AN INTEGRATED APPROACH TO GEOMETRIC MODELING

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ABSTRACT

Solid modeling has been recognized as a powerful computer-aided design tool, being informationally complete and semantically well-formed. However, it is insufficient by itself to support the design process of complex artifacts such as buildings, since it lacks the abstraction properties provided by computer-aided drafting tools.

This paper presents an integrated approach to geometric modeling that combines the power of solid modeling with the intuitive design and communication capabilities of drafting. Integration is achieved by representing the designed artifact non-redundantly in a 3-dimensional WORLD, and manipulating it through multiple 2-dimensional VIEWs. The WORLD consists of a collection of shapes that store all the formative information pertinent to the designed artifact, while the VIEWs consist of images of selected shapes, generated through particular two-way mapping transforms. Simultaneous display of several VIEWs that depict the same set of shapes through different transforms enables addressability of points in the 3-dimensional WORLD.

The shapes are represented by a data structure based on the hybrid edge model, which facilitates the integration of points, lines, polygons, and solids in one formative hierarchy. VIEWs reference the formative entities in the database, and include design and communication aids (e.g. - dimension lines, construction lines, annotations and graphic symbols) to enhance the visual content of the images without encumbering the representation of the shapes themselves. Modifications that are applied to the shapes through any VIEW are immediately apparent in all other VIEWs in which the shapes are imaged.

The integration of drafting and modeling simplifies the use of powerful modeling utilities by designers, facilitates communicating the results of the design process, and enhances the integrity of the designed artifact.

INTRODUCTION

The design of most artifacts is a process that employs different symbolic representations of the emerging product for the purpose of exploring and communicating the designers' intentions to clients and to craftsmen in various levels of abstraction. For example, sketches are used in early phases of the architectural design process to capture ideas[1]. They are developed into volumetric models, and later elaborated through annotated and symbol-laden two-dimensional drawings. Specifications are added to explain non-graphical aspects of the designed artifact, and to convey instructions regarding the fabrication or construction process itself[2].

The need to employ different representation methods stems from the complexity of the designed artifacts, which makes it humanly impossible to consider all their aspects at once. Instead, designers must concentrate on a few select facets of the artifact at any given time, and regard all others at a much more abstract level of detail. Moreover, the complexity of artifacts makes their design and fabrication by a single designer/craftsman impossible. Instead, a team of designers, representing different disciplinary expertise, are needed to completely design and specify a complex artifact (e.g. - a building). Their cumulative design specifications must then be conveyed to a team of craftsmen or builders, each of whom requires particular information presented in a particular manner.

Early work in computer-aided design was based on the vision that a single, comprehensive, and informationally complete computer-based model could be developed, which will automatically provide for the needs of all the representations and presentations used in design, fabrication, and management processes of complex artifacts[3,4]. Nevertheless, although many geometric and database models were developed in the past three decades, no single model was found to be capable of supporting even a limited number of design abstractions outside the primary one it was designed to support[5]. For example, the information architects often convey in sections through the building cannot be obtained automatically by means of a clipped projection of a solid representing the artifact, even though they are based on such clipped projections. Sections require enhancement through additional lines, cross-hatching, and most importantly--dimension lines, symbols, and annotations (Figure 1). On the other hand, drafting systems that specialize in supporting design communication are incapable of unambiguous, three-dimensional representation of volumetric artifacts without considerable enhancement and manual effort[6].

