AN INTERDISCIPLINARY LABORATORY FOR GRAPHICS RESEARCH AND APPLICATIONS

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This paper describes the facilities and operation of the Program of Computer Graphics at Cornell University. A variety of graphic procedures are used for both input and output. The laboratory has the capability for producing dynamic vector displays and for generating full color images. Numerous research projects in a variety of disciplines which are actively using this multi-user graphics environment are presented.

#### Introduction

An interdisciplinary laboratory has been established at Cornell University for:

- a) the development of computer graphics techniques,
- b) the utilization of these techniques to help solve various research problems, and
- c) the improvement of interactive design methodology.

Using primarily digitizing tablets for the graphical input tasks, the researcher may select any of several two dimensional or three dimensional input routines. These include volumetric input, serial sectioning, three dimensional input using two dimensional views, and extrusion methods. Display options include static or dynamic wire line drawings or full color static displays. Hidden line and hidden surface algorithms, based primarily on planar polygon descriptions are available.

The initial graphics work has provided a catalytic effect for the stimulation of joint research projects. Present applications include research in structural engineering, geological sciences, water resources planning, pollution analysis, energy conservation, bio-medicine, architecture and animation. A brief illustration of some of these projects is presented.

The large variety of projects has enforced the need for a general, rather **than** a disciplinespecific approach to interactive graphics. Most of the graphic inputting, editing and display routines that have been developed can be interfaced to either specialized applications programs or to each other. A brief description of these operating procedures as well as the equipment and facilities of the laboratory follows.

This article is not intended to be an indepth description of any aspect of interactive computer graphics. It is solely an overview of the objectives, operating procedures, and progress of a new interdisciplinary computer graphics facility. For more detailed information on the hidden surface and surface representation procedures or on the animation system, the reader is referred to other papers emanating from this laboratory and included in these proceedings..

## Equipment and Facilities

The functional configuration of the graphics laboratory is shown in Figure 1. The major graphical components of the system are the E & S "Picture System", the E & S frame buffer, and two Tektronix storage tube displays. Two computers, a DEC PDP 11/50 and a PDP 11/34, are used to perform all of the operations and control of the displays.

The E & S Picture System is a pipeline system which contains a picture processor, a refresh buffer, picture and character generators, and a picture display and is capable of producing complex dynamic vector displays.

The E & S frame buffer is used for the production of the color images and has sufficient capacity to store one standard video frame (480 rows by 512 columns) of 8 bit pixels. For any image, each pixel can be translated into any of 256 possible colors by means of hardware lookup tables which provide 12 bit intensity levels for each of red, blue, and green.

Output from the frame buffer can be directed to high resolution television monitors or to a large screen video projector. A 16mm motion picture camera has been interfaced to the support processor for creation of stop frame motion pictures.

The Tektronix 4014 display terminals are standard high resolution storage tubes with the capability for complex static and limited dynamic

The operation of the laboratory is partially sponsored by the National Science Foundation under grant number DCR-14694 entitled "Development of Computer Graphics Techniques & Applications."

90

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Siggraph '77, July 20-22 San Jose, California





image generation. A common graphics software package has been created which will drive both the dynamic and static display devices.

Digitizing tablets serve as the standard, general purpose graphic input devices in the laboratory. Several tablets of varying sizes, ranging from a standard 11" x 11" tablet to a large 36' x 48" digitizing tablet have been interfaced either directly to the host processor, or through the display terminals. One transparent digitizing tablet allows for the digitizing of rear projected images.

The host computer is a PDP 11/50 with 96K memory. It is interfaced to Cornell's IBM 370-168 when larger memory capacity is required. A magnetic tape unit and two small disk units are also attached. The PDP 11/34 processor has been added to the laboratory equipment configuration primarily for the generation of color images. A large dual drive 80 megabyte Diva disk unit, DD-52, has been installed to improve the efficiency of the multi-user operating system and to store the large quantities of required picture information.

## Graphic Input Procedures

In general, the characteristics of an interactive graphics environment can be described as consisting of three types of graphical operations:

- The creation of the objects to be displayed.
- 2) The editing of the object description.
- 3) The generation of the displays.

A typical user should be able to rapidly and precisely describe an object in two or three dimensions in addition to color and time. To this end, a comprehensive set of graphic input routines have been developed which can be adapted for most applications. Four different methods are provided for graphically inputting spatial information.

All of these methods rely on the availability of standard interactive graphic inputting and editing procedures (4).

