns. Since the marionette figure uses a generalized jointed figure database, its application is not restricted to human animation. One could conceivably envision a scenario with dragons or robots or insects, employing similar types of databases for their definition. Imagine guiding the trajectory of a bee in flight by tracking the motion of the hand!

The technique of scripting-by-enactment is being pursued as a more natural method for animation scripting. It will also aid in constructing parallel motions, one of the unwieldy aspects of computer animation. Actions in a virtual 3-D world can be the consequences of motion performed in the user's 3-D world. More sophisticated modelling programs will aid in yielding realistic animation of artificial characters. The graphic "Doppelganger", able to "do as I do, and not as I type" is the goal.

APPENDIX A:

A BRIEF USER'S MANUAL

Coordinate System Conventions

The world coordinate system itself is defined as having the positive z-axis pointing up, the positive y-axis pointing right, and the positive x-axis pointing outward from the display screen, making it a right-handed system. 0,0,0 is located in the center of the screen as the default position. The orientation of the z-axis is reversed while composing the viewing matrix. (The left-handed eye coordinate system in Newman and Sproull). All rotations are thought of as clockwise when looking along the positive rotation axis toward the origin.

Viewing Parameters

The figure may be viewed from any viewpoint. You specify a look from point, using one of two programs (view_globe.pl1 or view_xyz.pl1). View_globe requires the viewpoint to be specified as a longitude, latitude, and variable radius, as if the eye were located on a sphere. View_xyz is given in x,y,z coordinates, in the world coordinate system. The viewbox matrix specifies the perspective transformation, and provides clipping limits for the hither and yon planes. It is usually set at (1., 100.,2.), but can be altered to change the perspective effects. The viewbox matrix is concatenated with the viewing matrix. You can also specify a viewport, a rectangular area on the screen, given in device (Ramtek) coordinates. Your figure will be mapped into that area on the screen. As in the world coordinate system, I prefer to think of 0,0 as being in the lower left hand corner.

Matrix Utilities

The matrices$ program is based on the existing matrix routines which handle matrix multiplication for 3d transforms (scaling, rotation, translation). The usual convention is to pass a matrix and the corresponding arguments. The new transformed matrix is passed back to the calling program. There should be on-line documentation --try "help matrix."

Program Use

This section of Graphical Marionette documentation explains briefly how to run programs from the directory u>delle> body. In addition, each program is listed with a description containing the following: input, arguments, how declared and called, and which other programs may be called internally.

Programs You Can Run

Before you can run animate.pl1 to actually draw motion sequences, you must have created data files by running three other programs separately--make_body, moveit and make_script. These four programs are all you need to use directly in order to make animated sequences using the given rendering routines (axes and cloud).

MAKE_BODY

Make_body is used to create a data file containing body connectivity, limblength, and limb radius information. To be added are rotation limits on x,y,z at each node. In order to make a new file, you must edit the program in tv, recompile it, and run it. It will ask for one input:

body template name	(filename)

MOVEIT

Moveit is for making "keyframes" to be used in your animation. Each segment of the body can be rotated by some amount on x,y, and z. It is not intuitively obvious how these rotations work, so try many combinations.

keyframe name	(filename)

MAKE_SCRIPT

Make_script takes all those keyframes you have just created and makes a script file out of them. This allows you to combine the frames in many different orders and lengths. No need to edit this program in tv--just run it.

script name	(filename)
script title	(filename) no_blank_between_words
keyframe names	(filename)
number of frames between this keyframe and the next	(keyframe length)

If there is no next keyframe, enter 0 as this amount, and you will
exit the program. The script may consist of one to fifty keyframes.

NOTE: Using descriptive filenames may aid in keeping track of which is which, until the more sophisticated data structures are implemented.

ANIMATE

Now you should be ready to run animate, which is much more useful than one_frame. Animate asks for ten inputs:

viewport limits	(lowx, lowy, highx, highy) Remember that I define the viewport as having 0,0 at the lower left corner, and that these limits are in screen coordinates.
viewpoint	(longitude, latitude, radius) or (x,y,z) depending on whether you use lookfrom_globe or lookfrom_xyz.
drawing style style	(style number) (1) calls axes.pl1, and (2) calls cloud.pl1.
body_data	(filename)
script	(filename)

Program Declarations and Calls

Listed are declarations and calls for programs (if used within another program), which files are created or accessed, values returned (if required), and other programs which may be called internally. See the program listings for examples in context.

view.pl1

View.pl1 consists of the entries viewport, viewbox, lookfrom_globe, and lookfrom_xyz. These are declared and called as entries from other programs.

All view$ programs call matrices$ programs.

