

A MODEL KIT:

a system for constructing three-dimensional
interactive graphic models

by
Jane Nisselson

B.A., Bennington College, 1976

Submitted in partial fulfillment
of the requirements for the
degree of

Masters of Science in Visual Studies

at the

Massachusetts Institute of Technology

June 1983

Copyright © Massachusetts Institute of Technology 1983

Signature of Author

.....
Department of Architecture
Friday, 28 January 1983

Certified by

.....
Professor Patrick Purcell
Associate Professor of Computer Graphics
Thesis Supervisor

Accepted by

.....
Professor Nicholas Negroponte
Chairman, Department Committee for Graduate Students

Rotch

MASSACHUSETTS INSTITUTE
OF TECHNOLOGY

AUG 5 1983

1

LIBRARIES

A MODEL KIT:

a system for constructing three-dimensional
interactive graphic models

by

Jane Nisselson

Submitted to the Department of Architecture on January
28, 1983 in partial fulfillment of the requirements for the
degree of Masters of Science in Visual Studies.

abstract

The following project introduces an interactive graphic environment in which one can build and explore three-dimensional models. One can reach directly into this image space to construct a model from a database of components. A stereoscopic video display is combined with a real space by means of a semi-transparent mirror to create this three-dimensional workspace. The model's imagery is perceptible to both the visual and kinaesthetic senses as one directly places and moves it in space with his hand. An electromagnetic six degree-of-freedom digitizer mounted on a small wooden "wand", with a pushbutton mounted in the handle, tracks the user's hand in space to allow direct interaction with a computer mediated graphic operation. Models have been built out of images of cities, robots, the human eye, microscopic views of a metal powder, and cross-sections of a brain. The interactive models made with this kit can be saved, redisplayed and rebuilt.

Thesis Supervisor: Patrick Purcell
Title: Associate Professor of Computer Graphics

This work reported herein was supported by the Advanced Research Projects Agency of the Department of Defense, under Contract number MDA 903-81-C-0097.

Table of Contents

INTRODUCTION	5
Chapter One: MODELS	7
1.1 WHAT IS A MODEL?	7
1.2 MODEL AND FUNCTION	8
1.3 STRUCTURE	9
1.4 STRUCTURE AND SPACE	10
1.5 SPACE & DESCRIPTION	13
1.6 SPATIAL NARRATIVE	13
1.7 COMPUTER MODELS	15
1.8 INTERACTIVE MODELS	19
Chapter Two: MODEL BUILDING	20
2.1 TECHNOLOGIES AND MODEL BUILDING	20
2.2 DISPLAY	20
2.3 STEREOSCOPIC IMAGING	21
2.4 DEFINING A SPACE	22
2.4.1 LOOKING	24
2.4.2 USING SPACE	24
2.5 CONTACT WITH VIRTUAL SPACE	25
2.6 INTERACTING WITH VIRTUAL IMAGES	26
2.7 MEANS OF INTERACTION	27
2.8 SENSE AND INTERFACE	29
Chapter Three: THE MODEL KIT	32
3.1 INTRODUCTION	32
3.2 THE PHYSICAL STRUCTURE	32
3.3 HISTORY	34
3.4 REAL & VIRTUAL SPACE	35
3.4.1 THE DISPLAY	35
3.4.2 TRACKING IN SPACE	37
3.4.2.1 "WAND"	37
3.4.2.2 POLHEMUS	37
3.4.2.3 PUSHBUTTON	38
3.5 VIRTUAL SPACE	38
3.5.1 COMPUTATIONAL DEFINITION OF SPACE	38
3.5.2 CUES TO VIRTUAL SPACE	42
3.5.3 KINAESTHESIA	43
3.5.4 DYNAMIC CUES TO VIRTUAL SPACE	45

3.5.4.1 HAND MOVEMENT: THE CURSOR	45
3.5.4.2 "TOUCHING"	46
3.6 MENU	46
3.7 COMPONENTS	49
3.7.1 APPEARANCE OF A COMPONENT	49
3.7.2 ICONS	52
3.8 CASE STUDIES IN GRAPHIC MODELS	52
3.9 USING THE MODEL KIT	53
3.10 THREE MODELS	58
Chapter Four: SUMMATION	61
4.1 PROBLEMS	61
4.1.1 CUES: POINT IN SPACE	61
4.1.2 TRACKING	64
4.1.3 WORKING IN THREE DIMENSIONS	65
4.1.4 IMAGERY	66
4.2 FUTURE	67
4.2.1 GRAPHIC SYMBOLS	67
4.2.2 SOFTWARE	67
4.2.3 INTELLIGENCE	68
4.3 APPLICATIONS	68
4.4 CONCLUSION	69
PHOTOGRAPHY CREDITS	71
ACKNOWLEDGEMENTS	72
References	73

INTRODUCTION

Imagine a volume of space--a complete void--in which a person could place his hand and float images, independent of any material resistance. The following project introduces such an interactive graphic world. In it, one can build and explore three-dimensional models using stereoscopic images. The space of stereoscopic images is generally thought of as "seamless"; their enhanced depth appears an inviolable dimension. Here, the ideal picture which stereo's illusion of depth is used to realize is an image of an empty space. In this space, one can place, move or remove an image at any location directly with one's hand.

Such a virtual world is created by combining a stereoscopic video display with a real space by means of a semi-transparent mirror. While the images have no tactile cues, they are perceptible to both the kinaesthetic and visual senses as a person exercises his hand-eye coordination to place them in the space. By means of a tracking device and a menu, the virtual dimensions of the display become a three-dimensional workspace for working with images.

To demonstrate this particular approach to imaging--in which one's kinaesthetic and visual senses are engaged to build composite images in a three-dimensional space--the following pages describe a system for building models, a system which I call the "model kit". While models can serve many functions and may take a range of forms from a mathematical equation to a verbal paradigm, the models discussed here are visual ones.

Using this system, one can construct a model from a set of component pictures. One can "handle" the components, each of which represents a part of the model, as if they were objects: moving them around, putting each in its own particular location. A model which is built out of images can have the symbolic power of a representation yet the independent structural quality of an object. The parts out of which the model is built can present only one or, alternatively, many conflicting aspects of its subject; they can be symbols, fragments, metaphors or details. Using them, one can choose a style of presentation, constructing models in a range of ways. The model's components can be placed in space, interrelated at will, unconstrained by physical links and capable of structuring alternative ones. The power of the interface is the direct access it opens to the three-dimensional world of the image.

Two key parts make such model building possible. The first is the design process which provides a means to place and move images directly within the three-dimensional model space. That

is, a means to build. And secondly, one must have a set of components, or imagery, with which to build. What results is a model that once built, can be taken apart, explored, and recomposed by anyone who wants to understand or learn from the model.

Models--specifically visual ones--are discussed in the first section. Their function, structure, and composition are examined. Model building is then discussed, with a focus on the methods of construction which use interactive computer graphics. A description of the model kit, its design, components, and use is then presented. To conclude, the model kit's successes, limitations, applications, and future are summarized.

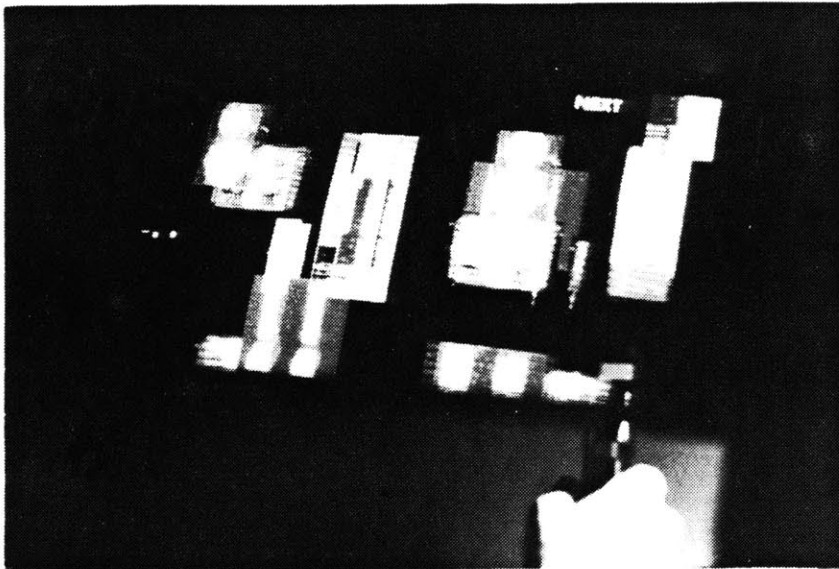


Figure 1. Constructing models with the Model Kit.

Chapter One

MODELS

1.1 WHAT IS A MODEL?

While scientists and philosophers have on the whole taken diagrams for granted, they have been forced to fret at some length about the nature and function of *models*. Few terms are used in popular and scientific discourse more promiscuously than "model". A model is something to be admired or emulated, a pattern, a case in point, a type, a prototype, a specimen, a mock-up, a mathematical description--almost anything from a naked blond to a quadratic equation--and may bear to what it models almost any relation of symbolization.

"Model" might well be...reserved for cases where the symbol is neither an instance nor a verbal or mathematical description: the ship model, the miniature bulldozer, the architect's model of a campus, the wood or clay model of an automobile....Models of this sort are in effect diagrams, often in more than two dimensions and with working parts; or in other words, diagrams are flat and static models, [Goodman, 1976]

An encyclopedia of models, their many forms and the fields that use them, would be a long and varied volume. In the field of architecture alone which has used the three-dimensional model as a design tool to embody a plan for a spatial structure,

The oldest acknowledged use of an architectural model is found in Herodotus, who mentions a model of the Delphi Temple in his writing (Herodotus V,62). Apparently no models were used in the early and high Middle Ages. Only since the 14th century has this form of representation become relevant to the practice of building; we know that a model of the Cathedral of Florence was made towards the end of the 14th century. Since the early Renaissance an increasing number of models exist showing buildings and urban districts, especially those of fortifications. [Janke, 1978]

In 1570, Andrea Palladio, wrote in *First Book of Architecture*, of the model's role in the construction of the perfect edifice:

Beauty will result from the form and correspondence of the whole, with respect to the several parts, of the parts with regard to each other, and of these again to the whole; that the structure may appear an entire and compleat body, wherein each member agrees with the other and all necessary to compose what you intend to form. When these several particulars have been duly examined upon the model or draught... [Palladio, 1965]

Independent of the subject it presents, in both scale and medium, the model's discrete figure is employed as a means to order, envision, and evaluate a subject in all of its parts. Palladio's models provided both the plan of specific buildings and paradigms of the principles inherent to ideal

construction.

1.2 MODEL AND FUNCTION

We are concerned here with such a particular scope of use of the model: descriptive models which present a subject's aspects of principal relevance; and, those which function as design tools, a catalyst for invention.

An illustration of this first use can be found in Kuhn's use of the model or paradigm in "normal science."

In a science...a paradigm is rarely an object for replication. Instead it is an object for further articulation and specification under new or more stringent conditions.... Paradigms gain their status because they are more successful than their competitors in solving a few problems that the group of practitioners has come to recognize as acute....Normal science consists in the actualization of that promise, an actualization achieved by extending the knowledge of those facts that the paradigm displays as particularly revealing, by increasing the extent of the match between those facts and the paradigm's predictions, and by further articulation of the paradigm itself. [Kuhn, 1970]

Accepted examples of actual scientific practice which "include law, theory, application, and instrumentation together--provide models from which spring particular coherent traditions of scientific research." [idem]

In this function, the model serves as a standard by which the subject that it formulates can be ordered and measured. When it no longer serves this purpose, it can be discarded and replaced by a more useful one.

In the second use, the model is a design tool:

The model has the effect of provoking unforeseen "structural" developments or even modes of perception in the processes of design....[the model can be used] as studies of a hypothesis, a problem or idea of architecture. [Hooper, 1978]

A model used as a design tool does not attempt to negate or reduce the gap between its scale, location and medium and what it represents--instead it uses its representational form to its advantage. It may be characterized by "its recoil from material reality" [Pommer, 1981] by which means models "could well have an artistic or conceptual existence of their own, one which was relatively independent of the project that they represented.... Models can provide the illusion of reality without being compromised by it." [Eisenman, 1981]

By heightening the tension between the model and what it models, the model can be refigured in diverse representations through which the designer can explore alternative configurations of its subject. "The model is always a model *of*. The *desire* of the model is to act as a simulcrum of another

object, as a surrogate which allows for imaginative occupation." [Hubert, 1981]

The model may be considered as a medium that stands between the object and the mental imagery by means of which the design takes shape--images which "are important by reason of the manner in which they prevent designers from moving too quickly to concrete graphic representations and becoming locked into certain solutions too early in the design process." [Hooper, 1978] In the case of the architect, the model serves as a medium for refiguring the relation between space and form which built at another scale will be reflected in the way its built form is occupied.

The type-forms out of which the model is built may consist of pre-existent and formally defined elements--such as the loggia, portico, and column--but it is through the process of design that their meaning is structured.

1.3 STRUCTURE

To make a model, the subject in question can be analyzed into a set of significant parts critical to the consideration of the whole. Each of its aspects is like a distinct image selected to contribute to a chosen conception of the modelled subject.

...to distinguish between information and fabrication--information is a pattern or design that rearranges data for instrumental purposes, while knowledge is the set of reasoned judgments that evaluates the adequacy of the pattern for the purposes for which the information is designed. Information is thus pattern recognition, subject to reorganization by the knower, in accordance with specified purposes. What is common to this and to all intellectual enterprises is the concept of relevant structure.... [Bell, 1979]

In being modelled, a subject undergoes a dislocation of place and a dissolution of scale. An independent structure results. In reconstructing the object in its new space, it appears by means of the "reasoned judgment" that determines a useful configuration.

Structure provides a universal metaphor...*everything* involves structural hierarchy...*nothing* can be understood without looking not only at it in isolation on its own level but also at both its internal structure and the external relationships which simultaneously establish the larger structure and modify the smaller one.....The world is a complex system and our understanding of it comes, in science, from the matching of model structures with the physical structure of matter and, in art, from a perceived relationship between its physical structure and the levels of sensual and imaginative perception that are possible within the structure of our brain's working.

Few entities are completely isolated without some residual connections to others....It is the stability of an overarching 3-D environment that allows special freedoms and local structures, for example the holding of feebly-bonded atoms within the chelated structure of some molecules... [Smith, 1981]

Location and relative position of a model's parts can mirror the subject it represents or have a

symbolic structure of its own. Interposition reveals the logic of its construction, the significance of its parts, to inform about its subject.

In the model, both the model maker trying to structure a given set of data, such as the motion of planets in space, and the model maker trying to arrange a practical space flow pattern in an automobile factory have a medium with which they can fluidly rearrange parts to present their subject.

While the subject to be modelled either has or ultimately will have a fixed structure, the model, as a conception of the subject, does not have a predetermined form. Typically the model can be more easily refigured than its subject; the model's "surrogate" form is a useful means to order and make a plan of the subject in question.

1.4 STRUCTURE AND SPACE

Whether figurative or symbolic, a model can be considered as a vehicle by which its subject can be visualized. In the model, each place of its specific spatial skeleton serves as a bifocal lens through which both object and a clearly defined relation to the whole can be viewed. Its dimensional representation may use more than two dimensions in which to build its subject and interrelate its properites with clarity.

Using this approach, structure becomes a syntax in which to articulate a description--mechanical, physical or logical--of the whole [figure 2]. A model uses structure to amplify or impose meaningful or functional relations between its units. In the model's condensed form, a complex of relationships important to the whole can be viewed in entirety. In a model of a house, for example, the transitions between the plan of the several floors can be easily viewed with respect to each other. Such spatial relations may never be entirely visible as such at a single moment to its occupants who instead experience such considerations as a point by point movement through the dwelling.

In translating a subject into a visible scheme, a structure may explicitly join each isolated element to the whole in many ways. It may offer a means to visualize an abstract concept of the relative position of planets in the fourth dimension such as in A.M. Noll's film which illustrates the motion of planets in four-dimensional space, by projecting space onto three-dimensional subspace which could be viewed stereographically [Noll, 1968]. Or, it may simply functionally format a subject. A model of an eye that might be found in an optometrist's office, is built of a few wood and rubber pieces. Taken apart it will reveal only the most basic parts of the eye and their interrelation.

The structure binding the units of a model--lattices, arrays, branches--typically reveals itself

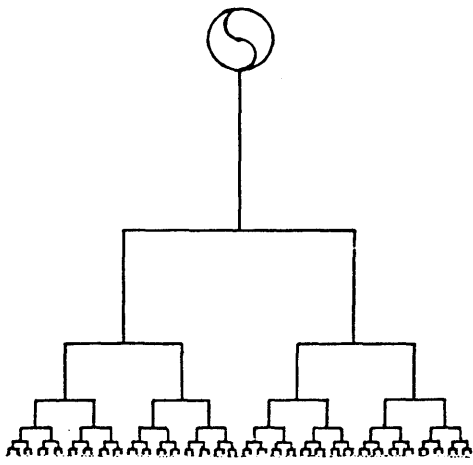


Figure 2.
The tree of logic, representing the conventional view of hierarchy as a one-directional system of dominance.

only in metaphor, sometimes conforming to the object being modelled, but often independent.

The links by which a model arranges its subject may be logical links which form joints of hierarchy, priority, sequence. They may reflect a physical or mechanical continuity and can also take the shape of associations found in history, memory, and conventions. Connections of necessity or whim may attach the parts of a model. The structure takes shape in various forms whether a tree which offers a breadth of branching alternatives or a grid in which each image is inset into a block of images.

In a model, the spatial metaphor sometimes used for generalized conceptual descriptions specifically defines workable dimensions in which to build a subject's parts in an ordered form. Space imbued with a metaphorical structure can function as a visual filing system for locating objects. Particular spatial configurations can be used as models to structure a subject which is abstract, invisible, imagined or simply extensive. In memory systems, for example, a structure's configuration is independent of what it positions. Such spatial structures use a model of a place, for example, simply to provide a set of locations for reaching and placing information in an organized manner. As, for example, a memory device in which parts of a speech are located in the rooms of a mansion. [Yates, 1966]

The positions in the structure can be facsimile of physical counterparts. "Spatial Data Management System" served as a prototype for translating physical locations--of a desktop--into a visual structure for reaching information with no comparable physical index in a computational environment. [Bolt, 1979]

As in the above system, the user interface for the Xerox Star workstation is a system that makes extensive use of metaphors. In such a system, by being linked to associative symbols, information is modelled into a useful structure. The position of each of the symbols is distinct but variable. "Much of the manipulation of information takes place by moving icons around on a 'desktop' that is simulated on the screen. The icons are pictorial representations of familiar objects like in-baskets, file folders, and filing cabinets. To the extent that this fantasy is analogous to real desktops, it presumably makes the system easier to learn and use." [Malone, 1981]

Structures have also been assigned to linguistic objects such as "phrase structures" by such theorists as Greenberg [Greenberg, 1963] and Chomsky [Chomsky, 1956]. They can be seen in the substructures used to model knowledge by the logic-oriented proponents of artificial intelligence in the "problem-spaces" of Newell and Simon [Newell, Simon 1956] "across" which "hill searches" for example are conducted, the "microworlds" of Minsky and Papert [Minsky, Papert 1969], and the "inner environments" of Simon's complex systems [Simon, 1981].