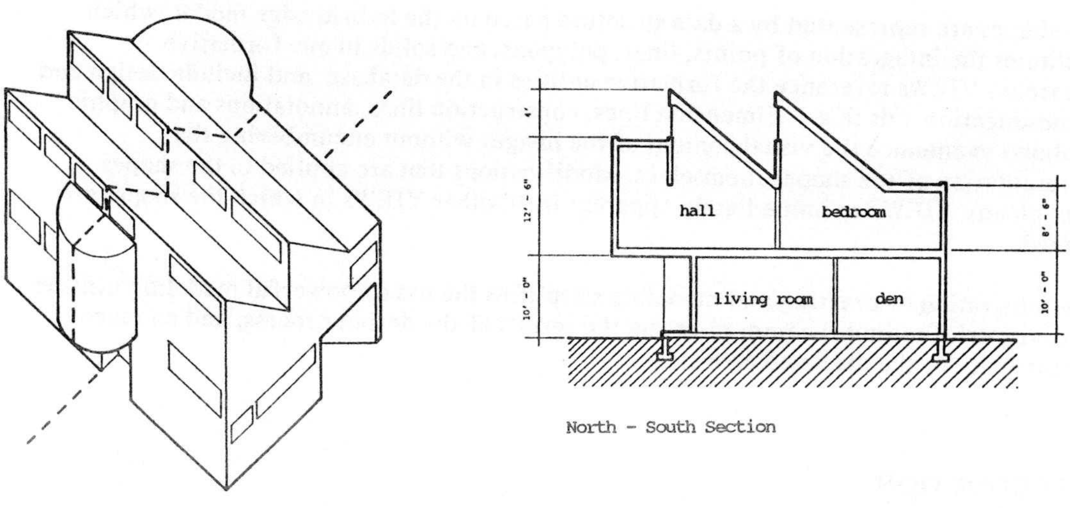

Figure 1: Sections demonstrate some of the many representations used in design processes

The different representational needs of design phases have been addressed, in the relatively short history of CAD, by two separate approaches to computer-aided design: computer-aided drafting, and computer-aided modeling. The <u>drafting</u> approach, conceived by Ivan Sutherland and implemented in his classic SKETCHPAD system, considered computers to be sophisticated drafting tools that can replace paper and pencil[7]. The modeling approach, which has been under development since the early 1970's, considers computers as symbolic modeling tools that are capable of storing accurate 3-dimensional, volumetric descriptions of designed artifacts, along with their non-graphic attributes, for use by analysis, simulation, and fabrication processes[8-12].

The informational completeness of the modeling approach has promised to revolutionize architectural design, by providing a single, unified database for a complete building description. It lacks, however, the relative conceptual ease with which designers can adopt computer-aided drafting. Instead, it forces them to exchange their traditional, 2-dimensional design practices, with 3-dimensional modeling through 2-dimensional display screens, a concept that requires a fundamentally different approach to the process of design. Drafting systems, on the other hand, provide designers with easy means to draw lines and to generate perspective or orthographic views. However, since drafting systems do not maintain a truly 3-dimensional volumetric model of the designed artifact, they cannot support operators that rely on volumetric and space-enclosure properties, such as interference testing, Boolean operations, point-in-polyhedron inclusion testing, mass and center of inertia computation, and their dependent applications.

This paper describes an approach that attempts to combine the advantages of both drafting and modeling approaches into a single CAD system. According to this approach, drafting-like tools are used to manipulate a true volumetric model of the designed artifact, thereby maintaining the integrity and consistency of that model, while providing intuitive design and communication aids that enhance the visual content of the images. Central to this hybrid approach is the recognition that both model and drawings are but different modes for representing the same artifact, and can, therefore, be linked, such that one can produce and manipulate the other. Hence, the approach proposed here does not address the particulars of modeling or drafting, only the relationships between them.

This paper describes the basic concepts for integrating modeling and drafting. These concepts have been implemented in the WORLDVIEW geometric modeling/drafting system, which has been discussed elsewhere[13]. The integration concept is described first, followed by separate discussions of the WORLD and the VIEW facilities and their related operators. The method of addressing points in the 3-dimensional WORLD through 2-dimensional VIEWs is the "glue" of the integrated concept. It is discussed separately, following the presentation of the WORLD and the VIEW. A discussion of design and communication aids concludes the presentation.

THE CONCEPT

The concept underlying the integration of drafting tools with modeling powers is predicated on the one-to-many relationship between the 3-dimensional model that represents the artifact and the 2-dimensional images of that model that are used to visualize and manipulate it. Accordingly, the formative properties of the designed artifact are stored in a single, 3-dimensional WORLD, which provides the unified information base for the integrated system. Designers can access and manipulate the model through multiple 2-dimensional VIEWs, as depicted in Figure 2. VIEWs are conceptually similar to conventional drawings, in that they depict a scaled 2-dimensional image of a 3-dimensional artifact, along with dimension lines, annotations, and other design and communication aids. They differ, however, from conventional drawings in that they do not actually store the artifact itself; instead, they store references (pointers) to the components of the 3-dimensional model that are visible in any given VIEW. When the designer uses a particular VIEW, those components of the model undergo a particular projection transformation, prescribed by the VIEW, which results in their 2-dimensional image that is displayed on the screen. By inverting the transformation, the changes that have been applied by the designer to the projected image are conveyed back to the 3-dimensional model, thereby providing the means to modify and to manipulate it. Since all VIEWs depict the same WORLD, they are not independent of each other; a change in the WORLD made through any VIEW is immediately apparent in all other VIEWs in which the modified component is imaged. VIEWs can, therefore, be likened to transparent sheets of glass through which the designer can selectively see and manipulate components of the artifact.