viewport

```
dcl view$viewport entry (ptr,flt,flt,flt,flt);
call view$viewport (viewptr,x1,y1,x2,y2);
```

viewbox

```
dcl view$viewbox entry (ptr,flt,flt,flt);
call view$viewbox (viewptr,dnear,dfar,screensize);
```

lookfrom_globe

```
dcl view$lookfrom_globe entry(ptr,flt, flt, flt);
call view$lookfrom_globe (viewptr,long,lat, rad);
```

lookfrom_xyz

```
dcl view$lookfrom_xyz entry (ptr,flt,flt,flt);
call view$lookfrom_xyz (viewptr,x,y,z);
```

make_body.pl1
Creates data file for body template
based on a pointer

moveit.pl1
Creates keyframe data file based on a pointer

make_script.pl1
Creates script file based on a pointer

one_frame.pl1
Opens keyframe and body template files
Creates view data file
Calls crunch_tree1
"   view$ programs
"   matrices$ programs

animate.pl1
Opens script and body template files
Creates view data file
Calls crunch_tree1
"   view$ programs
"   matrices$ programs

crunch_tree1.pl1

```
dcl crunch_tree1 entry ( ,flt,flt,fix);
```

call crunch_tree1
(body_data,viewmat,viewportmat,stylenum);
Calls axes
"   cloud
"   matrices$ programs

axes.pl1
dcl axes entry (flt,flt,flt);
call axes (limblength,finalmat,viewportmat);
Calls clip_draw
"   matrices$ programs

cloud.pl1
dcl cloud entry (flt,flt,flt,flt);
call cloud
(limblength,radius,finalmat,viewportmat);
Calls clip_draw
"   matrices$ programs

clip_draw.pl1
dcl clip_draw entry (flt,flt,flt,fix);
call clip_draw (pts1,pts2,viewportmat,color);
Calls matrices$ programs

matrices.pl1
Utility programs for matrix operations
are written as entries in matrices. They
return some value(s) to the calling program.
Anything named mat, mat1, mat2, oldmat, or newmat

is assumed to be a 4x4 matrix.

Pts is assumed to be a 1x4 array.

ident

```
dcl matrices$ident entry (flt);
call matrices$ident (mat);
```

Returns mat

trans

```
dcl matrices$trans entry (flt,flt,flt,flt);
call matrices$trans (mat,tx,ty,tz);
```

Returns mat

scale

```
dcl matrices$scale entry (flt,flt,flt,flt);
call matrices$scale (mat,sx,sy,sz);
```

Returns mat

rotx

```
dcl matrices$rotx entry (flt,flt);
call matrices$rotx (mat,radians);
```

Returns mat

roty

```
dcl matrices$roty entry (flt,flt);
call matrices$roty (mat,radians);
```

Returns mat

rotz

```
dcl matrices$rotz entry (flt,flt);
call matrices$rotz (mat,radians);
Returns mat

concatenate
dcl matrices$concatenate entry (flt,flt);
call matrices$concatenate (mat1,mat2);
Returns mat1

new
dcl matrices$new entry (flt,flt);
call matrices$new (pts,mat);
Returns pts

copyT
dcl matrices$copyT entry (flt,flt);
call matrices$copyT (newmat,oldmat);
Returns newmat

print
dcl matrices$print entry (flt,char(32)vary);
call matrices$print (mat,matname);

print_flt
dcl matrices$print_flt entry (flt,char(32)vary);
call matrices$print_flt (mat,matname);
Calls ioa_flts
 "    ioan_flts
```

ioa_flts.pl1

```
dcl ioa_flts entry (flt);
call ioa_flts (var);
```

ioan_flts.pl1

```
dcl ioan_flts entry (flt);
call ioan_flts (var);
```

bod.cm

Color matrix used with these programs

APPENDIX B

JOINT ROTATION LIMITATIONS

ENTIRE BODY

X	min	0	max	360
Y		0		360
Z		0		360

CENTER HIP

X	min	0	max	360
Y		0		360
Z		0		360

LEFT HIP

X	min	136	max	136
Y		0		0
Z		0		0

LEFT THIGH

X	min	0	max	48
Y		-120		15
Z		0		0

LEFT LEG

X	min	-50	max	50
Y		0		135
Z		0		0

The x-rotation only works if y > 0, else x is locked at 0.

LEFT FOOT

X	min	-45	max	45
Y		-110		40
Z		0		0

RIGHT HIP

X	min	-136	max	-136
Y		0		0
Z		0		0

Note sign change.

RIGHT THIGH

X	min	-48	max	0
Y		-120		15
Z		0		0

RIGHT LEG

X	min	-50	max	50
Y		0		135
Z		0		0

The x-rotation only works if y > 0,
else x is locked at 0.
(note anatomical limitations)

RIGHT FOOT

X	min	-45	max	45
Y		-110		40
Z		0		0

SPINE (lumbar region)

X	min	-20	max	20
Y		-85		30
Z		-38		38

SPINE (thoracic region)

X	min	-20	max	20
Y		-85		30
Z		-38		38

These ranges for both spinal areas are approximate combined ranges-

LEFT CLAVICLE

X	min	20	max	80
Y		0		0
Z		0		0

LEFT ARM

X	min	-120	max	50
Y		-160		50
Z		0		0

Not accounting for twist of humerus about z-axis

LEFT FOREARM

X	min	0	max	0
Y		-145		0
Z		-70		85

LEFT HAND

X	min	-19	max	33
Y		-90		60
Z		0		0

Z-twist controlled by action of the forearm

RIGHT CLAVICLE

X	min	-80	max	-20
Y		0		0
Z		0		0

RIGHT ARM

X	min	-50	max	120
Y		-160		50
Z		0		0

Not accounting for twist of humerus
about z-axis

RIGHT FOREARM

X	min	0	max	0
Y		-145		0
Z		-70		85

RIGHT HAND

X	min	-33	max	19
Y		-90		60
Z		0		0

Z-twist controlled by action of

the forearm

NECK

X	min	-20	max	20
Y		-5		10
Z		-45		45

HEAD

X	min	-20	max	20
Y		-5		15
Z		-45		45

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