1.5 SPACE & DESCRIPTION

As a representation, the model can be employed as a means to present explicit aspects of a subject which may be evident but not formally visualized and pronounced as such in the actual subject. The model's structure can use the physical layout of the subject to accentuate a particular function or meaning.

A model of a car engine may present a particular statement about a new design in its description of the overall vehicle. By figuring certain parts in bold colors, expanding the space between and making visible its parts in a way they might not be in the actual car, the model can present an emphatic statement about its engineering innovations.

A model can also reflect several descriptions of its subject in a single structure. In the model's singular form, the collective significance of its subject can be presented.

Marvin Minsky writes of his frame system for representing knowledge, "the problem of connecting two or more qualitatively different ways to represent the same thing is discussed, but not solved, in a later section" [Minsky, 1975]. Different kinds of information about the subject may be present in the model; one of which may appear central to its structure depending on the concerns of the person making or using the model.

Layered descriptions that create networks of associations can take the condensed form of visual puns as well as elaborate structures. An example of this can be seen in the model of an entry tower which is a camera-obscura room [figure 3]. Such rooms have been built for the observation of solar eclipses and the study of color. Kepler, in 1607 charted the path of Mercury in such a room. The model's interior is painted black and each of its two windows are marked with pinholes. Here, as an entry tower it functions as a metaphysical entry to a historical type as well as a transitional point, like the focal point through which an image is projected into the camera's interior, through which all that lies outside of its boundary passes inward. [Perkins, 1981]

By means of the relative interpositioning and layering of its parts, the model has an "elastic" construction. In its structure the model maker can transpose the scope of his approach to his subject onto the accommodating form of the model.

1.6 SPATIAL NARRATIVE

In exploring and defining a subject to be modelled, the model maker discovers the constituent elements to be presented. These variables can be juxtaposed to represent a subject's operational

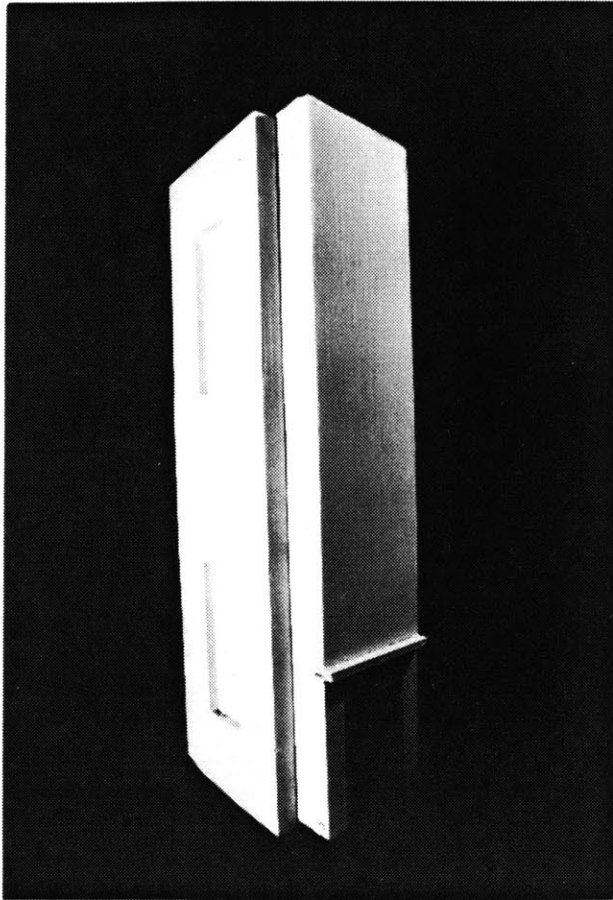


Figure 3.

Model of camera-obscura tower. Wood and paint.

qualities--the control and activity effected between the parts. Two examples may help to illustrate how very differently structured parts may be used to model a concept or a world.

An example of juxtaposed imagery suggestive of a three-dimensional world can be found in the boxes of Joseph Cornell. Here a model of subjectivity which is inviolable consists of imagery animated by their interposition within the confines of its glass-shielded space. [figure 4]

"At the extreme limits of stereoptic and anaglyphic perspective and of stereotyped vision...(Cornell)...has evolved an experiment that complete reverses the conventional usage to which objects are put" [Breton, 1942]. His boxes with glass fronts filled with fragments, objects, pictures, words function to make three-dimensional spatial fields for objects of "an intimate scale, holding captive a moment in a transient enclosed world" [McShine, 1980]. Cornell himself compared these to the philosophical toys of the Victorian era.

Perhaps a model of a very different kind, the toy which flourished

from the middle of the nineteenth century...was intended to combine a pedagogical function with entertainment, to instruct the child in the laws governing the natural universe while at the same time amusing him. It was a direct result of the great discoveries in science, and natural philosophy that had shaken the foundations of the Victorian world...So the laws governing movement, light, gravity, and so on were all illustrated in toys of remarkable ingenuity, inviting the child to learn by experiment. [Ades, 1980]

In a child's toy was found a dynamic model which when played with, demonstrated contemporary conceptions of physical laws. [figure 5]

1.7 COMPUTER MODELS

More recently, models with a function similar to that of the toys have been designed. A computer was used to generate pictures and graphical symbols for clarifying and demonstrating relationships and concepts that are difficult to convey with traditional physical apparatus. "Computer pantomimes" are symbols which are dynamic and pictorial: "They move about and change their shape with the passage of time so as to emphasize and highlight particular relations or properties." [Huggins, 1966]

W.H. Huggins exuberantly describes his "computer pantomimicry", which he developed at Bell Telephone Laboratories in 1965, as an "excellent exercise--and fun too!" [idem]. Huggins used the computer to make these learning models because computer animation "enables the creator to come in direct contact with the display medium" [idem]. The intention here was to develop a model that could teach by means of the computer's interactive qualities. But at that point Huggins observed that

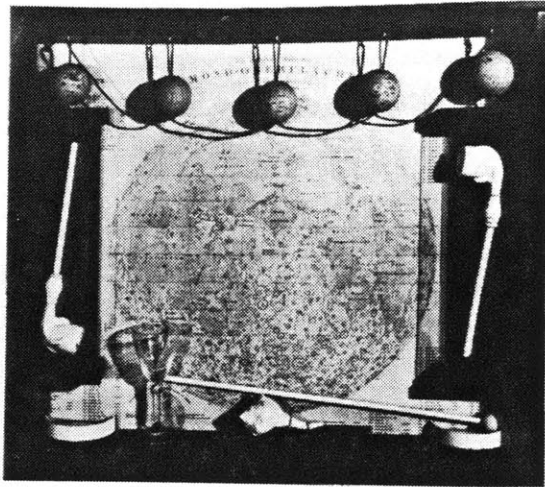


Figure 4.

Untitled (Mond-Oberfläche).
1955. Joseph Cornell.
15.7 x 17.2 x 2.1 inches.

Figure 5. Optical devices.

Left to right: Kaleidoscope, glass, brass, cardboard, wood, American, c.1873; Zoetrope, metal with wooden stand, images lithographed on paper, European, mid-nineteenth century; Stereoscope, metal, wood, and glass, "The Kinora", English, late nineteenth century.



See
Plate 10
p. 100
c. 1873
New York
The
Kaleidoscope
and
Stereoscope
Company
New York
City
Henry
H. Holt
of
Reading

emergence of the computer as a major tool for developing abstract concepts has

been delayed because of abysmally poor communication channels that have existed between the computer and human. With the new graphical displays, light-pen inputs, and other presentations matched to the human senses (Maurice Constant has described "light-gloves" with which one could tactually mold computer-simulated three-dimensional objects), the man-made world of the computer will become increasingly real and will provide a superb instrument for educational purposes. [idem]

A model is defined by the computer as a set of parts and the laws dictating their structure. The model can then be explored using the computer's interactive qualities to recompose the model within the boundary of its defining structure.

In turn, the computer has been used to extend the means of transposing, juxtaposing and structuring imagery to produce a desired model which would otherwise be mechanically difficult or impossible to visually conceive.

A model that represented Los Angeles sometime in the future in the motion picture, "Blade Runner", was visualized using Entertainment Effects Group's Compsy system--a servo-drive computerized multiplane system which also functions as a motion-controlled horizontal animation stand [figure 7]. It can be thought of basically as a large motorized graphic arts plane with a motion-controlled camera mounted perpendicular to it on a thirty-six-foot track. Physical models can be dynamically mixed with computer-generated animation. Basically the computer works as a modelling system, technically extending the available means for structuring imagery into a model of a given subject. [Shay, 1982]

Designers have worked with dynamic imaging systems in order to generate the varied representations compatible to the original conceptual design process.

...an important process in design is the continual evaluation of design solutions and their modifications. The use of computer graphics in architecture greatly facilitates this modification process (Negroponte,1970; Milne, 1968) [figure 6a]. These graphics allow for systematic changes of potential solutions in very short times. Whereas mental imagery and conceptual visual languages can represent design issues in an abstract form for consideration, the graphic media of the computer can provide concrete visual simulations of buildings that can be directly manipulated. [Hooper,1978]

Here the model's medium, computer graphics serves as a medium between the designer's mental conceptions of a subject and its visible realization. The computer's interactive graphic resources have been drawn upon as a design tool. In each of the above modelling systems, a means to fluidly manipulate the imagery of the model, lets one conceive (the architect), produce (the filmmaker), and explore (the student) models of very different things.

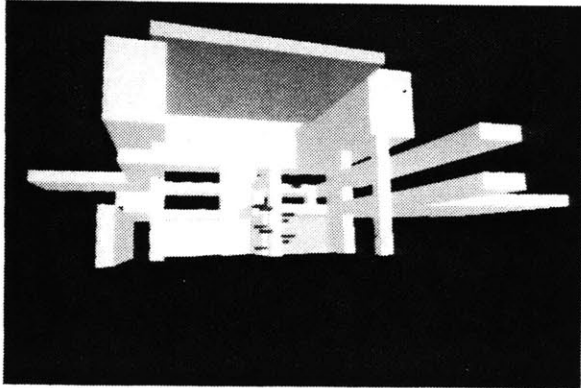


Figure 6a.

Early plan for Arts and Media Technology Building, MIT.
One view from three-dimensional database drawn with
interactive computer graphics system.

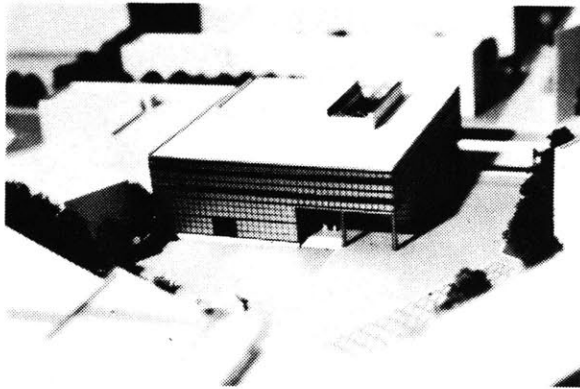


Figure 6b.

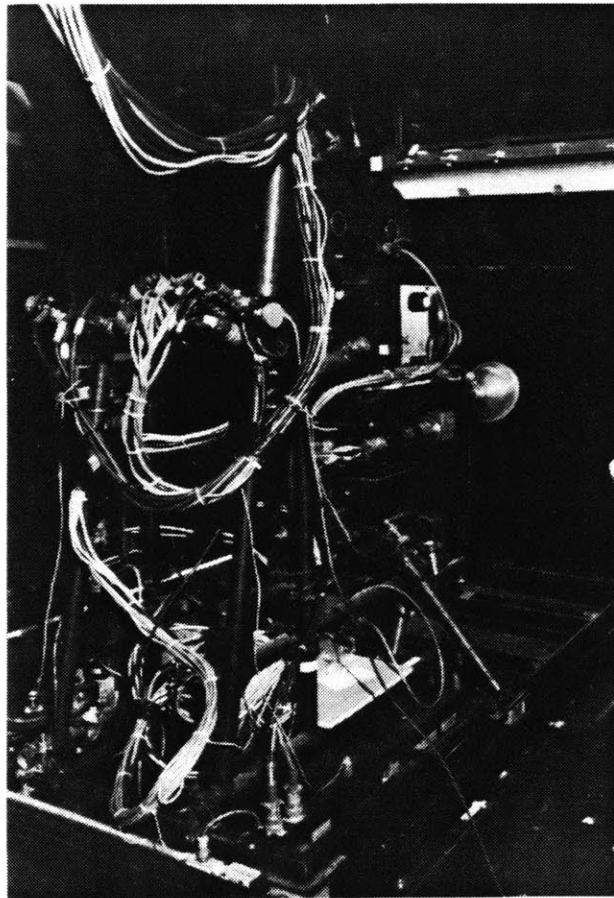
Final design, model of the same, hand constructed.
I.M. Pei and Partners.

1.8 INTERACTIVE MODELS

In its finite figure, a model brings together properties of the yet unbuilt, the micro or macroscopic, the abstract, or infinite. It enables one to organize, gaze upon and comprehend what otherwise lies beyond our reach in scope, material, magnitude or simply in the mechanics of construction. In the singular perceptible form of the model which gives dimensionality to concept, lies the pun of being able to "grasp" an idea.

In an ideal modelling medium, the imagery of the model would be as easily manipulated as one's mental imagery in which useful fragments are generated by lopping significant parts from a whole, grafting aspects of one subject onto to another, exaggerating some details, omitting others. Relative positions would be easily shifted and one image would not have to exclude another: images could be layered together so that structure replaces economy. The coherent model would be conceived without the labor of finding the foamcore and exacto knife, the woodlathe, or clay with which to build it. The medium resonates with a range of specific modelling requisites. And, the dynamics of the model's construction and internal configuration would reside in it as a means of subsequent exploration.

Figure 7. Entertainment Effects Group's computerized modelling system used to plot camera moves in previously photographed cityscapes and translate these moves onto a two-dimensional graphic arts plane.



Chapter Two

MODEL BUILDING

2.1 TECHNOLOGIES AND MODEL BUILDING

How is a model built? The model, as we are considering it, can be thought of as a means to visually structure a set of significant properties of a subject into a representative whole. The model takes shape in a given medium, of which some means of direct control is available. In representing its subject, a model will extend across a space of two or three dimensions. Whether as a facsimile of the modeled subject, a metaphorical spatial map, or a symbolic structure, space is encoded with information. The model defines its own context by the bounds of its structure.

How is a model, piece by piece, made into a whole? The first step is deciding upon some medium in which the parts of the model can be displayed and interrelated. In whatever material the model is to be visualized it must have two characteristics, the first is a capacity to display the appropriate aspect of the model and second, a means by which such a part can be placed into the correct position.

Here, the computer will be considered as a means for visualizing models, drawing upon its facility for a direct interaction with imagery which was demonstrated in each of the three previously described computer modelling systems. In each, the imagery could be dynamically juxtaposed and restructured to illustrate the subject in question.

2.2 DISPLAY

As the medium of construction and presentation the display is a principal factor in making a functional model.

If we imagine a volume of virtual space in which to build a model, the relations between the parts are free to be either directly joined or implied. In either case, the location of the part will tell something about its use or influence on the other parts. In a model of a robot, for example, the head will most likely appear *above* the torso; in a model of cross-sections of a brain constructed of a series of cross-sections, the first cross-section will most likely appear *in front of* the last. In this second

example, the configuration is a logical one but could on the other hand be rearranged according to a particular focus on a specific cross-section or to highlight significant areas of interest such as infection or function. The relation between the parts of a model can be implicit in each part and, as well, conveyed in their layout. Unlike the content-independent "windows" which can be seen, for example, in magazine and computer graphic layouts [Meyrowitz and Moser, 1981], the locations of parts of a model can serve to inform their meaning.

A virtual space of three dimensions offers a space to build dimensional models. Of course, two dimensional systems of representation have effectively diagrammed such relations as hierarchy, priority and juxtaposition. A three dimensional space offers the alternative of neither condensing elaborate interpositions nor conflating networks of interrelations. The generalized visual images, metaphors or allusions imaginatively used to conceive a model become crystallized in attempts to visibly present the model's many constituent aspects in a coherent structure.

2.3 STEREOSCOPIC IMAGING

The disparity in point of view between our two eyes, one approximately 2.5 inches or 65mm from the other, has been determined as one contributing factor in our depth perception, known as binocular parallax.

Among the means of synthetically constructing a visible dimension of depth, binocular depth cues have been singled out as one cue, which alone, provides enough information to read depth in an image [Grimson, 1981]. For this reason, it has been considered a promising tool in such fields as machine vision for detecting the location of an object in space. Image disparity offers a quantifiable means for predictably and artificially reading, or simulating, depth information.

Stereo pairs from artificially produced disparities have been practically applied as a means of visualizing three dimensional structures. Such images extend our powers of vision into a variety of spaces, both micro and macro, as can be seen in practical applications of microscopy whose binocular images are produced by a slight angular displacement of an object the surface of which is scanned to visualize depth information; or, in photogrammetry, a surveying technique in which elevations can be discerned from a stereo pair whose points of view are taken miles apart.

Stereoscopy is a means of simulating a volumetric display which requires an "interaction" with a spectator. The stereoscopic object remains only pairs of flat binocular images (left and right viewpoints) until synthesized by a viewer. The dimensions of the image are constructed by the viewer. "It is the *spectators* who make the picture" ("Ce sont les *regardeurs* qui font les tableaux")

[Schuster, 1957]).

The sensation of viewing depth revealed by a stereo image has been described,

...you need still a little more patience, you need to apply yourself really to *possess* the anaglyph: a moment comes when you see it rise and plant itself in front of you; it looks as if you could touch it, grasp it, and follow its contours with your hand. It's a strange, striking thing to see... [Vuibert, 1912]. [figure 8]

Stereo imaging is generally thought of in terms of its objects, the scenes it depicts, fine-tuned by its technicians to presume a greater and greater realism, aiming perhaps at substituting its imagery for the real object. "The reconstruction of spatial images has been a long held dream." [Okoshi, 1976].

Stereo imaging techniques offer a means not only to reconstruct spatial images but to construct them. Here it constitutes a way to define space in which to explore the capacities of three dimensions for supporting figurative, abstract, or symbolic structures.

... realistic media do not completely tame the wicked problem of good architectural design. For, as stressed earlier, the design process exists as an interaction of conceptual representations and alternative solutions. Realistic representations provide designers with techniques for evaluating their designs, techniques to judge whether or not the designs are as intended. However, designers must still rely upon conceptual language and mental imagery in the generation of these alternative design solutions. [Hooper, 1978]

The artificially produced depth of the stereo image suggests a space that can be molded by the model's presence. It opens a dimension in which to extend a model's structural configuration.