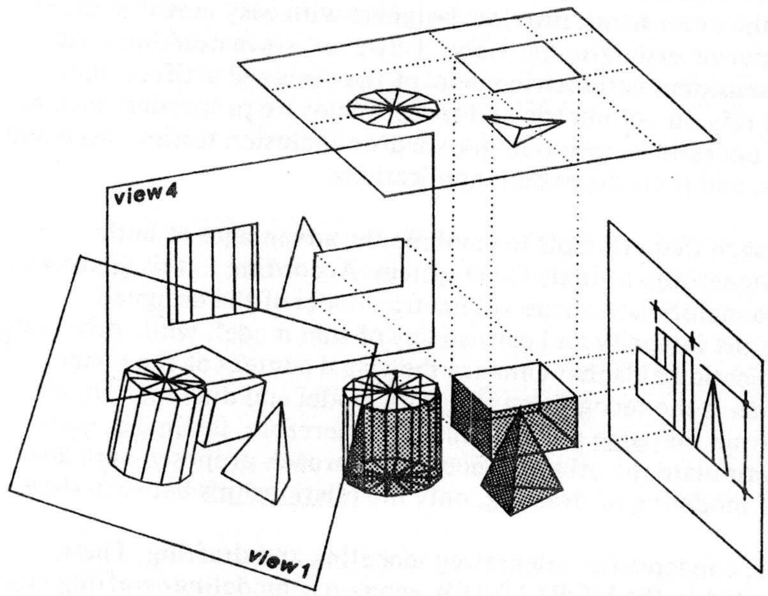

Figure 2: Integrating the WORLD with multiple VIEWs

Information that facilitates design and communication (such as dimension lines and annotations), but which is not part of the model itself, is contained within the VIEW rather than the WORLD (i.e. it is drawn on the "glass," using the former analogy). This information is, nevertheless, linked dynamically to the model, such that when the latter is modified the information stored by the VIEWs changes accordingly. For example, dimension lines that were set to show the distance between two points will automatically be updated to the correct (real) distance, after one or both points have been relocated. Furthermore, if one (or both) points are deleted through any VIEW, the dimension lines that rely on those points will be automatically deleted in all other VIEWs as well.

THE WORLD

The WORLD constitutes the system's formative database, which stores and provides means to modify the topological and geometric properties of the designed artifacts. It is based on the hybrid edge model, which provides an integrated framework for representing points, lines, polygons, and solids (with both planar and curved geometries). The schema of the integrated data structure is depicted in Figure 3, and described fully in[14].

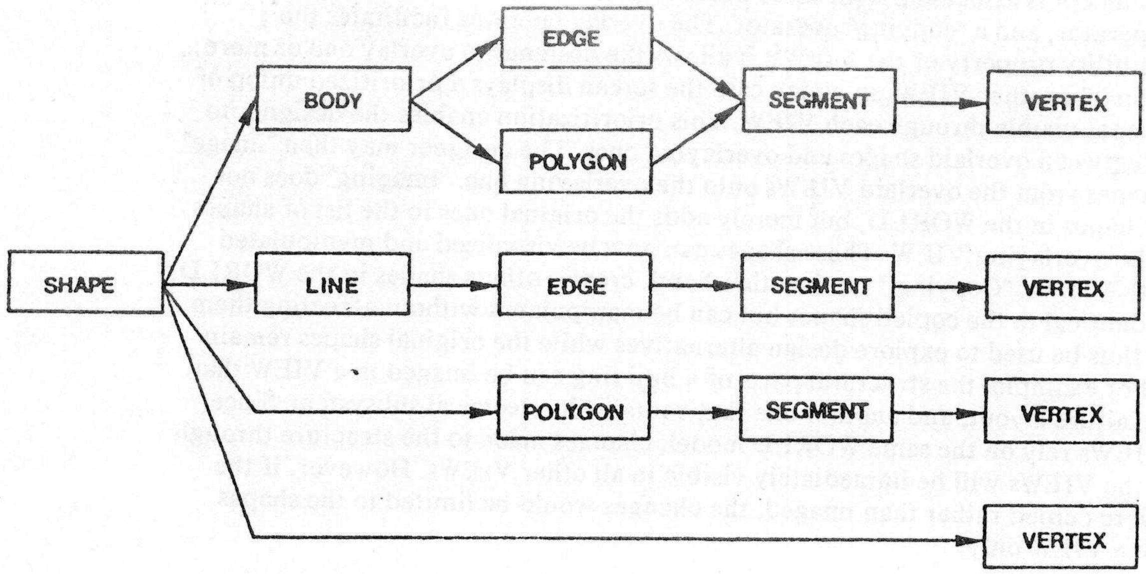

Figure 3: Schema of the WORLD database

Three sets of operators accompany the formative database: low, intermediate, and high level operators. The first set of operators facilitate creation, deletion, addition, and removal of topological entities and their association with geometric properties. The intermediate operators govern the invocation of low level operators, for such purposes as the creation of polygons, their manipulation, and their extrusion into prismatic solids. The set of high-level operators performs combined topological and geometric operations that transcend formative hierarchy levels, such as the Boolean operations (union, intersection, and difference), local extrusions ("pocketing"), fileting, etc. The operators, as the formative elements themselves, are hierarchically dependent, and maintain the well-formedness of the database.

THE VIEWS

VIEWs are means by which designers can visualize and manipulate the WORLD's formative database. Each VIEW represents a specific projection plane onto which images of selected shapes from the WORLD are mapped through an orthographic, isometric, axonometric, or a perspective transform. The scale and the position of the window in the WORLD (called "view box") that is mapped onto any given VIEW determines which components of the artifact are visible through that VIEW, and what their size appears to be. The designer may interactively control both the scale and the position of the view box, thereby achieving zoom and pan images of the modeled artifact. The designer can also create and delete VIEWs, and change their content dynamically. Each VIEW is mapped onto a user-defined window on the screen. Multiple windows, which may fully or partially overlap, can be displayed simultaneously. This facility enables the designer to see several projections of the WORLD for reference and better visual comprehension of the designed artifact (as depicted in Figure 4), and facilitates the addressability of points in 3-dimensional space.

The VIEW concept is associated with three unique operators: an "overlay" operator, an "imaging" operator, and a "copying" operator. The overlay operator facilitates the selective visibility property of the VIEWs; it allows the designer to overlay one or more VIEWs on top of another VIEW, in which case the screen displays a prioritized union of the set of shapes visible through each VIEW. This prioritization enables the designer to distinguish between overlaid shapes and overlaying ones. The designer may then "image" or "copy" shapes from the overlaid VIEWs onto the overlaying one. "Imaging" does not create new shapes in the WORLD, but merely adds the original ones to the list of shapes imaged in the overlaying VIEW. These shapes can now be visualized and manipulated through both VIEWs. "Copying," on the other hand, creates others shapes in the WORLD, which are identical to the copied shapes but can be manipulated without affecting them. Copies can thus be used to explore design alternatives while the original shapes remain unaltered. For example, the structural parts of a building can be imaged in a VIEW that contains furniture layout, and another one that contains its electrical subsystem. Since all these VIEWs rely on the same WORLD model, changes made to the structure through any one of the VIEWs will be immediately visible in all other VIEWs. However, if the structure were copied rather than imaged, the changes would be limited to the shapes visible in one VIEW only.