The "virtuality of the stereoscopic image...showed the way to a purely ideal configuration, the intelligible result of a synthesis certainly closer to the brain--and to the working of a *cosa mentale*--than to the retinal effect..." [Clair, 1978]

Virtual depth may provide a volume in which to compose images objects, fragments, symbols, graphs that otherwise might be disfigured in the volumeless two dimensional space. Such space need not be a passive repository of vivid, scaled elements--a three-dimensional *Wunderkammer* or curiosity cabinet in which one can view the collection of Sir John Soane's Museum in miniature (George Bailey, Sir John Soane's Museum, London. The Dome, Showing Marbles and Casts as Arranged in 1810. Watercolor) [figure 9]. Its dimensions characterize a site to be transfigured by the model maker's hands into axes of information.

2.4 DEFINING A SPACE

The model space is defined by cues which confirm the model maker's sense of the extent of its dimensions. The cues guiding the model maker in this space should match his own sense of the space,

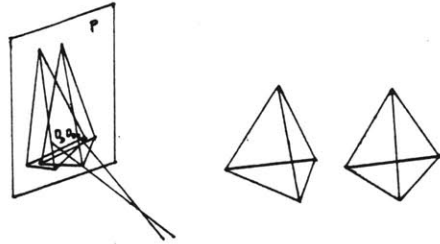


Figure 8.

Vuilbert's principle of anaglyphic vision.

P= picture plane; Og = left eye; Od = right eye.

The pyramid will appear to be in front of the picture plane.

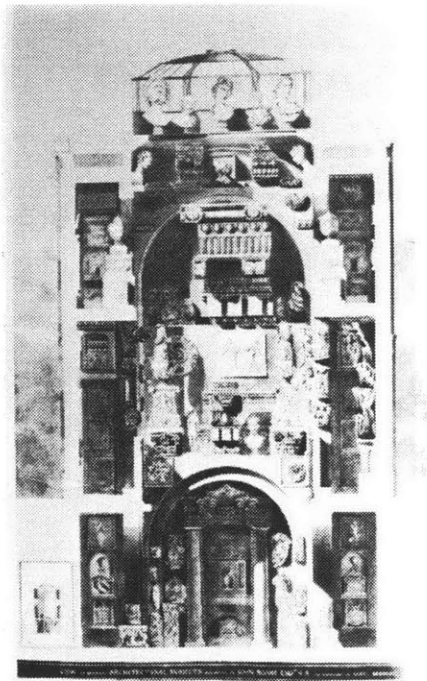


Figure 9.

Sir John Soane's Museum, London:

The Dome, Showing Marbles and

Casts as Arranged in 1810.

George Bailey. Watercolor.

37.9 x 24.5 inches.

both visual and kinaesthetic; as he moves his hand around to assemble a model. The space is also further defined by the presence of the model. As the model maker interposes components they help to distinguish foreground from background, "near" from "far".

The simulation of the model parts lies in the hands of the model maker who determines what his model should look like. Not all models are literal in their presentation of their subject; many models represent invisible or unreachable objects. Nonetheless, the space itself, as a location in which to assemble a model, must be clearly defined by cues that can guide the model maker in his movements within its boundaries.

2.4.1 LOOKING

The "laws" for depicting how things appear in space have been variously applied. No matter how inconsistently, they ultimately take the form of a code by which we can unquestioningly comprehend a space.

By the pictorial rules, railroad tracks running outward from the eye are drawn converging, but telephone poles (or edges of a facade) running outward from the eye are drawn parallel. By the "laws of geometry" the poles should also be drawn converging. But so drawn, they look as wrong as railroad tracks drawn parallel. Thus we have cameras with tilting backs and elevating lens-boards to "correct distortion"--that is, to make vertical parallels come parallel in our photographs; we do not likewise try to make the railroad tracks come out parallel. The rules of pictorial perspective no more follow from the laws of optics than would rules calling for drawing the tracks parallel and the poles converging....the artist who wants to produce a spatial representation that the present-day Western eye will accept as faithful must defy "laws of geometry." [Goodman, 1976]

2.4.2 USING SPACE

The space of a representation is only accessible if one can orient himself by its cues. One rule stands clear in defining such a modelling space:

Only the utmost conviction of the authenticity of the illusory context of a space guarantees the continuation of that space, sustains it, at once holds open its portals and maintains its elastic limits; so that it may be entered, may be possessed, without endangering the requirement that the one who enters, possesses shall always be able to find his...way out again. [Frampton, 1978]

Flight training systems use interactive computer graphics to simulate the visual cues by which a pilot orients himself when actually flying. Such systems visualize a space in which the pilot must be able to navigate trusting its cues to be able to predictably move as if he were actually in the air. Even

the rules for representing these "correct" cues, judged by the pilot's responses are not always consistent.

We had our real-time laboratory system working, and driving a wide-screen display in front of a simulated cockpit. We were modelling the world they (the customers) would fly in. ...CGI (computer generated imagery) scenes had been criticized for looking too stylized, too cartoonish, unnatural. We did all we could to cure that. Fields were made a variety of shapes and sizes--not just square. Roads were laid with varying directions, not in parallel patterns. We did all we could to make things look natural--to add realism.....The visitors flew the system..... Every pilot who had flown the system had praise for many aspects of the simulation, but stated he was "unable to maintain his glide path."Then a couple of them made the comment which provided the critical clue...our land scene was providing counter-cues.

We redid the terrain. We made all fields square, and roads parallel. We took all the naturalness out of it....Many of the visitors...were persuaded to fly it again....A typical comment, "I don't know what you did to it, but you sure fixed it.".... In retrospect, we know what we did. We did not have many scene edges then...those we had were devoted to providing..."stimulus gradient" derived from the parallelism of scene features, rather than destroying this cue in an attempt to achieve a more real appearance.

The conclusion of the simulation research,

In all cases, we are not attempting to apply the principles ...to assure that we do not go after realism for the sake of realism, but that we achieve advances where they are most needed. [Bunker, 1968]

In another situation in which a visual simulator for teaching Navy pilots to land airplanes on aircraft carriers, the color of the landing area and the white lines were reversed from their actual colors in order to guide the appropriate control decisions,

The fact that carriers don't have white decks was trivial to the Navy pilots. The important fact was that they could get the information needed in the normal way at the normal distance. Common sense and simple rules for simulation would have predicted that the more faithful display would work better. The fact of achieving better simulation with an invented display cannot be explained by the nature of the picture without going through an analysis of the pilot's informational needs. [Ritchie, 1978]

2.5 CONTACT WITH VIRTUAL SPACE

A representation of a space which is "used" cannot be static. The space is subjected to an exploration which can only take place if the senses are dynamically guided.

When sensory information is used for guiding action, it must control movements which are appropriate to the positions and sizes of surrounding objects. Sensory information must be scaled approximately to the external world, for control and prediction to be possible. Similarly, the readings of instruments cannot be in arbitrary units but must be, at least ultimately, tied to familiar objects. Vision demands that every received pattern be

interpreted according to a theoretical construction of the world of external objects.
[Gregory, 1980]

The computer's powers of simulation are used for their interactive graphical qualities so that despite changes within the framework of representation, a consistent understanding of it can be maintained by cues.

Interaction between viewer and image begins with the synthesis of stereo image to open a more extensible exchange. Stereo imaging is used to conceive a dimensional world the presence of which is to be confirmed by the senses. One simply reaches into virtual space. The successful model virtually draws the properties of its subject into its own dimensions. How does one reach into the space of the model?

...we might imagine that the brief ascendancy of the roughly isotropic painting of mammoth dimensions proceeded from an impulse to exceed anatomical scale without making the painter walk too far or overstrain his imagination, and that such seeming tactics of physical distancing as Jackson Pollock's paint-slinging and Yves Klein's use of a flame thrower amounted to temporary strategies, transforming the vast surface of the workplane into a miniature and extending across the interval of an enlarged studio the long arm of painting itself. [Frampton, 1978]

2.6 INTERACTING WITH VIRTUAL IMAGES

Even a virtual world of a model is always within reach; it is pieced together with the hand, the eye guiding and informing its movement. The full play of a dimensional model's imagery invites a range of perceptual means. Its imagery of spatiality, dimensionality, and structure should not defy the kinaesthetic sense.

In research in display control compatibility in three-dimensional displays [Getty and Huggins, 1981], the effects of orientation have compared different responses to a three-dimensional display (the stimulus) by means of correlated response mechanisms. At the very least the test demonstrates that a person can be prompted to respond to a virtual image. An object's location in a synthetic space can be gauged by the eye. In turn, these visual terms of physical dimensionality can be translated into a correct muscular response as measured by the hand.

The concept of a controlled muscular response to a stimulus, or the distinction between the mechanisms that control reflex action and those that regulate perceptually guided behavior and voluntary movement was made in the late nineteenth century and is credited to Marshall Hall [Flourens, 1824] who showed that reflex activity in a frog persisted after decapitation and, Flourens [idem] who isolated and studied the separate parts of the brain. From this distinction, one hundred

years later has grown neurogeometric theory which states,

We believe that the cortex represents one of several levels of motion regulation, and that its growth and proliferation in the human species was correlated with man's progressively more complex perceptually controlled manipulations in the use of tools and related symbolic operations. [Smith, 1962]

The neurogeometric theory of perceptual-motor integration is a body of theory that describes space-structured motion, how an apparently simple movement is subject to continual corrective adjustments to make a motion pattern conform with the stimulus pattern as a man, for example, follows with his eyes, hands, head, or body, an object moving across his field of vision.

The general postulates of the theory are explained,

...that motion is multidimensional; that it is primarily space-structured; that this spatial patterning depends on neural sensitivity to spatial differences in stimulation; and that the temporal continuity of motion is determined by sensory feedback mechanisms...all patterned motion involves relative displacements between perception and motion, e.g., between the line of sight and the plane of manipulation, or between the vertical axis of the body with respect to gravity and a horizontal transport movement of the arm.

....It is fairly well established that the central factor in human evolution was man's use of tools, not only in survival but in positive control of the environment. The evolutionary development of man's distinctively human characteristics--his upright posture, stereovision, apposition of thumb and fingers, mobility of head and eyes, forward disposition of shoulder and arms, and oversized brain to level simultaneous control over these varied mechanisms of behavior--has been determined by tests of survival based on the fitting motions to use tools. [idem]

2.7 MEANS OF INTERACTION

What means or tool is available that lets one "enter the picture"? In an interactive computer graphics display using the finger as a "graphical stylus" to move an image by means of touching a pressure sensitive digitizer that accepts force input, it has been observed that,

...touch and pressure sensing open a rich channel for immediate and multi-dimensional interaction....The excitement generated by TSD's [touch sensitive devices] derives directly from their ability to provide a more natural input path to the computer without dislocations caused by separate input and presentation surfaces.

....While potentials for more natural, coincident and even multi-finger input are obvious...little exploration has been undertaken in the area of multidimensional input....Yet this domain offers a rich potential for man-machine interaction....It is not difficult...to imagine more elaborate uses for a pressure sensitive device. For example, a three-dimensional dynamic modelling system... [Negroponte; Herot; and Weinzapfel, 1978].

To indicate "where" in depth is difficult on a two-dimensional display. Does "further back"

conform to a linear perspective in which "higher" can also mean "deeper"? If something already appears at a spot defined by a position on horizontal and vertical axes, how does one indicate "in back" or "in front"? It is not too difficult to put one's hand on a particular point in space in a three-dimensional image that is already composed. But to add something to an image at a particular place in depth is less simple.

Tracking devices have been used as a means for "interacting" with a three-dimensional graphic environment or display in which the space of interaction can be coincident with the display. They have been used to track heads, wands, fingers, bodies and helmets. The means for tracking have ranged from acoustical, mechanical, electro-mechanical, and illumination to electro-magnetic.

"Touchy Twisty" a system which was designed in part for modelling illustrates a mechanical tracking device used not only for detecting movement but for guiding touch by means of force-feedback. A three-dimensional force-position system which tracks force, torque, position and orientation was designed "to permit the user to feel the docking of one three-dimensional object with another; in other words, to allow the assembly of computer simulated objects....The human proprioceptive system can thus be used to judge three dimensional location by reaching into three-dimensional space." [Geyer and Wilson, 1975]

Its designers suggest that

The primitive systems we describe could communicate touch information over long distances. For example, two engineers working on the design of a mechanical device could construct a model on the computer, touch it, "play" with it, alter it, discuss it, and look at visual representations of it, all without having to leave their offices. [idem]

The prototype for such graphical tracking devices was Lawrence G. Roberts' Lincoln Wand designed in 1963. It used an ultrasonic signal and four microphones mounted in a rectangular configuration. The path lengths from the point source of sound to each microphone were determined by the arrival times of the pulse at each microphone. [Roberts, 1966]

The tracking system was later used to interact with virtual images projected in a real environment by means of a "wand" and a head-mounted display designed by Ivan Sutherland. Here the four sensors were mounted near the ceiling, in the corners of a 45 inch square "shower stall" to pick up the 37 KHz sinusoidal output of the wand. The head-mounted display projected virtual images into real space (semi-transparent mirrors were placed in the eyepieces of a helmet, reflecting image pairs from small video monitors) which could be manipulated by means of the wand. [Sutherland, 1968]

A.M. Noll's electro-mechanical three-dimensional input device in conjunction with a stereo display allowed direct graphic input to be given in the same terms that defined the display, a

Cartesian coordinate system [Noll, 1972]. However in most cases such systems must convert the tracking area which is measured by light or sound into a coordinate system in which the imagery is defined--sometimes contributing more dynamic terms in which to understand space. Science Accessories Corporation's acoustic table, for example, defines a position in space as

the time required for sound to travel from a small spark source to each of three mutually orthogonal linear microphones. [Science Accessories Corporation, 1970]

Tracking devices have been developed with the consideration of independence of the sensor from its source so that the object being tracked has freedom of movement and can fully exercise natural movement including gestures such as pointing.

"Twinkle Box" was designed to facilitate gesture input by simultaneously tracking more than one point in space.

Rather than drawing with the point of a three-dimensional pencil, a user might make broad gestures using his fingers separately. He might grasp objects to move them, indicate sizes by gesturing with two hands, or otherwise make use of the many three-dimensional motions with which humans...are said to communicate. [Burton and Sutherland, 1974]

This system used three sensor lights coupled with a one-dimensional mechanical scanner that rotates at 3500 rpm for 1900 scans a minute and four detector-pair units to collectively calculate the position of the sensor lights.

2.8 SENSE AND INTERFACE

By means of tracking devices, machines can be applied to tasks which use coordination between perceptual and motor skills. Remote control of robot arms in hostile or distant environments has attracted the investigation of extending the range of sensory modalities in their operation. Yet the increased range of senses can be used close at hand to enhance a computer-mediated operation.

Each sense contributes to the reception of information and subsequent action or thought. In the following statement, Gilbert Ryle explains how the senses can be exercised to extend our perceptions.

We should notice that tactual and kinaesthetic detection is unlike seeing, hearing, tasting, and smelling in one important respect. What I detect by seeing, hearing, tasting, and smelling are with extremely few exceptions, properties or features of things and happenings outside me. What I detect tactually and kinaesthetically *may* be properties or features of external though contiguous things and events; but they may be and quite often are properties or features of anatomically internal things and events...

In this sense of "feeling", feeling is a species of perception or perceptual discrimination. We have to learn to do it; we may be better or worse than other people at doing it. There is room for care and carelessness in doing it; and there is always the possibility of making

mistakes....In all cases alike there can be trained or untrained observers. [Ryle, 1965]

In being able to exercise the kinaesthetic sense when working in a virtual world, one can directly shape it with the skills developed in an exchange with a real one.

A modelling system suggests a means for a designer or anyone who working with visual images--whether to build, organize, analyze, or hypothesize--to have access to a dimensional world, which he can rapidly construct, or slowly put together in a manner which is less remote to his senses and direct expression of his thought.

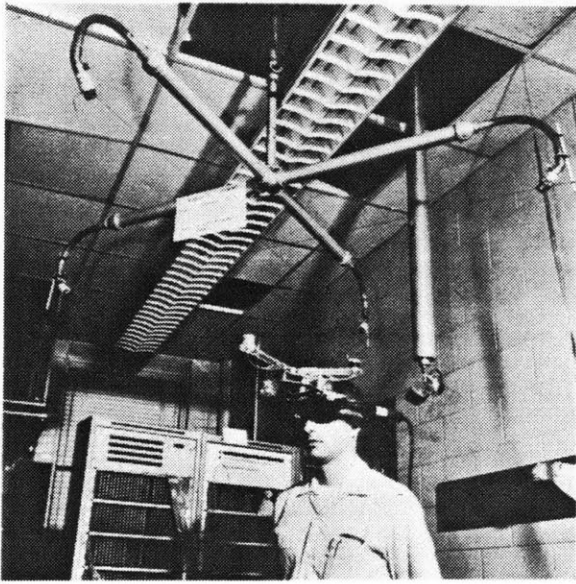


Figure 10.

Mechanical head position sensor in use with Ivan Sutherland's headmounted display. This tracking device used a mechanical arm hanging from the ceiling. The arm was free to rotate around a vertical pivot in its ceiling mount. It had a universal joint at the top and one at the bottom, and a sliding section to measure translation and rotation from six motions. Each joint's position was measured and given to the computer by a digital shaft position encoder [Sutherland, 1968].

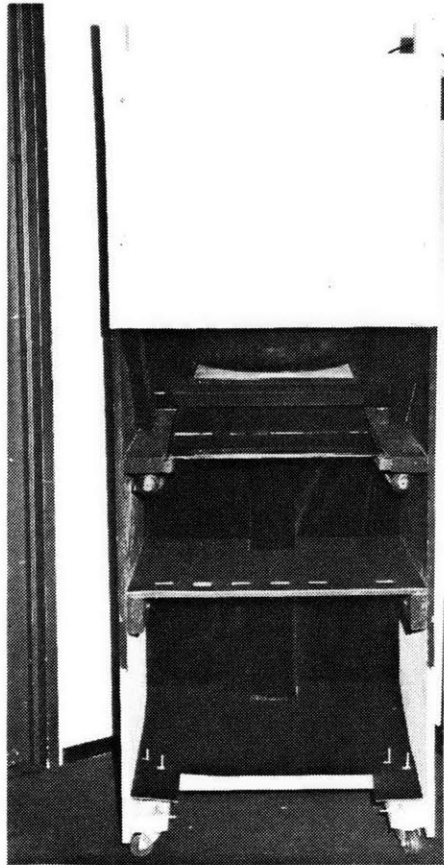


Figure 11.
Model Kit system. Front view.

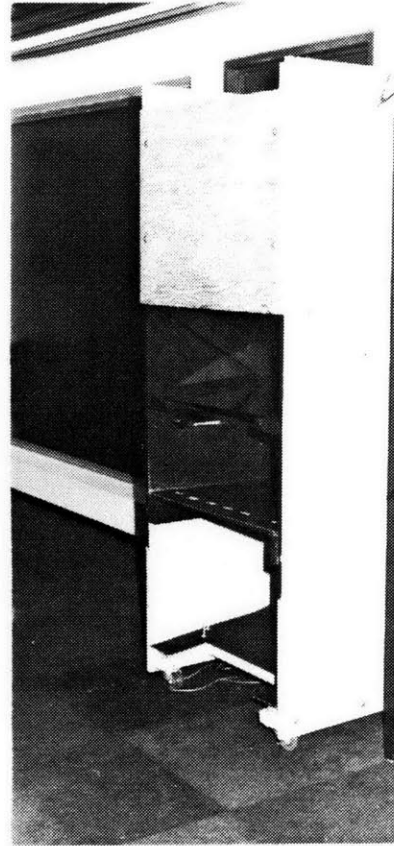


Figure 12.
Viewed from the right.

Chapter Three

THE MODEL KIT

3.1 INTRODUCTION

The model kit is a prototype for introducing three dimensional images, by hand, into a real space. The system uses stereoscopic video to display computer stored images of objects in a virtual space which, by means of a semi-transparent mirror, is optically combined with a real space. The images are reductions and pieces of larger images of objects and scenes which form model "components". Holding a "wand" to which a tracking device, and a pushbutton switch are mounted, a person can extend his hand into the real/ virtual space and begin to build a model. By means of this tracking device, which is only encumbered by a light-weight cord extending from one end, a person can directly manipulate images in space simply by pushing the button. The components form parts of a model that can be stored, redisplayed, and taken apart and rebuilt by either its model maker or anyone learning from the model.

The combination of two systems, stereographic video and a magnetic tracking device was chosen to create a means of easily working with three-dimensional "synthetic" objects. "One problem with many systems offering three-dimensional control is that the volume of control does not coincide with the volume of observation, thus utilization of a person's natural pointing ability and sensorial means of comprehending space is restricted. Is it possible to use the same volume for interaction and display?" [Vickers, 1974]

3.2 THE PHYSICAL STRUCTURE

The "model space" in which someone can move virtual images is a real space, at table level, (20 inches wide, 20 inches deep 12 inches high), housed in a tall wooden booth in front of which one sits. The space is sliced in half horizontally by the half-silvered mirror. The space is truncated at its upper dimension by the 45 degree angled plane of the monitor on which the virtual images appear, generated from a frame buffer's video signal. The actual face of the monitor is not intended to ever be viewed directly by a person using the system whose angle of vision naturally looks out and slightly

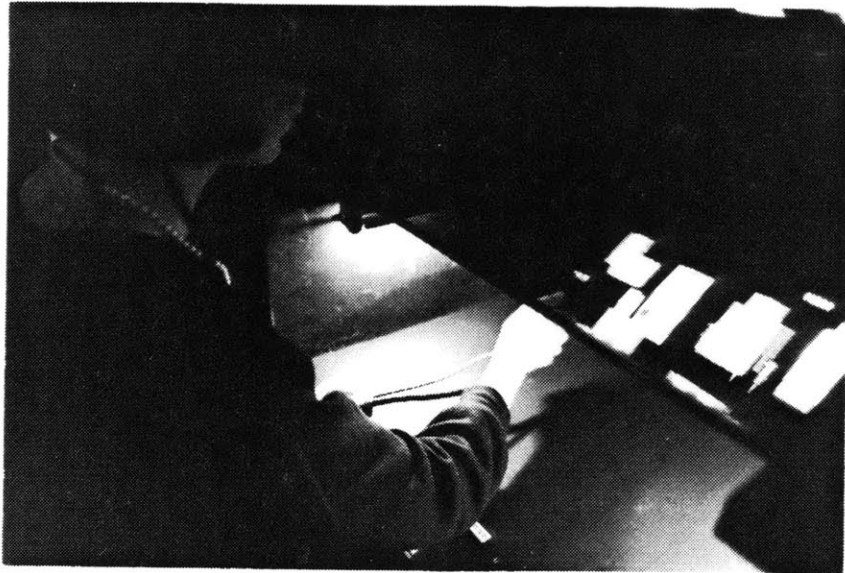


Figure 13.

Model Kit, with model maker, in use.

downward to the mirror which reflects a virtual image. The virtual image appears in a space that appears to recede downward into the real space below the mirror. Any object placed in this space, which is illuminated by four adjustable lights, is also visible. It is in this space that one can place his hand in a free and natural way--extending it in the virtual space.

3.3 HISTORY

The structure of this system evolved out of a series of projects in which a virtual display is optically combined to coincide with a real space or object so that direct manipulation of the computer generated imagery is possible. That is to say, the interface by which one indicates changes in the display is spatially constructed to share the space of the virtual image.

The technique of using the semi-transparent mirror as an optical sleight of hand to create the illusion that the virtual image is accessible to one's hand was developed by Ken Knowlton. In his original system, a display was superimposed on a telephone operator's button set by means of a semi-transparent mirror:

The user looks through the mirror and views his/her hand directly as it pushes buttons. The display--a television monitor--and mirror are so arranged that the virtual image of displayed light buttons conforms in three-dimensional space exactly with the position of the physical keytops.

...This combines the flexibility of light buttons with the tactile and kinaesthetic feel of physical push buttons; it permits a user to interact more directly with a computer program, or a computer-mediated operation, in what subjectively becomes an intimately shared space. [Knowlton, 1977]

The user need not be distracted from his point of focus--the computer generated imagery--in his work modifying the image.

This work motivated further exploration at the Architecture Machine Group in which a system using the same mirroring technique was designed "to test three aspects of man-machine interaction: (1) interaction with a flat display; (2) co-planar input and output; (3) the ability to "see through your hand" to a display below." [Lippman, 1981]

Using the above mirroring technique, this system allowed a person to work on a horizontal rather than vertical surface and the additional advantage of being able to see through the display to his hand supported on the input tablet. Mirrors were arranged to direct a projected television image to a back-projection screen which, in turn, was superimposed onto a data tablet surface by means of a semi-transparent mirror. In experimenting with several ratios of reflection/transmission the 45%/45% was found most suitable.

This system was then elaborated to allow direct input in three-dimensions. A three-dimensional paint and polygons system was designed [Schmandt, 1982]. In this system, the rear-screen projection and mirrors were replaced by a CRT monitor placed directly above the mirror. Instead of a tablet, the "wand" with mounted tracking device was designed and used for direct spatial input in three dimensions.

3.4 REAL & VIRTUAL SPACE

Before discussing how the virtual space is subjectively perceived to be a real one, the technologies used for projecting and sensing a point in space will be described.

3.4.1 THE DISPLAY

This system uses a stereoscopic imaging technique to present a left view to the left eye and right to the right eye, which is known as the "eclipse" method (also called "phenakistoscopic"). As early as 1858 [Lipton, 1982], a mechanical device for viewing stereo pairs was used, in which shutters were placed in front of left and right projection lenses and shutters are used in spectacles worn by the audience. Both left shutter in projector and spectacle are opened simultaneously and right shutter in projector and spectacle respectively so that the observer sees only the appropriate image for each eye. The New York Times mentions this technique in 1922 [New York Times, 1922], in a favorable review of a slide show shown in which individual viewers were mounted to theater seats; projector and analyzer motors were run off the same alternating current to keep the shutters in synchronization.

Many inventors have used this technique for displaying stereo on television. In this case, the left and right images can be "interleaved" in the interlaced or alternate odd and even fields of the scanned television image. In the United States, thirty pictures are shown a second, each generated in two parts or "fields." Sixty fields are "refreshed" a second, scanning the television picture in the odd lines, or field, and the even lines respectively to make a complete picture. Goldsmith first used this in a system which did not use viewing glasses. He proposed to rotate the raster 90 degrees and view it through a parallax stereogram barrier which has slits that allow the left and right eye to see only their respective images [Goldsmith, 1951]. This was then modified by Kratomi (1973) [Lipton, 1982] and Roese (1975) [Roese, 1975] who used electro-optical shuttering devices worn in spectacles. Such spectacles require synchronization with the fields by means of a cable or wireless device for connecting them to the receiver.

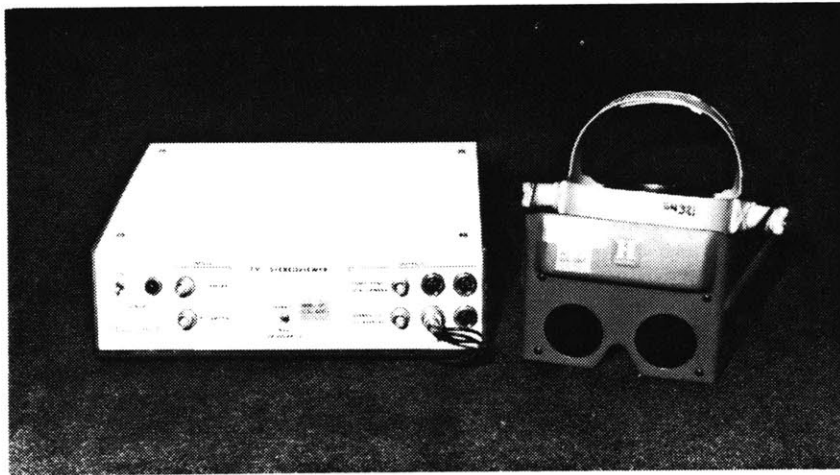


Figure 14.
Glasses with PLZT lenses for viewing stereoscopic display.

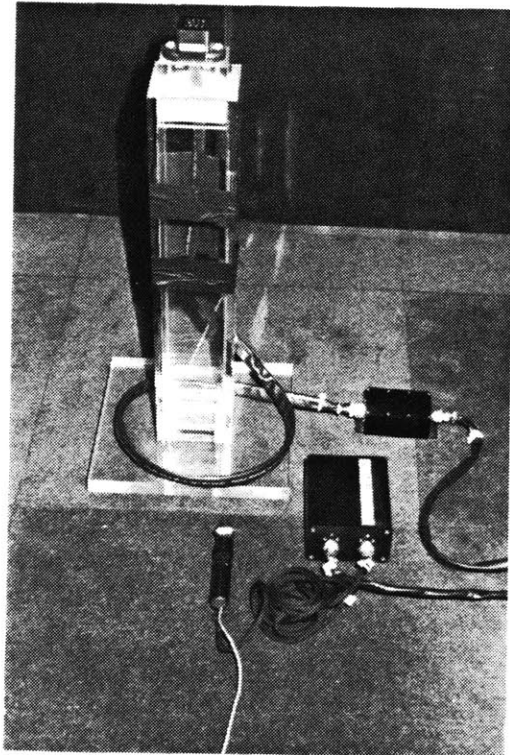


Figure 15.
Polhemus: sensor and source units, electronics. Source unit is on tall plexiglass stand; "wand" on ground: cord extends from one end with white rectangle marking the sensor at opposite end. Electronics in black units to the right.

To see the video image, the person using the system must wear glasses. In the lenses are PLZT ceramics which are electro-optically rotated to opened and closed positions in synchronization with the field refresh cycle [figure 14]. This technique is also called the time-division method. [Okoshi, 1976]

3.4.2 TRACKING IN SPACE

3.4.2.1 "WAND"

The wand, a familiar name used for the graphic pointer or indicator, is simply a short stick of wood with two parts built into it: the Polhemus sensor and pushbutton. The wand's graphic extension is the cursor, a visual cue marking the wand's location in the virtual space which will be discussed later.

The power of the technique is that indications of what is to be done with these visible, out-there-on view items can be expressed spontaneously and naturally in ways which are compatible with the spirit and nature of the display: one is pointing to them, addressing them..not [in] typed symbols. [Bolt, 1980]

By means of the wand one can indicate directly at the exact location in three-space, where and when he wants to place or move an image.

3.4.2.2 POLHEMUS

The Polhemus is a three-dimensional digitizer based on electromagnetics to ascertain x,y, and z positions of the input device, in this case, the hand [figure 15]. It generates up to 40 points a second. This device has been used for helmet-mounted sight to measure the orientation of the helmet and consequently its wearer's line of sight. [Raab;Blood; Steiner; and Jones, 1979]

As well as position, it tracks the orientation described by three Euler angles on the sensor body with respect to a reference radiator body. The position and orientation measurement is based on near-field, quasi-static characteristics of an electromagnetic field. The system consists of two independent remote components which are connected by electronics to a Nova minicomputer. In one of the remote bodies, the radiator, are the electronics which transmit a signal and an antenna system mounted in a 4 cm. plastic cube. The other is a sensor body which holds the receiving electronics. Connected to the sensor by a flexible cable is a small 1.5 cm. plastic cube housing another antenna system.

The transmitting component produces a nutating dipole (magnetic) field. Three mutually orthogonal dipoles form the antenna system, the varying signal strengths of each allows the axis of nutation to be pointed in any direction. By means of measuring time variance in the signal induced in the receiver, the axis of nutation can be pointed at the receiver itself, defining the line of its position at a particular orientation with respect to the radiator. From induced signal strength (its proportion is the inverse of the radius cubed) the distance along this line can be computed. The attitude or orientation of the sensor can be derived from differential relationships of currents induced in each of the three receiving dipoles.

For a given piece of sensor locational data from the Nova the following computations were performed. The x,y,z location of the sensor, relative to the radiator, combined with the knowledge of the radiator position...and the physical dimension of the sensor positional measurement units relative to physical size of a single pixel on the display, all lead to the position of the sensor in screen pixel x,y,z coordinates. [Schmandt, 1980]

This corresponds to knowledge of the sensor's location in the modelling space.

3.4.2.3 PUSHBUTTON

The small switch or pushbutton is connected to a Perkin-Elmer 32-bit minicomputer by a separate interface. The user simply presses it at the moment he would like to either execute an action in the image space or select a command from the menu.

3.5 VIRTUAL SPACE

To a person building a model, the model space is defined by his visual apprehension of the images in a space before which he sits, the dimensions of which he can simultaneously gauge by his movement of his hand.

The perception of being able to work with images within the real space is effected through a number of contributing factors. [figure 16]

3.5.1 COMPUTATIONAL DEFINITION OF SPACE

The space is measured by an artificially constructed coordinate system in which the correct placement of the binocular images with respect to the viewer can be calculated. [figures 17b and 17c]

The "image space" is defined by the frame buffer parameters, the changing contents of which

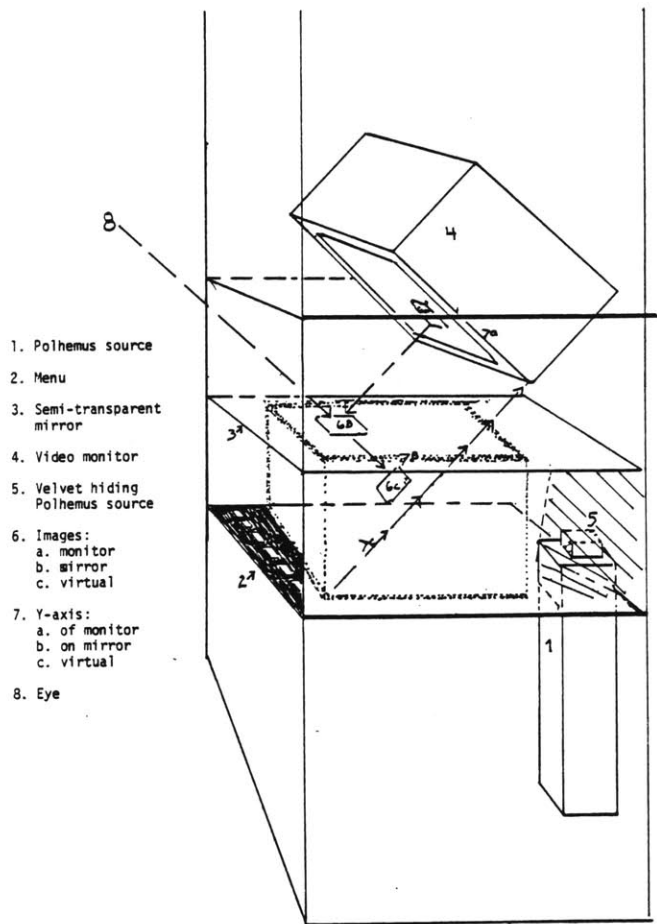


Figure 16.

Diagram of virtual image space projected onto real space inside the Model Kit system.

appear on the video monitor which is pointed downward to the mirror. Displayed images are reflected to appear directly in the space encompassed by the viewing range of the model maker. [figure 17a]

The placement of the images within this reflected, or virtual, display space is defined both with respect to the point of view of the person building a model and the location of his hand and by the boundaries of the frame buffer.

The "model space" (within which the image or display space is located) is defined within the x,y, and z axes of a Cartesian coordinate system defined in screen pixel units. The space's x-axis extends across approximately the width of the physical structure housing the modelling system. From its beginning at the corner of the modelling space coinciding with the origin of the reflected display, the y axis extends--at an angle defined by the angle of the monitor--out to encompass the space occupied by the seated model maker. And the z axis extends from the horizontal lower boundary of the space below the mirror --defined by physical structure housing the modelling system out, like the y axis, to an extent that also encompasses the modelmaker.

Within this space two eye coordinates (left and right) are defined at a set interocular distance, as well as height and distance from the modelling space that approximate the actual location of an "average" person seated in a chair before the modelling space. The eye coordinates and image plane can also be reset if someone using the system wishes to change the perspective.

Also within this space, an "image plane" is set at a location a little less than one-third way between the mirror and the base of this space in which the model maker can place his hand. All of the images will appear either above, on, or below it as projected with respect to the left and right "eye" coordinates.

The image is drawn on a display, limited to the frame buffer coordinates, 640 in the x and 480 in the y directions. The appearance of an image somewhere along the z axis is defined purely as a function of image disparity. That is, if an image appears on the image plane, there is no, or zero, disparity. All images that appear below it have "positive" disparity; that is, the left image appears to the left of the right eye image. All images that appear nearer or in front of it have "negative" disparity; the right image will appear to the left of the left eye image. The image plane is set a little low so that a greater part of the z axis would be shown by means of a positive disparity, considered for some people to be a less tiring to fuse than a negative disparity.

The location of where an image will appear is initially defined by the hand's position in x,y, and z space (read in from the Polhemus, noise filtered with respect to its proximity to the monitor, and converted into the coordinate system [Zamiska, 1982]). The location of the image is then calculated

Figure 17a. Real and reflected images of model space.