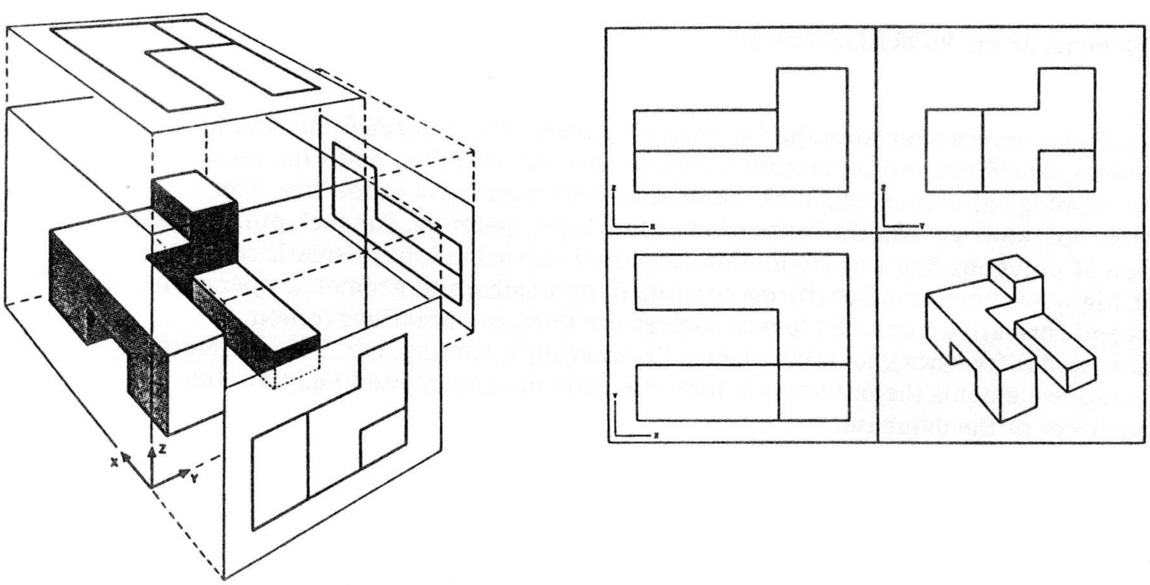

Figure 4: Simultaneous projections of WORLD entities through multiple VIEWs

The particular projection that is displayed by any VIEW is defined by the designer, allowing him to produce VIEWs that are oblique to the major planes and use them to manipulate artifacts in the WORLD. Such VIEWs are particularly useful to obtain face-on projections of non-orthogonal facades of buildings and other artifacts. All the VIEWs that have been generated in this manner are grouped in a "VIEW family" (also referred to as a "port"), and share the list of images that depict WORLD shapes (Figure 5). The sharing of images guarantees that all VIEWs in one family depict the same shapes.

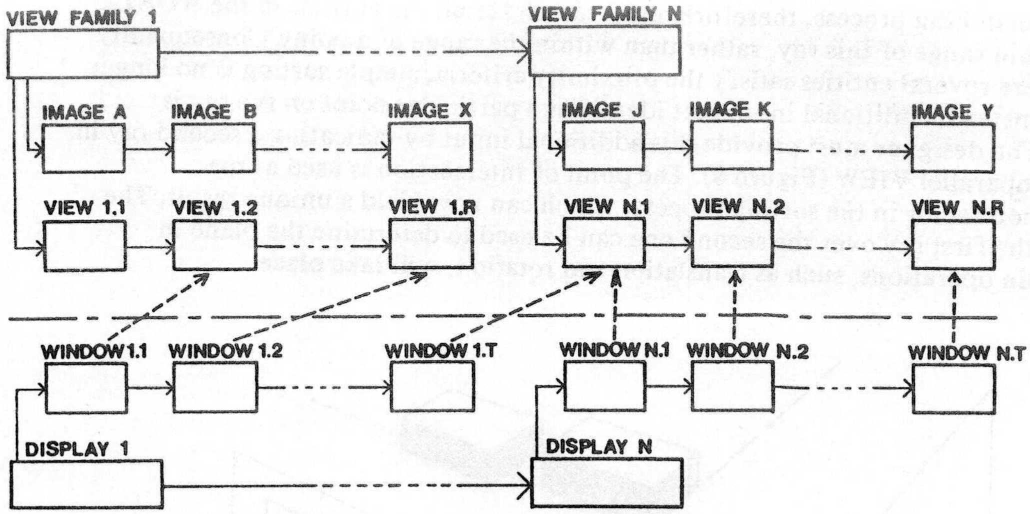

Figure 5: Schema of the VIEWS data structure

ADDRESSING WORLD POINTS THROUGH VIEWS

Multiple VIEWS of one WORLD constitute only half of the integration concept: They facilitate display of the formative database. To manipulate the database, we need means that can access the WORLD through the VIEWS, and address specific points in it.