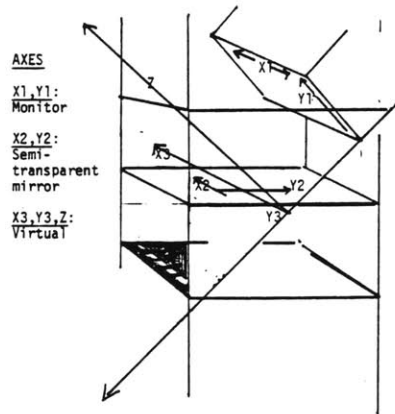
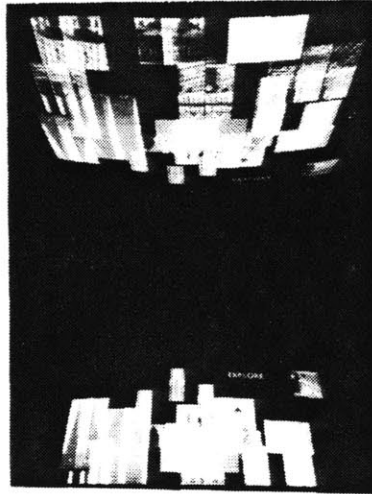


Figure 17b. Axes define coordinate system of display monitor and virtual space; and, reflected on monitor.

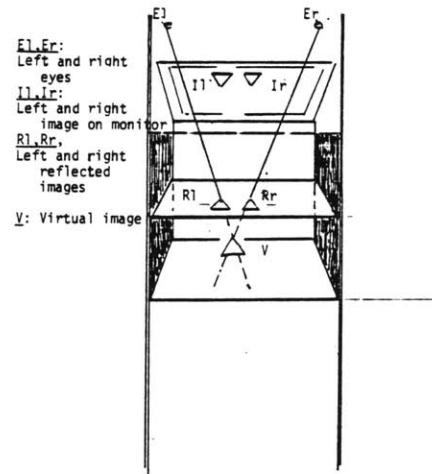


Figure 17c. Projection of a stereo pair of images.

twice, as projected onto the image plane from both left and right eyes. After being "clipped" with respect to the boundaries of the monitor, the image is then drawn twice, the left and right images drawn in alternate fields; the y location remains unchanged, the virtual z axis is defined by the projected disparity which is represented by a shift of each image along the horizontal axis.

The visible parts of images which are in front of where the image is placed are then redrawn to complete the appearance of the image at the indicated location.

The space is not completely three-dimensional. That is, an image must remain on one of the 488 planes in the z direction. If an image were to be drawn spanning the z axis, the disparity would have to be calculated for each plane which it crossed. The time it would take to calculate these disparities and correct foreshortening of an image would interfere with "real-time" imaging; the appearance of images throughout the space, though each confined to its own plane, could, in a prototype, sufficiently fill the space to give a sense of three-dimensionality--although without realizing the full potential of the space.

Consequently the space, in a way, can be imagined to be somewhat like a loaf of bread, each of its planes, like the slices, lying one behind the other. The orientation of this "loaf" which recedes downward at a slight angle is designed to be compatible to the natural perspective of someone using the space--whose eyes naturally are directed slightly out and downward. The model maker only has contact with the reflected three-dimensional space of the display, the furthest depths of which the viewer's hand could never reach to short-circuit the sensation of moving one's hand throughout its space.

3.5.2 CUES TO VIRTUAL SPACE

The space is not defined only in terms of a coordinate system and appropriate projections. Of the eleven visual cues generally considered to contribute to the perception of depth--retinal image size, linear perspective, aerial perspective, light and shade, textural gradient, motion parallax, and interposition (overlapping)--all are considered psychological cues. Those considered physiological are accommodation, convergence, and binocular parallax, the last two being the only depth senses that depends on our having two eyes. Of these cues, the latter four are extensively used in the virtual space, while retinal image size, or scaling, is used for the cursor which dynamically marks the hand's movement.

In addition to binocular parallax, interposition, (that is, the appearance of an image in front or in back of other images) serves as another important cue. Each image keeps in its database a list of

which images are in front and in back of it so that every image affected by the insertion or removal of an image can be quickly determined. The database also keeps the dimensions of the image and its location in x,y,z space as well as its dual x and y locations so that the necessary data is available for rapidly reprojecting and redrawing the image at a new location with the correct cues both of disparity and interposition.

3.5.3 KINAESTHESIA

In addition to the above visual cues are those which dynamically confirm the model maker's sense of placing and moving images in space. As one reaches into space with his hand, the kinaesthetic sense comes into play. As the viewer moves and sees his hand in the real space of the modelling system, he directs his movements in exactly the same way he would to complete any task that uses visual-motor coordination. The perception of his hand movement in the coincident *virtual* space is guided by several graphic cues. The model maker's sense of "placing" the model part in space is ultimately confirmed by the appearance of the image at the location indicated by his hand.

The visual cues generated by the modelling system which confirm the model maker's kinaesthetic sense are simple and few. If one has to read an intricate symbolism to move around in the space, progress would most likely be slow. On the other hand, if no deviations of scale were permissible, much of the exploration that the modelling system offers, such as the design and juxtaposition of worlds of micro and macro scales could not take place. The system invites innovation such as metaphors of scale.

However, to successfully use such a space as a design tool, to visualize models in various dimensional structures, the space must be legible. Given a means to enter a three-dimensional image space, the image must neither confuse the viewer's eye nor elude his hand. Natural hand-eye movements must "work" in this space.

In the field of psychology, the operation of visual-motor coordination skills has been investigated using the task of aiming with unseen hand at a visual target at eye level as a paradigm for experimentation.

The physical components involved are the target, the retina, the eyes, the head, the body, and the arm. Each component is linked to the next at what may be called an articulation....The whole system is therefore in open-loop, in series control system. It becomes a closed-loop system as soon as the person is allowed to see the error of his aiming response.

A person is normally able to point with unseen hand to within approximately one degree of a visible target at arm's length. [Howard, 1973]

To understand the scope and adaptability of such coordination, experiments have been conducted in which the optical array is displaced (typically a subject will wear glasses with prisms). A subject can learn "recalibrate" or compensate for the difference from his normal vision. The first precise model to account for the adaptability of visual-motor behavior was Held [Held, 1961]. It contains the primary point that,

the adaptation of the system to displaced vision requires self-produced movements to be associated with the new sensory consequences of that movement (reafference)....The view of the author is that sensorimotor behavior will develop and change in response to properly displayed *discordance* including (a) intersensory discordance, or an unusual spatial association of stimuli in different modalities, (b) sensory-motor discordance, or unusual association between motor innervation and consequent sensory inputs (reafference). [Howard, 1973]

To what degree does movement depend on a point by point visual identification of one's hand in space? The perceptual recognition of one's own movements has been investigated in experiments by using simulated delayed visual feedback of motion.

One such experiment tested maze-tracing with delayed visual feedback. A two-camera, close circuit television system was set up. A subject traced a drawing of a maze while prevented from seeing his own motions directly and instead guided his movements by watching the monitor image before him.

The subject was told that the televised image of his performance was delayed electronically in transmission. However, the image seen by the subject was not of his own hand but of the hand of a trained observer in the next room. Both observer and subject wore white gloves and black arm covers which the subject was instructed to wear "to improve the television image". After a set time delay, the observer would reproduce the movements of the subject on a duplicate maze of his own--the image of the observer's movements was transmitted to the subject's monitor. Only one subject spontaneously commented about the substitution. Some of the subjects acted disappointed about their performance.

The limited results of this study...suggest...that the organization and motivation of patterned motion does not depend on the perception of one's body image....Given a visual feedback, they [the subjects] were motivated to use the information in patterning their motions....In learning to use tools, the performer does not identify what the hand is already doing and then decide where it shall go next. Rather, the hand in motion is perceived immediately in terms of visual and kinaesthetic feedback and its continuing movements are adjusted according to the differential spatial information. [Smith, 1962]

Visual cues are given, as a general guide, to help the viewer move with an understanding of the correspondence between his movement in real and virtual space.

Letting the model maker use his hand and arm in space directly in placing and moving images

gives him a broader physical engagement and feedback which usefully guide his work. While the match between real and virtual space relies on the compatibility of the two sources of cues (real and virtual), the discrepancy is marginal enough that the model maker can work in this synthetic context.

In another project using the same tracking device to draw figures,

It was observed that attention is paid to the visual feedback...rather than hand position; as long as changes in hand position produce the same *relative* changes in visual position, a high degree of accuracy is felt. This suggests that linearity and repeatability are far more crucial than absolute position in the context of visual manual 3-d coordination of input. [Schmandt, 1980]

This project, however, used a large-screen display and a greater distance between hand and object which may have made such discrepancies less obtrusive.

In using his familiar gestures of hand movements to place and move images directly within this space, one can rely on his natural abilities to compensate and recalibrate within his larger movement in order to achieve his ends. He relies, in part, on the same ability used to guide one's hand to the proverbial door knob in the darkened room.

A person building a model is not divorced from his skills learned throughout his life that guide his movements. The manner of "building" in this space exercises his habitual practice of hand-eye coordination rather than imposing an entirely foreign set of learned skills and symbolic languages which are called upon in indirect methods of locating an image in space when keying in an image in a coordinate system, for example.

3.5.4 DYNAMIC CUES TO VIRTUAL SPACE

3.5.4.1 HAND MOVEMENT: THE CURSOR

The cursor is a small white rectangle which is a virtual image of a small white rectangle affixed to the sensor at the end of the wand which the user holds. The placement of the stereo cursor, in space, like the components, is determined as a function of disparity between two images of the cursor. It also has a scaling cue, becoming larger or smaller as the user moves his hand more and less deeply into the space. Its width and height are calculated as a function of the plane on which it appears.

The cursor, which is always visible when a person places holds the wand in the space, bridges the real movement of the hand in space and its appearance in virtual space, tightening the fit between the two combined spaces. Such visual feedback plays an important role when using a virtual space to give the constant graphic information that the user typically expects.

The floating white marker in space is an artificial index to the space. As a cue, it helps the user to gauge where his hand is in the virtual space. It also identifies where a component will appear in space as gestured by the model maker's hand; its position indicates the upper right hand corner of where the component will appear in space.

This cue was also introduced to bridge discrepancies between actual hand movement and the Polhemus reading of its location. If the deviations are bothersome to the person using the system he can always dim the lights which illuminate the space in which he puts his hand. Its location is therefore only judged by kinaesthetic sense and virtual cues of the cursor.

3.5.4.2 "TOUCHING"

As no mode for tactile sensing has been implemented in this system, other means of "feedback"--in this case visual cues-- were designed to cue someone working in this space that he has "touched" an image.

When a person "places" his hand on the model in the space--indicated simultaneously by the presence of the cursor within the area of the component--the component will be "highlighted" in a blue tone. This highlight instantly lets the model maker know that he had "touched" the image.

In using such a prototype of a virtual space, even though feedback may deviate from what a person senses about his hand movement within it, the ability to dynamically "recalibrate" and compensate minimalizes this interference.

Finally, in using more than one sense to construct the model, and not leaving the rest in oblivion, one does not, after all, leave a session of model building with sense of only mental and visual exertion. In building a model, one works in a three-dimensional space, exercising his ability to gesture and point, to work with hand and eye.

3.6 MENU

Just outside the virtual space, at its threshold so to speak, extending horizontally across the base of its outer edge, is the menu. It contains six options, each specified by its name written in black on a small white rectangle [figures 18 and 19]. The menu is a continuation of the interactive space, although it does not use more than an inch of the z-axis. Each option is differentiated spatially by its position on the x axis. One selects a command by placing the wand over the appropriate rectangle and pushing its button. To leave as much room as possible for model construction, the menu of

virtual "buttons" is not shown on the display monitor; it lies just on the border of the modelling space. However, a selected option is printed in white in the space's upper right hand corner as well as a miniature image of the component that the model maker is placing in the space.

The menu was a solution to the problem of being able to give several different types of commands using only one pushbutton--as opposed to the multiple buttons often found, for example, on a puck. With the menu right in front of the person using the model kit, he need never turn to the keyboard of the computer terminal while constructing a model. The menu allows all the construction to take place dynamically in space, within the bounds of the modelling space.

Using the menu, the model maker indicates what he wants to do in the space--place or move an image--before moving his hand into the modelling space. He then can realize this indicated action directly at the location--at the moment he pushes the wand's pushbutton.

The construction of a "spatial" menu which is accessible by means of a tracking device has been used in several other projects. Vickers, who used a wand to interact with a graphic environment, designed a menu in the form of a wall chart, suggesting that a "whole room could be filled with charts if desired." [Vickers, 1974] In this case the wand had four pushbuttons as well. In the design of the Lincoln Wand it was suggested that the wand be "used to point to target areas an pictures of library parts which are completely off the scope [display]. Since the WAND has more range in x and y than the field of the scope and can operate in free space, it can be used to point at large boards of both photographs and typed sheets of function names...perhaps even more significant is the ease with which a user can simply point at which he wants..." [Roberts, 1966]

Half of the six options are to select and place the component in the modelling space: DISPLAY, NEXT, and PREVIOUS. The last two are used to cycle through the components which are displayed in miniature in the upper right hand corner of the display along side the current menu option in use. DISPLAY is used, after a component has been chosen and a location given, to make the component appear in space. The other three are used to manipulate components already in the space: MOVE, ERASE, and EXPLORE are used respectively for moving, erasing and looking behind components. In the latter three modes the "highlighting" cue colors any component in the area of his hand.

In the "spatial hierarchy" of the system, when the wand is in the model space an the model maker presses the button, there is a one-to-one spatial relation between the location at which the commands signalled (the button is pressed) to be executed and its execution. Directly outside the model space, a command is given, still defined by means of a particular location of the wand but there is not a direct spatial response at that location--it is executed as the result of an indication within

Figure 18. Menu and wand. Menu commands read: Erase, Explore/Restore, Move, Previous, Next, and Display. Wand is on front left side of the modelling space.

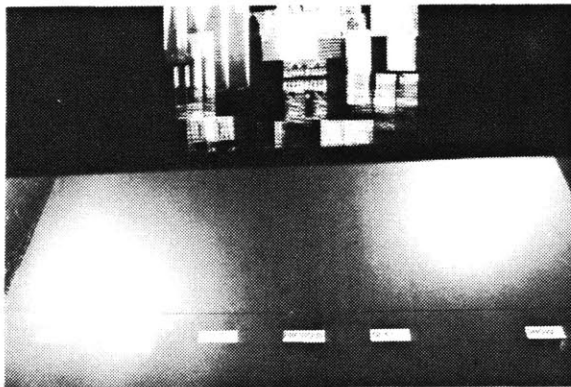
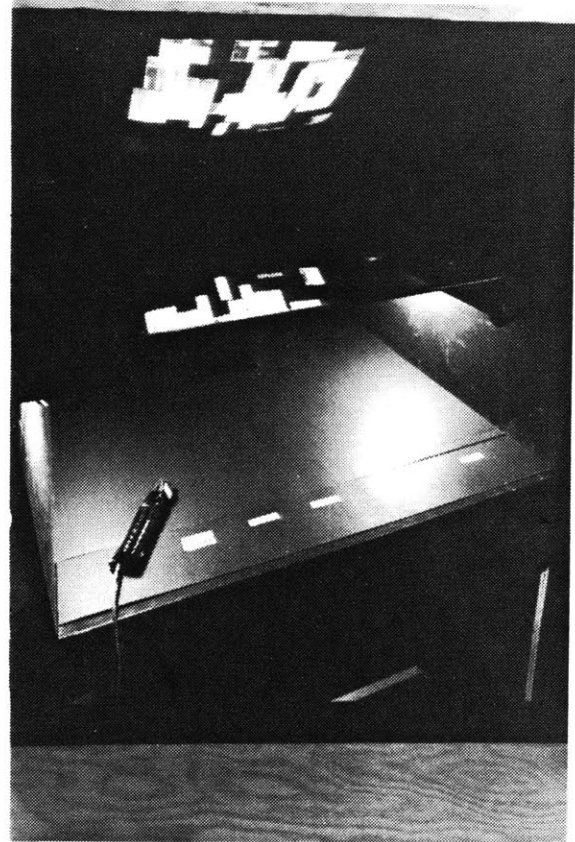


Figure 19. Close-up view of virtual image (reflected on mirror), modelling workspace, and menu.

the model space.

More abstract commands--those which do not have a singular spatial visualization are given from the keyboard of the computer terminal. The "break key" causes the program to list eight additional options and temporarily exit the program to execute the given command. These options allow the model maker to 1) save a model (by saving its database); 2) clear the model space; 3) display a saved model in the model space (which can be subsequently remodeled); 4) select or discard the wireframe option; 5) recalibrate the sensing device; 6) reset the image plane; 7) change the component type; 8) read the database of the model under construction.

The menu, during its design included more options such as a "select" option which let the user select a component and then continue to look through the components. In this way he could anticipate his next step, or speculate in general about possibilities, hesitating before placing a selected component in space.

It was found that the fewer commands needed to achieve a desired result, the more satisfying the kit was to use. One of the assets of three-dimensional "input" is the straightforward manner in which one can work with images and space. This experience is best not diluted by intermediate steps, too many options and subtle degree of result.

3.7 COMPONENTS

Let us look back to our icons....Through the noise of colors, the sound of materials, the assemblage of faktura, the people are called to beauty, to religion, to God...(the icon is) a nonreal image. The real world is introduced into its essence through the assemblage and incrustation of real tangible objects. One could say that this produces a combat between two worlds. Vladimir Markov, 1914

3.7.1 APPEARANCE OF A COMPONENT

A model is built in this system out of a set of "components", each one being a different image. The components are rectangular pictures which can be black and white or up to 256 different colors. The images can be monocular or stereo pairs. A stereo pair has a different left and right version for each image [figure 20]. If the image is monocular, then by using the same image for left and right the image can be placed at any location in the model space but will not have three dimensions of space within it. Images can be scenes--of landscapes or groups of objects--appearing almost like postcards floating in space. Or they can be of objects or object fragments.

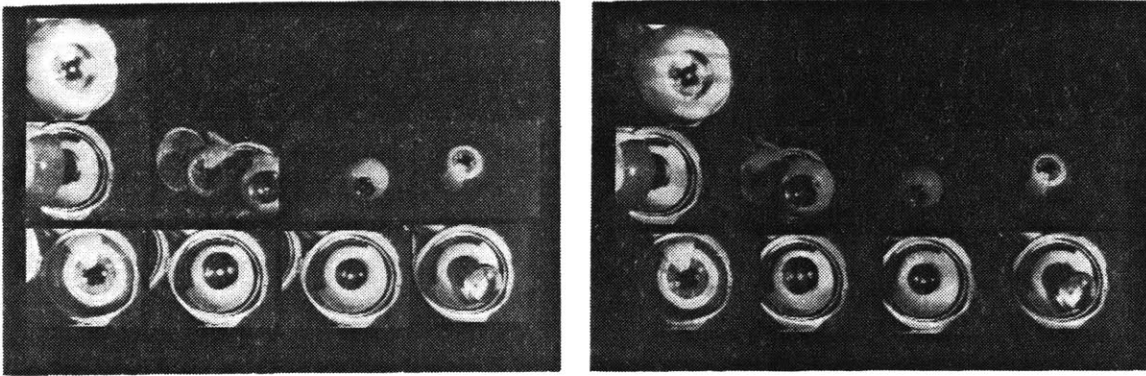


Figure 20.

Eye model. Left and right images of stereo pair. Each of the model's parts is a different picture of a model of an eye built out of wood and rubber. Each part of the model shown here is a stereo pair with different left and right views. The point of view is visibly different if one compares the left and right image of each part.

The imagery of a particular set of components depends on what is to be modeled. In the course of the model kit's design, the imagery of models was collected from various sources, derived from many people: a cardboard model of an eye in a sequence of rotated positions (Scott Fisher; videodisc); histological sections of a mouse brain (R. Pearlstein, Department of Neuroscience, Children's Hospital Medical Center, Boston; videodisc); microscopic views of a nickel powder (Elisabeth Shaw, MIT Scanning Electron Microscopy Laboratory of the Center for Materials Science and Engineering; Polaroid stereo pairs); a wood and rubber model of the eye (Department of Psychology, MIT; digitized stereo pairs); robots ("Robot", Pierre Boogaerts; photographs); a series of different view of bathroom fixtures (Steve Gano; stereo pair slides); skyscrapers ("Skyscrapers-Skycities", Charles Jencks; photographs).

The design of model kit is not intended to anticipate every model that might be built in this space with one comprehensive set of elements or universal symbols. It is designed so that a model maker can add a set of components appropriate to the subject of the model being built.

Each set of components has a fixed number and is conceived as a kind of alphabet which spells out or forms another object.

Wherever the artist turns his gaze he can only make a match, and out of a developed language select the nearest equivalence...In our response to expression no less than in our reading of representations, our expectations of possibilities and probabilities must come into play. Given such a keyboard of relationships, a matrix or scale that has intelligible dimensions of "more" or "less", there is perhaps no limit to the system of forms that can be made the instrument of artistic expression. [Gombrich, 1960]

It is in the context of other parts that each part's own significance becomes clear, one that can change in the presence of different elements. In making a model, the designer does not have an exhaustive number of images through which to look in order to find a single ideally detailed image that can stand alone. The notion of making an interactive model suggests that the ideal image is *composed*--and then can be taken apart.

The method by which the images of the components were obtained can also inform the model, suggesting an approach to the subject. Images formed by such means as electron scanning microscopes inform about the detailed analysis of form or structure defining the subject and method of inquiry. For a choreographer of ballet, a set of components of the primary ballet positions may model the interplay of posture and step sequence that compose a dance.

3.7.2 ICONS

The components are files of digitized images produced from a program, "Icon" [Gano, 1981]. The images are eight-bit pictures that can be as large as approximately one fourth of the size of the display. The program can either digitize images at the scale they are to be used or reduce them from a larger image. The digitized image can then be further divided into pieces using the "Grabicon" program [idem].

The components are stored in a database, each of images having the same component name (EYE, NICKEL, BRAIN...) and an identifying number (.1,.2,....,n). A list of each component type is stored with its number of elements, and its dimension--that is, whether the image is monocular or stereo.

3.8 CASE STUDIES IN GRAPHIC MODELS

During this system's design over one hundred and fifty components were produced: monocular and stereo images, digitized from real objects, slides, videocdiscs, books, Polaroid photographs, taken from animation sequences, whole objects, disembodied parts, interiors, exteriors, close-up, rotated, microscopic and distant views, color, and black and white.

The elements of the model in this case are usually somewhat narrow "anatomies" of objects that refer to a temporally or spatially displaced point of view on a object (eye, bath), phases of analysis (brain: coronal sections of original tissue; nickel: magnifications produced from electron scanning microscope), and types or parts that constitute an object (robot: heads, arms, legs; city: skyscrapers, towers, bases, fountains).

An attempt was made to generate one kind of component with which a method of "assembly" or organization would be obvious enough to entice participation or construction. One characteristic of a component type discovered to prompt construction was a fragmentation of its subject into a set of parts that could be built into a variety of models--such as parts of a city. As well, a set of parts that could be indexed spatially into useful categories were readily moved around in space (cross-sections of the mouse brain, for example, were aligned and ordered, receding in space in the z-dimension--sorted by degrees of magnification, or visibility of a particular aspect). The fragmentation or anatomy of the given topic seemed to suggest construction. During the course of the system's design, a person given such a set of components, without instruction would spontaneously begin to construct, composing and recomposing whole images that seemed appropriate. Larger images seemed to dominate the space and preclude spatial and elemental play.

Secondly, simple images were found to be most suitable. The nuance and degree of detail that could ultimately be more useful and necessary for a professional would be meaningless to someone initially sitting down to work with a given set of components.

To understand the present symbols in electronics it is essential to know something of the fundamental processes of electronics. Its logic must be understood. The symbols are words in a language--a language adapted to express certain kinds of interacting processes....symbols can represent structures in abstract realms of thought where the mechanics of objects may be of little concern.... functional properties of the components and their interactions ...are represented by the symbols of circuit diagrams. These symbols have become a special language to represent the principles and practice of electronic systems. [Gregory, 1970]

Typically, if it was necessary to closely "read" the meaning of each part then it was more difficult for someone unfamiliar with the components to work with them and shape a model.

Finally, the elements more vivid in color and shape were most successful, enticing someone to reach for them, "touch" them, build with them in space.

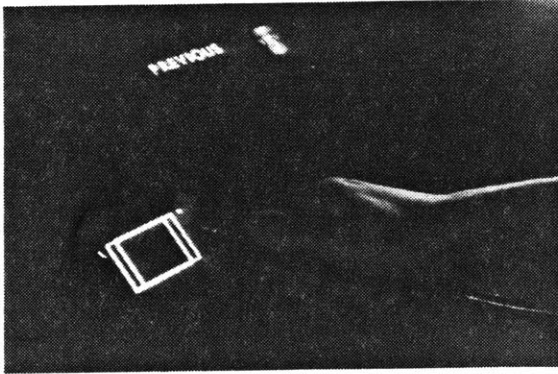
3.9 USING THE MODEL KIT

One begins to make a model by sitting in a chair in front of the system and putting on the "PLZT" helmet. At the beginning of the program, he indicates what type of component he is using to build his model. To look through all the parts in his chosen set of components, he uses the NEXT and PREVIOUS options. By placing the wand at the NEXT option of the menu and holding down the button he will see one component after the other displayed in miniature in the upper right hand corner of the display space. If he wants to look back at a component he has previously seen, he can do so by putting the wand at the PREVIOUS option, thus not having to look through the entire collection of components again. To select a component to add to the model, he releases his finger from the pushbutton while the component he wishes to use is being displayed.

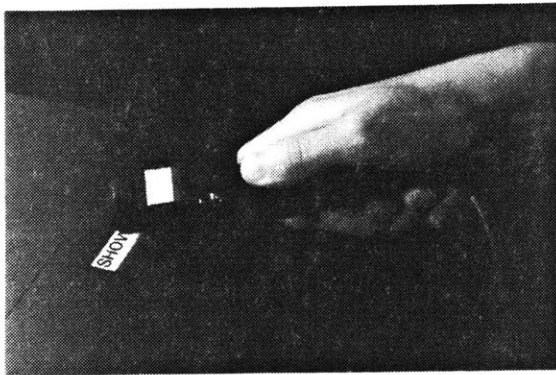
To place his chosen image in space, the model maker simply extends his hand into the modelling space, while holding the wand. He moves his hand to the location where he wants the image to appear, the cursor marking the location of his moving hand.

The model maker can construct the model in two different ways. Some designers produce a work using intermediary sketches or shorthand notation [figure 21] to anticipate the final product. In this case, the model maker may work using a wireframe which displays the outline of the component he plans to add to the model. Whenever he presses the button at the place where he wants to see the component, a wireframe appears at the location indicated by his hand. When he releases the button,

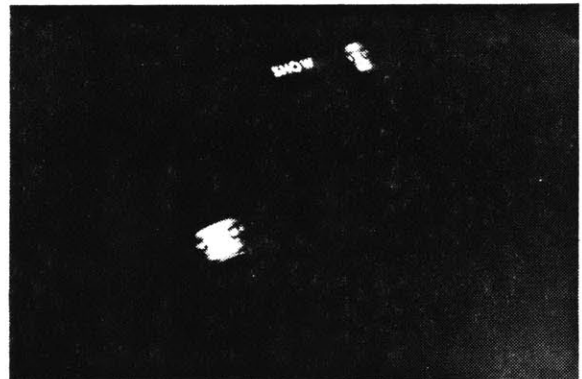
Figure 21. "Placing" an image in the model space.



1) Wireframe outlines where part will appear as indicated by model maker's hand.

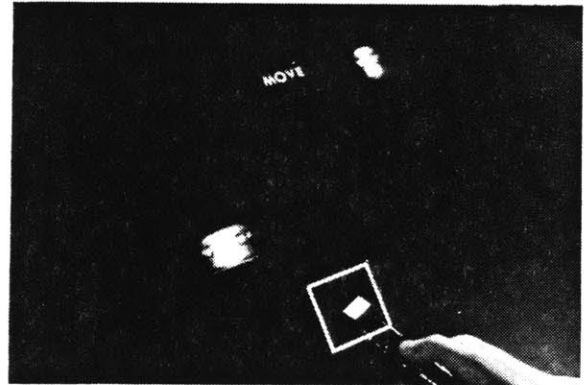
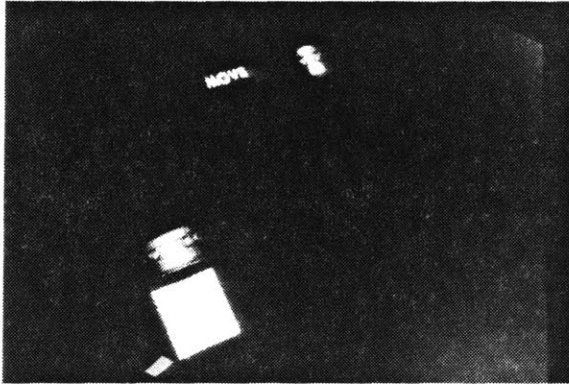


2) Satisfied with the position, model maker indicates "DISPLAY".



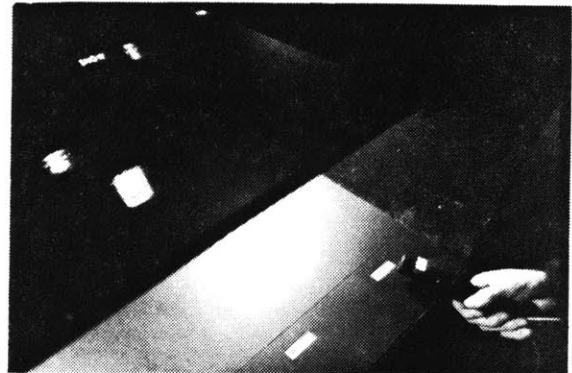
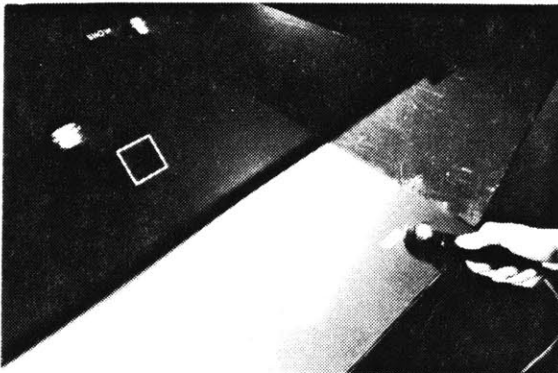
3) Image appears in space.

Figure 22. "Moving" a part of a model.



1) "Touched" image (within range of model maker's hand and the cursor) is highlighted.

2) Image is erased; wireframe indicates new position.

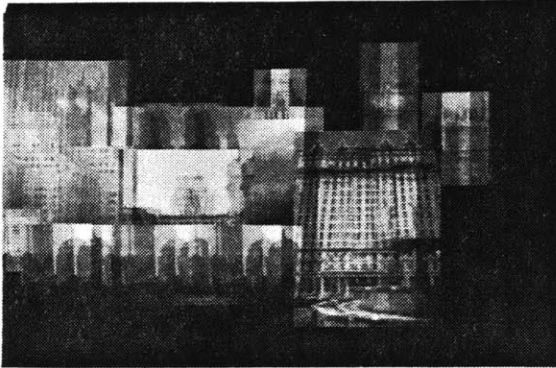


3) Display command is indicated.

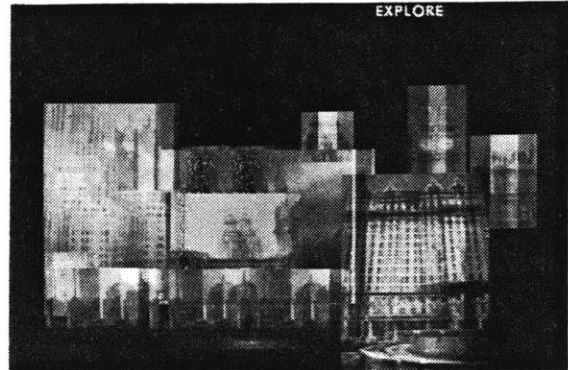
4) Image appears at new location.

Figure 23.

1) Model of a cityscape.



2) "EXPLORE" mode removes images hiding the highlighted part that model maker wants to view.



3) Occluding images are removed; the part is revealed.



4) The removed images are then restored with "RESTORE" command.



the wireframe is erased. The wireframe allows the model maker to see where the model part will appear in relation to the other model parts without having to repeatedly place each part in the space, change his mind, erase it and then replace it. He can reposition the wireframe as many times as he wants. When he has chosen a location, he presses the button at that point and does not release the button. While continuing to hold the button, he moves his hand to the DISPLAY option. The part will appear at the location indicated by the wireframe, which is then erased.

The model builder can also work without the intermediary wireframe. In this case, as soon as he presses the button at the location where he wants to place the model part, it appears. If he doesn't like the location, he then can immediately erase it by pressing the wandbutton at the DISPLAY option (which in this case erases the image rather than a wireframe). The image previously drawn is erased. He then can reposition the element elsewhere simply by pressing the button at a new location.

When working with a part already in the space, the modelmaker reaches into the space and puts his hand on the component he wishes to move or remove. The cue that signals to the model maker that he has "touched" or reached a component is the highlight function. After selecting either the MOVE, ERASE, or EXPLORE option, the model maker moves his hand to the component he wants to manipulate, the cursor still marking his hand movement. Any component within the area of his hand will be highlighted, giving him a visual rather than tactile cue that he is touching the component with his hand. The "highlight" appears makes the image appear in a blue shade, as if a blue gel were placed over it.

To erase an image, the model maker presses the wandbutton at the ERASE menu option. When the component he wishes to erase is highlighted, he presses the button--and the part is erased. If he is only moving, rather than erasing a component, he uses the MOVE option [figure 22]. Moving an image consists of the same steps as erasing one except that the erased image must then be repositioned--by going through the same steps of putting a component in space (without selecting a new component). The component the model maker is moving will reappear at the new position indicated by his hand when he presses the wandbutton. To remind the model maker that he must complete the move by indicating a new position for the erased component, both cursor and wireframe are red during the MOVE mode.

If exploring, (indicated at the EXPLORE option), the model maker "touches" an occluded image he wishes to see [figure 23]. The highlighted image is not erased. Instead, all the components in front of it are temporarily removed. By means of this option, he can look at totally or partially hidden components. The obscuring images which have been erased are restored to their position when he indicates this by means of the EXPLORE/ RESTORE option which always restores images

before letting the model maker explore further.

3.10 THREE MODELS

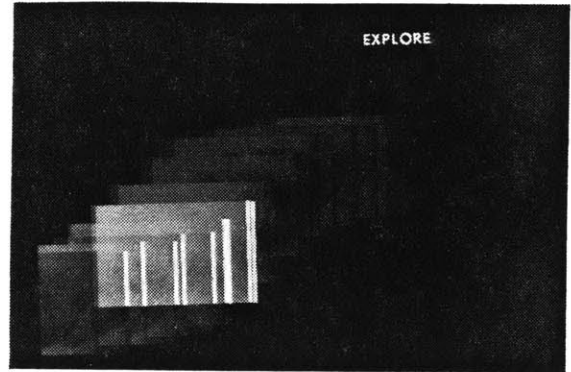
Here three different instances of models built using the model kit will be described. The first instance describes how the model kit might be used to produce visual models helpful to an urban planner. Two sets of components are used. The first is a set of buildings from cities including New York, Boston, Chicago, and London; the second are parts taken from the images of the cities such as towers, bases, and fountains. The primary format of the model is a layered one. The z-axis or depth of the space is used to explore "alternative" structures for the urban space. The different components can be variously placed in space to explore alternatively configured city plans. The space described by the fountain in front of the Plaza Hotel in New York can be juxtaposed with the area at the base of the Hancock Tower in Boston. The visual effect of a particular monument in a city can be observed by placing the Sears Tower of Chicago to hide the Empire State Building. The two can be compared by means of the EXPLORE/RESTORE option which will remove and restore the occluding images. The skylines of the cities may be intermingled to observe each city's layout and to visualize congruencies and differences between them. Towers can be added at various distances in the space to conceive the effect of increased density in a given area. Buildings such as the two World Trade Centers of New York can be repositioned at varied distances with respect to each other by using the MOVE option. The structure of the model of the city which spreads across the horizontal axis and is built up in the vertical dimension observes the actual appearance of a cityscape which extends vertically from a horizontal base. Composite images of cities can be made alternatively by layering buildings in the z-axis and juxtaposing them on the horizontal axis.

In the second instance, the components set is composed of slices of a mouse brain [figure 24]. Here the model structure serves as a kind of "virtual slide tray." The cross-sections are layered in the z-axis. Using the EXPLORE option, the occluding slices can be removed to reveal a particular slice in question and then repositioned with the RESTORE option. Any slice can be taken out of the whole by using the MOVE option with which it can be placed in an open area of the space to be studied. The slices can be reordered by priority of interest depending on the current focus of the study.

The third instance is more whimsical. Here the components are a set of robot parts and whole robots [figure 25]. One can compose a robot with the characteristics he desires by putting together the head, torso, arms and legs of his choice. Or he can take an existing complete robot and overlay a

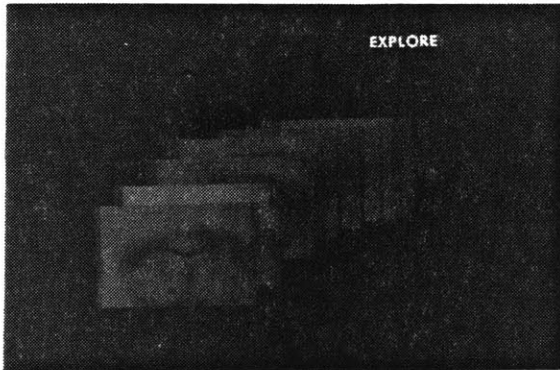
Figure 24.

Cross-sections of a mouse brain are layered in space.



1) "EXPLORE" command is used to reveal a slice in the middle of the model.

2) Image to be revealed is "touched".