While the process of projecting a 3-dimensional shape onto a 2-dimensional image plane is well defined in the computer graphics literature[15,16], the inverse of that process is not. More specifically, to construct and address 3-dimensional shapes through 2-dimensional orthographic projections we need more than a single source of information, which will compensate for the transition from the lower to the higher dimensionality. The work that was done in the area of constructing 3-dimensional polyhedral objects from their orthographic projections includes Sutherland's hardware and software for digitizing[17], and Thornton's[18] and Preiss'[19] methods for building a 3-dimensional model from its 2-dimensional projections.

However, since the integration of modeling with drafting is intended for design purposes, it does not require generation of the 3-dimensional model solely from 2-dimensional projections. Instead, 2-dimensional projections are generated from or along with the 3-dimensional model, which is built incrementally as the design progresses. The incremental construction of the WORLD requires addressability of 3-dimensional points through the 2-dimensional VIEWS. This capability is provided by a process that matches a particular WORLD entity (shape, solid, polygon, line, or point) with the screen location indicated by the designer, for the purpose of applying to it some design operation. The process involves mapping the screen location that is indicated by the designer to a particular WORLD location, and searching (parts of) the formative database to find the entity which is within some predefined range of that location. In cases where several entities fall within that range, a sorting process may be applied for the purpose of identifying the entity that is closest to the indicated point.

In 2-dimensional drafting systems, where the relationship between the screen and the WORLD is one-to-one, only mapping is necessary to identify the matching entities. By integrating modeling and drafting, however, each point on the screen corresponds to a line (or, more precisely, a ray) in the WORLD, resulting in a one-to-many relationship.

The entity-matching process, therefore, must search for all the entities in the WORLD that are within range of this ray, rather than within the range of a point. Consequently, in cases where several entities satisfy the proximity criteria, simple sorting is no longer sufficient; instead, additional input that identifies a particular point on the ray is necessary. The designer must provide this additional input by indicating a second ray in another, nonparallel VIEW (Figure 6). The point of intersection is used as the discrimination factor in the sorting process, which can now yield a unique result. The priority of the first ray over the second one can be used to determine the plane in which certain operations, such as translation and rotation, will take place.

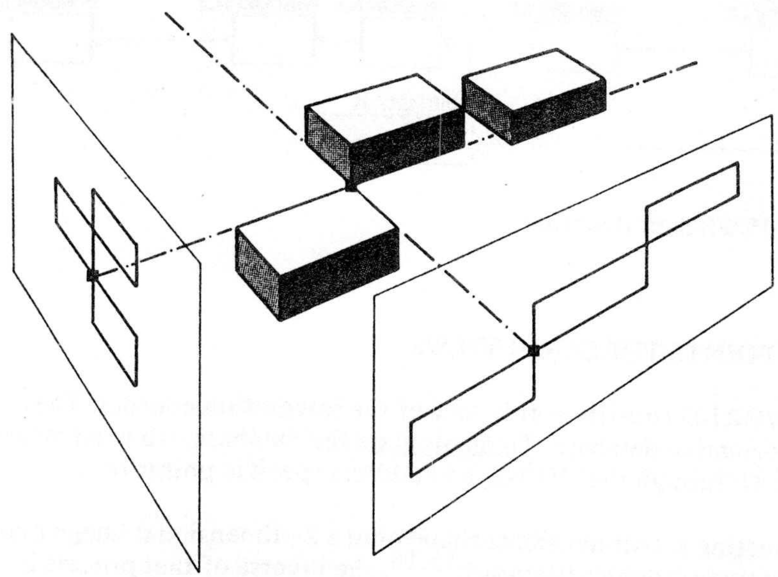

Figure 6: Addressing a point in the WORLD through multiple VIEWS

MAPPING BETWEEN THE WORLD AND THE VIEWS

The transformations from the WORLD to the VIEWs and back require a series of steps through three coordinate systems. First, images of shapes in the right-handed WORLD coordinate system are mapped into a normalized 3-dimensional, left-handed VIEW coordinate system, via a transform whose parameters were specified (indirectly) by the designer as described above. In the VIEW coordinate system the images are clipped to a view-box whose dimensions are determined by the prevailing zoom factor and the proportions of the window in which the image will be displayed. Foreplane clipping is determined by the VIEW plane itself, and backplane clipping is obtained from designer input, or from defaults that depend on the zoom factor. The resulting images are then projected onto the Z=0 plane of the normalized VIEW coordinate system, and mapped onto the selected window (Figure 7). This allows for zooming and panning of individual windows without effecting other ones. The transformation from the VIEWs back to the WORLD is achieved by an inverse process, consisting of first transforming the 2-dimensional point indicated in the VIEW into the left-handed, normalized VIEW coordinate system, then adding the third coordinate which was obtained by the process described earlier, and finally mapping the resulting 3-dimensional point into the right-handed WORLD coordinate system.