3) Occluding slices are erased; part is in full view.

4) Slices are then put back in their positions in the model.

preferred head, torso or limb. To compose the robot, he can overlay five, ten or fifteen different heads and reveal different ones using the EXPLORE option. In this way he can fluidly compare various compositions. Another person might later look at this robot model and remove different heads to view the array of designs which the model maker proposes, and delete any parts he finds unnecessary.

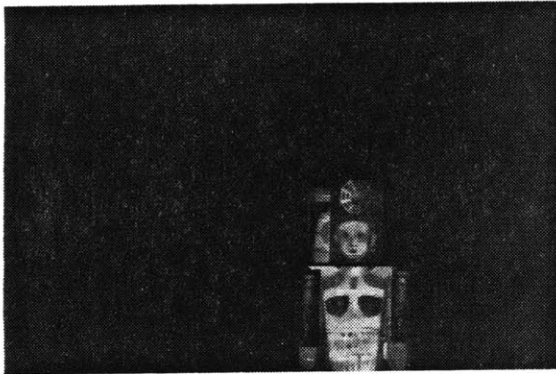
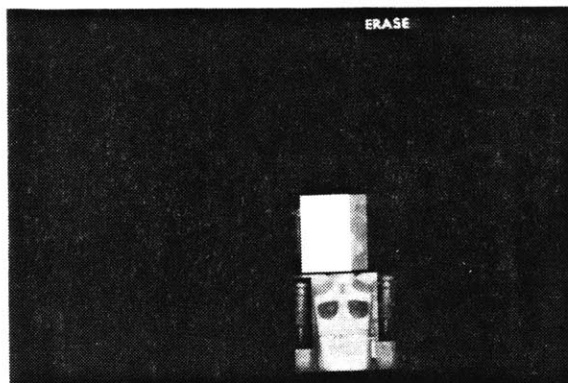
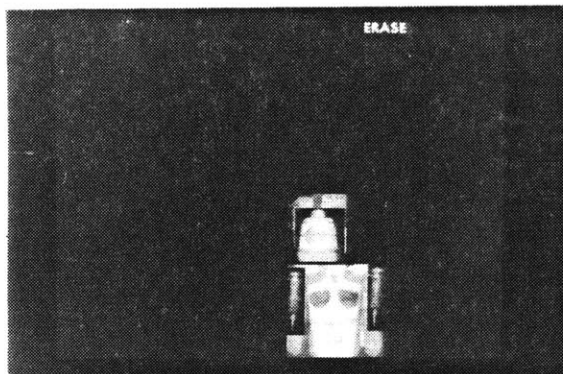


Figure 25.

1) A selection of heads for a robot are layered one behind the other.



2) Head to be discarded is indicated.



3) Head is erased to reveal another behind it.

Chapter Four

SUMMATION

The model kit demonstrates a system in which interaction with a computer driven imaging process takes place within the volume of the virtual image of the display. The location of interaction with the computer takes place directly at the point at which a change is to occur in the display. The shared volume of display and interface creates an intimate workspace in which one's attention can be focussed solely on the area of the image instead of being diverted away to a separate interface where the sequence of graphic commands are given in a form remote to direct visual expression. During the course of the design many observations were made with respect to its operation, application, and future. These will be discussed in the following sections.

4.1 PROBLEMS

A prototypical system at first may seem awkward to use. While the model kit's direct interface to a three-dimensional display lets spatial structures be easily designed, its system will only be flexible and accurate with subsequent modifications. Even the ease with which a light-pen which is now used to draw at one time seemed improbable:

At that time, September 1961, the light-pen was available, but considerable skepticism existed about its use as a precision drawing device. A project spokesman allegedly noted, "drawing with a light-pen is like trying to write your name on a wall fifty feet away with a pistol." [Johnson, 1963]

4.1.1 CUES: POINT IN SPACE

Until a component was put in the space, judging by the appearance of the cursor alone, the space seems quite large. Guided by the model maker's hand, the cursor, as it moves from the surface of the space to its deeper reaches, becomes smaller and smaller giving the same visual sensation that one might have when watching a penny drop in a well or in seeing a piece of paper float downward from the upper stories of a building. The changing scale offers a distinct cue.

The moment components are placed in the space, their dimensions define a new index to the

space's size. The dimensions of the space are visually defined relative to the proportions of the component. For most people, disparity alone sufficiently cued a difference between the planes of the components. Interposition further distinguished between the priority of the planes in space.

In interpreting the space, size constancy became an issue. If the same component or objects known to have the same size were placed at various locations of depth without a respective change in scale, the space sometimes appeared to flatten out.

The impressions of scale and distance are so related to one another that with increasing distance there goes an unvarying scale. This is the rule for ordinary perception of the visual world. If the observer tries to see the world in perspective like a flat picture, however the relation between them is the same but the impressions are different: with unvarying distance there goes a decreasing scale [figure 26]. The reason for the landscape-painter's ability to see perspective in his visual field is that he has retinal stimulation which ordinarily yields joint impressions of both distance and scale. [Gibson, 1950]

This suggests that despite the fact that they can place their hand in the "virtual" space, most people read the space as a picture, in which retinal stimulation ordinarily yields joint impressions of both distance and scale rather than expecting, as they would see a real object, size constancy to be maintained.

In light of this, additional cues seem necessary to maintain the impression of the space's volume.

Two solutions may be considered. The first would be geared toward presenting the images as "real objects". Motion parallax cues could be incorporated so that by moving his head, the model maker could see the space around each part and distinguish between the area of each component. On the other hand, the components could be scaled according to their position in space. The second solution is more practical in terms of computer memory and tracking; that is, it is easier to store an array of scaled images and compute the correct image to use when the component is placed rather than storing an array of views relative to each component and recomputing which one should appear relative to the observer's changing point of view.

The choice of cues used to enhance the space's volume therefore lies not only in a decision as to whether the model should be seen or "read" as a real or depicted object but with respect to the cost of memory. Given the decreasing cost of memory and increasing availability not only of storage but of real-time digital video systems in which visual information can be dynamically refigured, the latter consideration should figure less strongly in the decision. Whether an accurate means of head-tracking will be available is another question altogether.

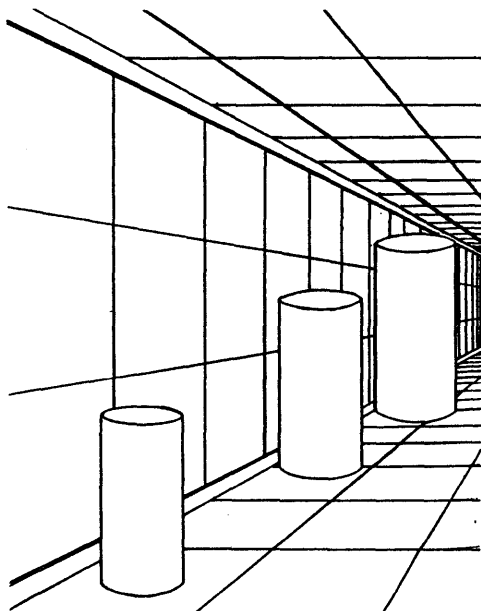


Figure 27.

Figure size is determined by distance.

4.1.2 TRACKING

When a component was placed in the space, its position generally conformed with the model maker's intention. The activity of "touching"--that is, putting the cursor in the area of an image--a part of the model already in the space was less predictable. This could be explained in part in the orientation of the viewer with respect to the space when trying to differentiate between the planes. A particular component in space must be identified with an accurate indication of its position. This requires a specificity not exercised when placing a component in space. "People are very poor at handling magnitudes or intensities on any absolute scale; they cannot reliably classify size, loudness, pitch, and weight into even so many as ten reliably distinct categories. In comparative judgments, too, many conclusions that might seem to require numerical information are already implied by simple order, or gross order of magnitude." [Minsky, 1975]

To locate a particular model part in space with one's hand requires not only the model maker but the tracking device to accurately detect its position. In reports on graphical tracking devices, difficulties in obtaining accurate spatial readings were consistently observed, whether noise of a frequency that interferes with the medium in which the sensor is tracked--such as the noise of typewriters interfering with the Lincoln Wand's sonic pulse--or temperature and breeze variations that interfere with continuous wave sonic devices. In the case of the mechanical, physical restrictions can cause discomfort for the person being tracked.

In the case of the Polhemus, it was observed from the beginning of the design of the system used in the model kit,

There have been considerable problems with noise produced by radiation from color CRT's in the vicinity of the radiator or sensor... [Schmandt, 1980]

The addition of a notch filter in the receiving electronics, as well as software filters, has somewhat alleviated but far from solved this problem.

Reaching for or "touching" an image at this point recalls a certain kind of hunt and spirit of gamesmanship in which the person is willing to repeatedly try to put his hand on an image, accepting the misses in his overall pursuit of an image. Certainly this demands more than is required when one simply wants to move a picture. A temporary solution might be to make the system more intelligent. Rather than requiring the model maker to land the cursor inside of the part he wants to move, the system can compute what component the cursor is nearest, within a reasonable range, assume that this is the part that model maker is attempting to touch, and highlight it.

An alternative means of hand tracking seems to be the ultimate solution to this problem. Given the scale of the working area of the model kit, a cubic array of infrared LED's might be used to

determine position indicated by tip of one's forefinger--a practical solution which would not be possible in a larger graphic environment. Two dimensional arrays of such devices have been used to simulate touch-sensitive screens.

4.1.3 WORKING IN THREE DIMENSIONS

Any kind of pointing system requires hand-eye coordination. As a graphic skill it requires practice. To apply this skill in a novel context also requires a certain amount of practice. This has been observed by the designers of systems intended to allow a more natural means of working with computer graphics.

When a touch sensitive device was introduced as a means of direct graphic input on a two-dimensional display,

Use of the force cursor has produced some surprising results. While its function is obvious to all who observe it, many people experience initial difficulty making it behave as they expect. Most notably, novice users have difficulty making the vector point in the directions they desire. This difficulty derives not from the equipment, but from the fact that people do not always press in the directions which their fingers appear to indicate....The novice will press the tablet causing an arrow to appear in proper alignment with the finger; but as the finger is rotated, the direction of the vector often fails to follow. Close observation has revealed that this results from the fact that the user actually maintains pressure in the original direction though the finger change orientation.

Fortunately, the learning curve with this routine is quite steep. Following initial difficulty, most users are able to control the direction of their vectors with less than a minute's practice. [Negroponte, 1978]

In reporting on the use of a graphic wand for manipulating virtual images in space, its designer, Vickers mentions,

Some can use it well the first time, but most require several sessions on the system to pass the "tolerance limit"--that point when the system becomes useful instead of merely tolerable. [Vickers, 1974]

During the course of this system's design, the many people who used it demonstrated a range of skill. Yet, there was no one who couldn't use it, after instruction, within a few minutes of practice. This suggests that the aid of habitually used visual and motor skills can be successfully applied in an initially unfamiliar context.

To effectively use a three dimensional space begins with the coordination to move freely and predictably in its dimensions.

...early experiments with three-dimensional graphics have shown that people are not very good at drawing in space without the support of a writing surface. The years of training that grade school children go through in learning to write do not facilitate three-

dimensional input. [Burton and Sutherland, 1974]

In this system, it was not uncommon for someone to select a component, and without putting his hand in space, press the button and expect to see it in space. Where? On one hand, perhaps the notion of three dimensions of space before them didn't present numerous possibilities, one of which could be chosen. That is, to such a person, a component was either "out there" or not. On the other, it might be speculated that given the notion of an intelligent graphic interface, a person feels he doesn't need to lift a finger, that the system either automatically knows where he wants to put the component or else will simply know the "best" place itself.

It is hard to imagine that without practice or exercise, one can any more easily visualize than place things in a three-dimensional space. Even if one had the manual skill and medium for placing them there, such visualization can only become lucid with use.

"Visual thinking" here is spatial thinking. The generalized term which describes the physical configuration of a cell [Hubel and Weisel, 1968], microchip [McGlynn, 1980], and fashion [Sidlauskas, 1982] --"architecture"--borrows from a field with very specific spatial conventions. This suggests that many fields may in some sense be looking for a vocabulary of spatial terms, a medium in which to realize their concerns in a more dimensional way.

4.1.4 IMAGERY

The model's imagery was less vivid than it might have appeared due to the overall darkness of the model space. This was a compound result of the semi-transparent mirror in which a quarter of the brightness was lost, the PLZT lenses required to see the stereo image, and finally a result of the method of stereo imaging.

One of the main drawbacks of alternate interlace is the low resolution of the images which have half as many lines as a typical television picture. High quality three-dimensional television may only be obtained as a result of either high resolution television or some alternate method of displaying the stereo image such as some form of autostereoscopic television.

To transmit a television signal having resolution and frame frequency both comparable to the ratings of today's commercial television, the required bandwidth will be as high as several 10GHz or more. Therefore, development of information-reduction techniques will be indispensable...

...if three-dimensional television becomes common in future society, it will inevitably be autostereoscopic as well as of very high resolution. It is widely believed that high-quality, superwide screen television systems will appear within ten years, prior to the age of three-dimensional television. Any three-dimensional television scheme will not be able to supercede the superwide screen television unless the former is superior to the latter also

in resolution and screen width. [Okoshi, 1976]

4.2 FUTURE

4.2.1 GRAPHIC SYMBOLS

In working with various component sets, the notion of a three-dimensional graphic symbol system arose. What would a three-dimensional graphic symbol be? Would such a symbol cast a shadow? Could two three-dimensional symbols occupy the same space at the same time? Symbols reduce their messages to graphic elements, retaining the traditional sense of graphic media as being flat. A three-dimensional graphic symbol is one, which if translated to two dimensions, would undergo such a loss of information that it would be meaningless. The atom has been suggested as one of the few three-dimensional symbols. Although it can be drawn in two dimensions, its meaning lies in a three-dimensional structure. Two images, which are not symbols, suggest how meaning might be structured in a single three-dimensional figure: the moebius strip and the spiral.

4.2.2 SOFTWARE

For this system to be effective, certain problems will be resolved with different hardware: alternative tracking systems, autostereoscopic video, real-time digital image processing. Two other improvements might be implemented in the near future to improve the system.

The first would be to let the model maker use his own voice to express what he wants to do in the model space, using a speech recognition system. Each component could have a name. To place an image in space, one would hold his hand at the location where he wishes to place it and state the image name. To look through the components one would state the image name (keeping his hand outside of the modelling space) and a small version of the image could appear in the upper right corner of the display space. Alternatively, using a video switcher, the modelling space could switch to another frame buffer and the full size image of the component named would appear. When moving an image, the image nearest the model maker's hand when he stated, "move" would vanish and reappear where indicated by his hand and the command "here" or "there." Such a system would thereby incorporate another natural means of expression, speech, and leave the spatial gesture entirely to the task of building. One's focus in space need never be distracted from the area of the

model.

A second improvement, without which the system's potential will most likely never become evident, is to implement building in three dimensions. At present, as earlier described, a single image cannot occupy more than one plane of the z-axis. Such a constraint limits a natural use of space and a dimensionality that useful structure demands. The space, at present, may never appear a demonstrable improvement over two dimensional imaging, simply because truly three-dimensional structures cannot be built in it. The problem of calculating and drawing many disparities in real-time might be solved by making a "disparity look-up table" in which the correct disparity for each plane would be available rather than having to be repeatedly recalculated.

4.2.3 INTELLIGENCE

Finally, the system might link the "graphic intelligence"-- that is, knowledge about the model's appearance (knowing where the model maker's hand is, whether an image is associated with that location, and whether it is to appear, disappear or reappear elsewhere) to information about how the parts of the model work and what they mean. The database would contain information about each part such as its functional or logical relation to other parts. Information about an element could be inferred by the computer according to its place and respectively added to the database. In this way, information would be available for a symbolic manipulation of the model which could be effected after or during its graphic construction. A computational "structural analysis" could be transacted on the components of a handbuilt model.

4.3 APPLICATIONS

A means of working directly with imagery in a real three-dimensional space may be a useful tool in many applications. First, any person who must work with three-dimensional imagery such as a metallurgist [figure 27] or medical researcher would use the space as one in which he could gather related stereo images into an organized structure. A neurophysiologist could use the system to juxtapose, transpose, and focus on three-dimensional images of the entity in question--a task which is much more difficult when shuffling through binocular pairs of photos which can only be viewed one at a time through large stereo viewers.

Choreographers, who rely on diagrammatic overviews of a stage to represent the relative positions of dancers moving through space could use the system to simulate the overview and easily

move around a set of figures through the space. But more importantly, the spatial relations of the figures could be viewed frontally rather than in an overview using virtual space in the model kit. Using a set of dancers as the "parts" of the model, the figures could be dynamically repositioned within the space. Various moments of the dance could be saved as separate models.

Finally, an architect could use the space to compose spatial constructions. The various planes of the space could be layered with images such as walls, columns, corridors, windows. Any architectural component which the architect wishes to work with could be introduced and repositioned in the space. Also, he could actually layer images with the historical allusion or associations which his design is intended to imply. Or, secondary images could be introduced as a kind of counterpoint to his design concepts.

4.4 CONCLUSION

Despite the problematic areas of the system's design, whether the accuracy of Polhemus or the skilled use of hand-eye coordination, anyone can sit, building and exploring both images and space, without ever having to turn away to the keyboard of a terminal. The model maker need never translate his intentions into typed-in alpha-numeric symbols nor deflect from the space of the model except to its edge to indicate that he wants to place, move or erase an image.

In graduating the space of a display from two to three dimensions, the system has been designed so that in its virtual space, by means of a tracking device, the model maker can directly interact with the images of the model parts that the computational processes generate. In a synchronized exchange between model maker and presentation, the cursor and appearance of the components both reflect and prompt the model maker's movements. The model maker can work with resources of a computer-driven graphic process and the perceptive qualities of his visual and kinaesthetic senses.

The experience of working with the model kit represents a good basis for using a range of senses for building with images. Only a portion of one's perceptive capacities used in working with real objects are used at its interface. However, the model kit initiates a more extensible means of contact with imagery than is typically found in a computer mediated graphic system. In the future, additional senses, such as that of touch, may be added to the model kit to further its fundamental steps towards giving graphic objects fully perceptible forms.

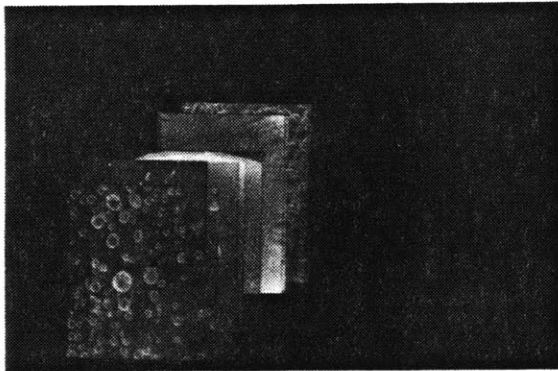
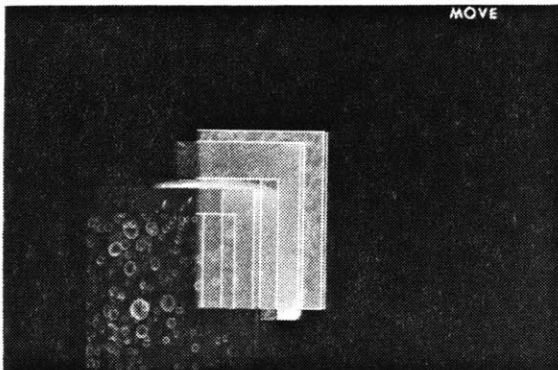
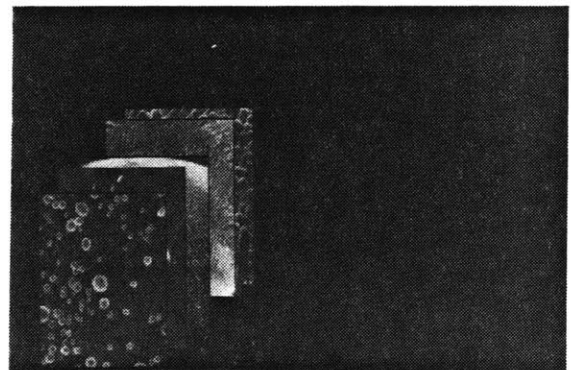


Figure 28.

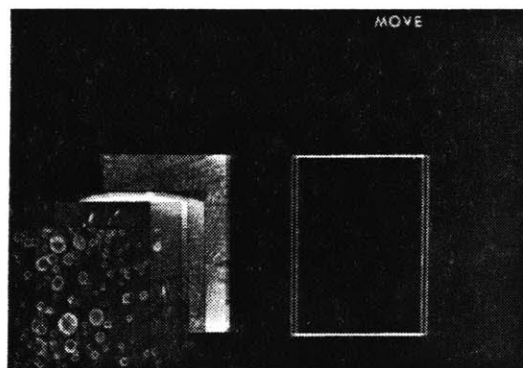
1) Stereo pairs taken at a range of magnifications compose a model of a nickel powder.



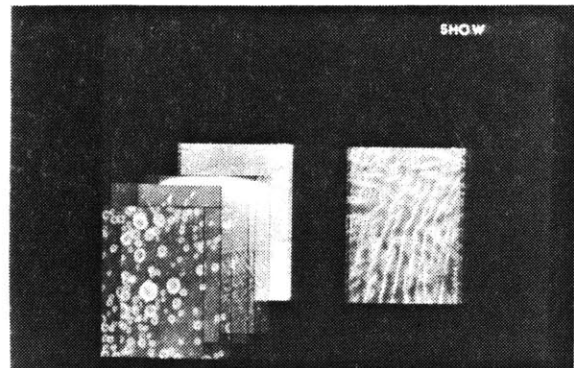
2) An occluded image is moved from its position in the model.



3) Indicated picture is removed from the model.



4) Wireframe outlines new position.



5) Picture is moved to a position where it is in full view.

PHOTOGRAPHY CREDITS

Figures 1, 10-16, 18-19, and 21-22: Barry Aarons.

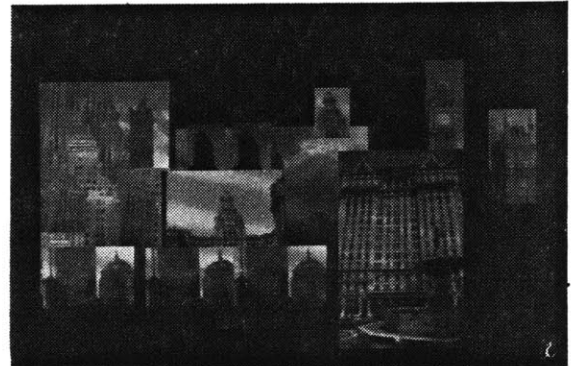
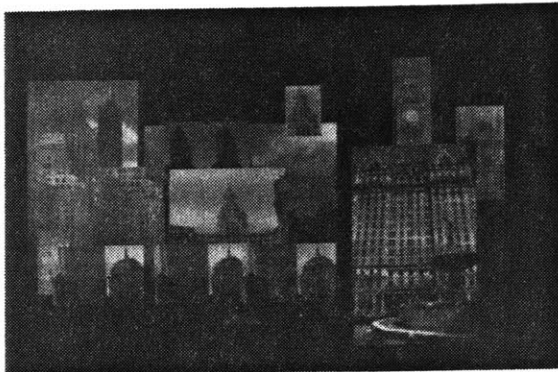
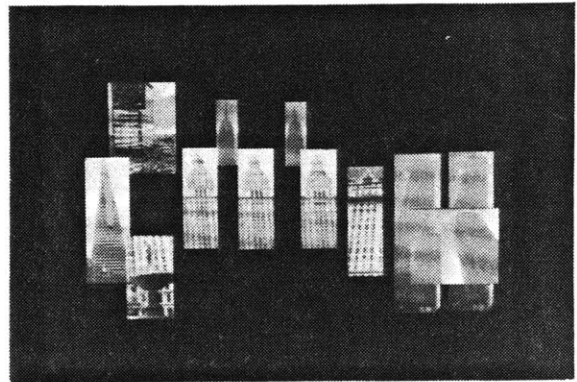
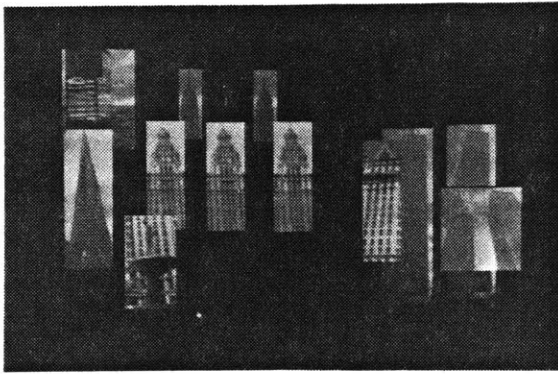


Figure 29. Two models of cityscapes.

Left eye view.

Right eye view.

ACKNOWLEDGEMENTS

To Professor Patrick Purcell for his insightful critique of my thesis work.

To Professor Stephen Benton

Professor Andrew Lippman

Professor Nicholas Negroponte

Professor Ken Sloan

for my education in Media Technology.

To Steve Gano, Peggy Weil, Scott Fisher, Susan Brennan, and Walter Bender
for being my models.

To Chris Schmandt and Jim Zamiska

for introducing me to the virtual workspace.

And my thanks to

My admirable and supportive colleagues in Office 9-532, and

ALL the members of the Architecture Machine Group.

References

[Ades 80]

Ades, Dawn.
The Transcendental Surrealism of Joseph Cornell.
In Kynaston McShine, editor, *Joseph Cornell*. Museum of Modern Art, New York, 1980.

[Bell 79]

Bell, Daniel.
The Social Framework of the Information Society.
In Dertouzos, Michael L.; and Moses, Joel, editor, *The Computer Age: A Twenty-Year View*.
The MIT Press, Cambridge, 1979.

[Bolt, Richard A. 79]

Bolt, Richard A.
Spatial Data Management.
Technical Report, MIT Architecture Machine Group, 1979.

[Bolt, Richard A. 82]

Bolt, Richard A.
'Put-That-There': Voice and Gesture at the Graphics Interface.
In *Computer Graphics, SIGGRAPH '82 Conference*. SIGGRAPH-ACM, July, 1982.

[Boogaerts 78]

Boogaerts, Pierre.
ROBOT: ROBOTS et autres FUSEES d'avant la LUNE.
edition Futuropolis, Paris, 1978.

[Breton 72]

Breton, Andre.
Artistic Genesis and Perspective of Surrealism.
In Peggy Guggenheim, editor, *Surrealism and Painting*. Icon Editions, Harper & Row, New
York, 1972.

[Bunker, W. Marvin 68]

Bunker, W. Marvin.
Training Effectiveness Versus Simulation Realism.
In *Visual Simulation and Image Realism*, Volume 162. SPIE, 1968.

[Burton, Robert P.; and Sutherland, Ivan E. 74]

Burton, Robert P.; and Sutherland, Ivan E.
Twinkle Box--A Three-dimensional Computer Input Device.
In *Conference Proceedings*, Volume 43. American Federation of Information Processing,
1974.

[Chomsky 56]

Chomsky, Noam.
Three Models for the Description of Language.
Transactions on Information Theory IT-2, 1956.

[Clair 78]

Clair, Jean.
Opticeries.
October 5, 1978.

[Eisenman 81]

Eisenman, Peter.
Preface.
In Richard Pommer, editor, *Idea as Model*. Rizzoli, New York, 1981.

[Flourens 24]

Flourens, P.
Recherches experimentales sur les proprietes et les fonctions du systeme nerveux dans les animaux vertebres.
Bailliere, Paris, 1824.

[Frampton 78]

Frampton, Hollis.
Improptus on Edward Weston: Everything in its place.
October 5, 1978.

[Gano, Steve 81]

Gano, Steve.
Icon and Grabicon.
software

[Getty, David J.; and Huggins, A.W.F. 81]

Getty, David J.; and Huggins, A.W.F.
Display-Control Compatibility in 3-D Displays.
Technical Report 4724, Bolt Beranek and Newman, Inc., November, 1981.

[Geyer, Karen E.; and Wilson, Kent R. 75]

Geyer, Karen E.; and Wilson, Kent R.
Computing With Feeling.
In *Computer Graphics*, pages 343-349. Institute of Electrical and Electronics Engineers, 1975.

[Gibson 50]

Gibson, J.J.
The Perception of the Visual World.
The Riverside Press, Cambridge, Massachusetts, 1950.

- [Goldsmith, Alfred 51]
Goldsmith, Alfred.
Stereoscopic Television System.
Patent No. 2,578,298; Ap. Oct. 25,1946; Pat. Dec.11, 1951
- [Gombrich 60]
Gombrich, E.H.
Art and Illusion.
Pantheon Books, New York, 1960.
- [Goodman 76]
Goodman, Nelson.
Languages of Art: An approach to a theory of symbols.
Hackett Publishing Co., Indianapolis, 1976.
- [Greenberg 63]
Greenberg, Joseph H., editor.
Universals of Language.
The MIT Press, Cambridge, 1963.
- [Gregory 70]
Gregory, E.L.
The Intelligent Eye.
McGraw-Hill Paperbacks, Great Britain, 1970.
- [Grimson 81]
Grimson, William Eric Leifur.
From Images to Surfaces: A Computational Study of the Human Early Visual System.
The MIT Press, Cambridge, 1981.
- [Held 61]
Held, R.
Exposure history as a factor in maintaining stability of perception and coordination.
Journal of Nervous and Mental Disease , 1961.
- [Hooper 78]
Hooper, Kristina.
Perceptual Aspects of Architecture.
In Edward C. Carterette and Morton P. Friedman, editor, *Perceptual Ecology, Volume X:
Handbook of Perception.* Academic Press, New York, 1978.
- [Howard 73]
Howard, I.P.
Orientation and Motion in Space.
In Edward C. Carterette and Morton P. Friedman, editor, *Perceptual Ecology, Volume III:
Biology of Perceptual Systems.* Academic Press, New York, 1973.

[Hubel 68]

Hubel, D.H.; and Weisel, T.N.
Receptive fields and functional architecture of monkey striate cortex.
Journal of Physiology 195:215-243, 1968.

[Hubert 81]

Hubert, Christopher.
The Ruins of Representation.
In Richard Pommer, editor, *Idea as Model*. Rizzoli, New York, 1981.

[Huggins 66]

Huggins, W.H.
Educational Pantomimes.
In *The Human Use of Computing Machines*. Bell Telephone Laboratories, June, 1966.

[Janke 78]

Janke, Rolf.
Architectural Models.
Architectural Book Publishing Co., New York, 1978.

[Jencks 80]

Jencks, Charles.
Skyscrapers-Skycities.
Rizzoli, New York, 1980.

[Johnson 63]

Johnson, Timothy Edward.
Sketchpad III, Three Dimensional Graphical Communication with a Digital Computer.
Master's thesis, Massachusetts Institute of Technology, Department of Mechanical Engineering, 1963.

[Ketchum 81]

Ketchum, William C. Jr.
Toys & Games.
The Smithsonian Museum, Washington, D.C., 1981.

[Knowlton 77]

Knowlton, Ken.
Computer Displays Optically Superimposed on Input Devices.
Bell Telephone Technical Journal, March, 1977.

[Kuhn 70]

Kuhn, Thomas S.
The Structure of Scientific Revolutions.
University of Chicago Press, Chicago, 1970.

[Lippman 81]

Lippman, Andrew.
And Seeing Through Your Hand.
Proceedings of Society for Information Display 22(2), 1981.

[Lipton 82]

Lipton, Lenny.
Foundations of the Stereoscopic Cinema: a Study in Depth.
Van Nostrand Reinhold Company Inc., New York, 1982.

[Malone, Thomas W. 81]

Malone, Thomas W.
Heuristics for Designing Enjoyable User Interfaces: Lessons from Computer Games.
In *Proceedings. Human Factors In Computer Systems*, 1981.

[McGlynn 80]

McGlynn, Daniel R.
Microprocessors: Technology, Architecture, and Applications.
John Wiley, New York, 1980.

[McShine 80]

McShine, Kynaston.
Introducing Mr. Cornell.
In Kynaston McShine, editor, *Joseph Cornell.* Museum of Modern Art, New York, 1980.

[Mellinger, David 82]

Mellinger, David.
Icon Hidden Surface Removal.
software

[Meyrowitz 81]

Meyrowitz, Norman; and Moser, Margaret.
BRUWIN: An Adaptable Design Strategy for Window Manager/Virtual Terminal Systems.
In *Proceedings. 8th Annual Symposium on Operating Systems Principles*, 1981.

[Minsky 75]

Minsky, Marvin.
A Framework For Representing Knowledge.
In Patrick Henry Winston, editor, *The Psychology of Computer Vision.* McGraw-Hill, New York, 1975.

[Minsky Marvin; and Papert, Seymour 69]

Minsky, Marvin; and Papert, Seymour.
Perceptrons. An Introduction to Computational Geometry.
The MIT Press, Cambridge, 1969.

[Negroponte 78]

Negroponte, Nicholas; Herot, Chris; and Weinzapfel, Guy.
One-Point Touch Input of Vector Information for Computer Display.
Technical Report, MIT Architecture Machine Group Report, 1978.

[New York Times]

New York Times, December 28, 1922.

[Newell 56]

Newell, Alan; and Simon, Herbert A.
The Logic Theory Machine.
IRE Transactions on Information Theory IT-2(3), September, 1956.

[Noll 72]

Noll, A.M.
Man-machine Tactile Communication.
SID Journal, July/August, 1972.

[Noll, A.M. 68]

Noll, A.M.
Computer Animation and the Fourth Dimension.
In *Conference Proceedings*, pages 1279-1283. American Federation of Information Processing,
December, 1968.

[Okoshi 76]

Okoshi, Takanori.
Three-Dimensional Imaging Techniques.
Academic Press, New York, 1976.

[Palladio 65]

Palladio, Andrea.
The Four Books of Architecture.
Dover Books, New York, 1965.

[Perkins, Raleigh 81]

Perkins, Raleigh.
Camera-Obscura Tower.
Handbuilt model

[Pommer 81]

Pommer, Richard.
Postscript to a Post-mortem.
In Richard Pommer, editor, *Idea as Model.* Rizzoli, New York, 1981.

[Raab 79]

Raab, Frederick H.; Blood, Ernest B.; Steiner, Terry O.; and Jones, Herbert R.
Magnetic Position and Orientation Tracking System.
Transactions on Aerospace and Electronic System AES-15(5), September, 1979.

[Ritchie 68]

Ritchie, Malcolm L.
Object, Illusion and Frame of Reference as Design Criteria for Computer-Generated Displays.
In *Visual Simulation and Image Realism*, Volume 162. SPIE, 1968.

[Roberts, Lawrence G. 66]

Roberts, Lawrence G.
The Lincoln Wand.
In *Fall Joint Computer Conference*, Volume 29, pages 223-227. American Federation of Information Processing, 1966.

[Roese, John A. 75]

Roese, John A.
PLZT Stereoscopic Television System.
Patent No. 3,903,358; Ap. May 22, 1974; Pat Sept 2, 1975

[Ryle 65]

Ryle, Gilbert.
Sensation.
In Robert J. Swartz, editor, *Perceiving, Sensing, Knowing*. Anchor Books, Doubleday & Co. Inc., Garden City, New York, 1965.

[Schmandt 80]

Schmandt, Christopher.
Some Applications of Three-Dimensional Input.
Master's thesis, Massachusetts Institute of Technology, Department of Architecture, 1980.

[Schmandt, Christopher 82]

Schmandt, Christopher.
Interactive Three-Dimensional Computer Space.
In *Proceedings of Conference on Processing and Display of Three-Dimensional Data*. SPIE, 1982.

[Schuster 57]

Schuster, Jean.
Marcel Duchamp, vite.
Le Surrealism, Meme (2), Spring, 1957.

[Science 70]

Science Accessories Corporation.
Graf/Pen Sonic Digitizer.
Southport, Conn., 1970.

[Shay 82]

Shay, Don.
Blade Runner - 2020 Foresight.
Cinefex (9), July, 1982.

[Sherrington 06]

Sherrington, C.S.
The Integrative Action of the Nervous System.
Yale University Press, New Haven, 1906.

[Sidlauskas, Susan J. 82]

Sidlauskas, Susan J.
Intimate Architecture: Contemporary Clothing Design.
Catalogue. Hayden Art Gallery, Massachusetts Institute of Technology, 1982.

[Simon, Herbert A. 81]

Simon, Herbert A.
The Sciences of the Artificial.
The MIT Press, Cambridge, 1981.

[Smith, C. 81]

Smith, Cyril Stanley.
Structural Hierarchy in Science, Art and History.
In Judith Wechsler, editor, *On Aesthetics in Science.* The MIT Press, Cambridge, 1981.

[Smith, K.U.; and Smith, W. 62]

Smith, K.U.; and Smith, W.
Perception and Motion.
W.B. Saunders Co., Philadelphia, 1962.

[Sutherland, Ivan E. 68]

Sutherland, Ivan E.
A Head-mounted Three Dimensional Display.
In *Fall Joint Computer Conference*, Volume 33, pages 757-766. American Federation of
Information Processing, December, 1968.

[Vickers 74]

Vickers, D.L.
Sorcerer's Apprentice: Headmounted Display And Wand.
PhD thesis, University of Utah, Department of Electrical Engineering, 1974.

[Vuibert 12]

Vuibert, H.
Les Anaglyphes Geometriques.
Vuibert, Paris, 1912.

[Yates 66]

Yates, Francis A.
The Art of Memory.
University of Chicago Press, Chicago, 1966.

[Zamiska, James 82]
Zamiska, James.
Cage and Sample – pol .
software