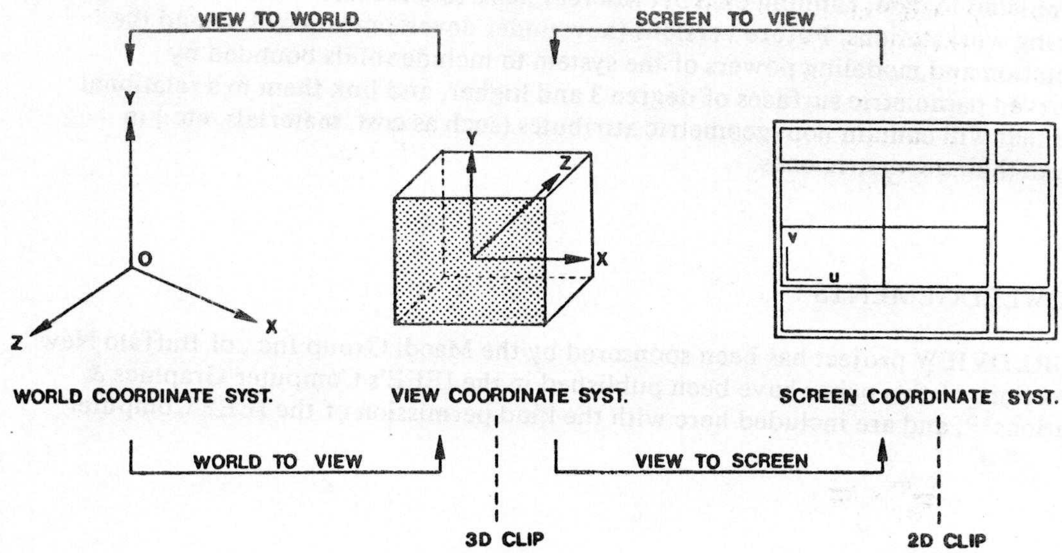

Figure 7: Mapping between the WORLD and the VIEWS

COMMUNICATING THE DESIGN

The purpose of the integration, as stated earlier, is to facilitate the manipulation and presentation of volumetric information through drafting-like interfaces. To achieve this goal, design and communication aids must be provided to facilitate accurate placement of formative elements in the WORLD, and to enhance their visual informational content. These aids are not part of the WORLD database, since they add no design-specific information. Their purpose is to facilitate the generation, manipulation, and communication of design information. Therefore, design and communication aids are considered parts of the VIEWS. Design aids include construction lines, grids, and scales. Communication aids include dimensions, annotations, and other graphical symbols.

This additional information transforms VIEWs from a design tool, whose main purpose is to facilitate visualization and manipulation of the shapes in the WORLD, into drawing-like documents whose primary purpose is to communicate the result of the design process. Like drawings, VIEWs are temporary and partial "snapshots" of the designed artifact, and must change as the artifact changes.A collections of multiple VIEWS, perhaps containing VIEWS from several different "ports," constitute the cumulative displayed result of the integration concept.

CONCLUSION

The integration concept discussed in this paper have been developed as part of a larger research project for developing a knowledge-based computer-aided design system, and was implemented in a geometric modeling/drafting system called WORLDVIEW. This system is currently used by students of the School of Architecture and Environmental Design in SUNY at Buffalo. A commercial version, named WORLDPORT, is being marketed by AISA Computer Products, of Buffalo, New York.

Written in Pascal and C (under the UNIX operating system), four major versions have been completed to date, running on SUN Microsystems and Hewlett-Packard 9000 series engineering workstations. Future versions (now under development) will extend the representation and modeling powers of the system to include solids bounded by multi-curved parametric surfaces of degree 3 and higher, and link them to a relational database that will contain non-geometric attributes (such as cost, materials, etc.) in addition to their geometric ones.

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