The first graphical input approach consists of building up a complex environment from a set of predefined volumetric elements (2,6,11)(Figure 2). The three-dimensional data required for the composite object description is obtained by interactively combining a set of primitive shapes and forms and by utilizing their original numerical definitions. To achieve these capabilities, the actual three-dimensional coordinates of the primitive objects are separated from the transformational parameters that are applied to the data before display. This method permits multiple elements to be constructed from the same set of data and displayed many times with different transformations. It also allows for individual transformational parameters to be altered without affecting those of any other object. To separate the coordinate data from the transformational data, two files have been established. The first contains the actual untransformed three-dimensional coordinate data of the original primitive objects. The second file contains the transformational parameters for translation, scaling, and rotation in each of the three coordinate axes. These files are read from a mass storage device at the beginning of each work session and can be written back to storage if the user makes an alteration that needs to be saved for future sessions.

The advantage of this approach is that it allows the creation of complex object descriptions with a minimal amount of data input and provides dynamic visual feedback using perspective images so that the researcher can work in three dimensions The major restriction is that the speed of the display may be limited by the referencing structure. This hierarchical process is particularly applicable to analytical routines based on sub-elements such as structural finite element analyses or multi-zone energy simulations.

A second and extremely promising method is to digitize three-dimensional information into the computer using multiple sets of two-dimensional photographs (8,9). By identifying the appropriate number of known reference points on a two-dimensional drawing or photograph, it is possible to determine the mathematical transformation matrix that uniquely transforms the three-dimensional spatial data to the existing two-dimensional picture. If two drawings or photographs are available, and the matrices defining their projections can be established, the process just described can be inverted. The user can input the true three-dimensional object space information by using a digitizing tablet and successively identifying each point in the pair of photographs. When combined with dynamic displays of the object as it is being defined, this procedure is a versatile input method (Figure 3). There are two major restrictions. First, the process requires an existing set of photographs or drawings.



Second, due to the inaccuracies of digitizing, powerful editing routines insuring planarity and automatic joining and aligning are necessary for practical usage.

A third method is to define a set of serial cross-sections of an object and automatically combine these planar definitions to create the three-dimensional shape. All information is input in two-dimensional format. Normally the major constraint is the large amount of data required to accurately define amorphous shapes. For this reason, numerical procedures utilizing B-splines which can accurately represent these two-dimensional contours with compressed data have been implemented (1,5,12). Automatic webbing routines or lofting procedures using Cardinal splines can provide the three-dimensional surface interpolation (Figure 4). Several applications, including the structural engineering finite element analysis project, are presently using this input method. Perhaps more important is the potential use of this approach to the entire field of medicine where information describing arbitrary, threedimensional objects is readily obtained in twodimensional format.

The last graphical input approach can be thought of conceptually as an extrusion method. A line can be generated from a point, a plane from a line, and a solid from a plane. In each case, the direction of the extension can be controlled and has a unique relationship to the original two-dimensional definition. Elements can be created by digitizing on any two-dimensional plane, transformed into a three-dimensional element, and positioned appropriately. This process is particularly applicable to the field of architecture. For example, a designer can create a three-dimensional object description by the extrusion of a base plan or building cross-section (Figure 5). Furthermore, by using the same graphic routines, the user can accurately and interactively describe details of the elevations.

Although each technique has its unique advantages, the inputting procedures are even more powerful when these methods are combined.



Figure 2 - Primitives

These displays were generated by a program which builds up complex objects from a set of primitive shapes. Two primitive elements, one duplicated twice, are combined to form a set of three (Figure 2a). Each set is tripled and the nine objects are displayed in Figure 2b (ProgramPRIMITIVES by Nicholas Weingarten).



Figure 3 - Three Dimensional Input from Two Dimensional Views

Figure 3a shows the forming of polygons from established three-dimensional data points. The dashed lines indicate the polygon being formed. A bird's eye view of the completed house is shown in Figure 3b. The user can view the completely defined object from any observer position (Program MODEL by Robert Thornton).



Figure 4 - Serial Sections

Figure 4a shows the display of a television tower on a mountain that was described in less than aminute by tracing in the contours. The tower contours were subsequently "webbed" by connecting lines between contours to produce a more realistic surface (Program WIRE by Marc Levoy). The amorphous shape of Figure 4b was modeled by utilizing B-splines to represent the two-dimensional contours. Lofting was accomplished using Cardinal splines for the three-dimensional surface interpolation (Program SURF by Sheng Chuan Wu).



Figure 5 - Extrusion Method

Figure 5a shows an isometric view of the plan of a building digitized by an architect. "Rubber-banding" techniques were used to ensure that lines are straight and parallel. Figure 5b shows the building after the plan has been extruded to a preset wall height (Graphic Input Program by Harvey Allison.)

# Graphic Display Capabilities

The display environment has the capability for generating dynamic black and white line drawing images. Views using any orthographic or perspective projection are easily obtained from any viewport. Static displays can be generated on any of the output devices, but complex dynamic displays necessitate the specialized hardware of the vector display system. For editing, and non-dynamic display requirements, a graphic software package has been developed which operates on the storage tube terminals and simulates the powerful vector display system. Hard copy drawings are software generated on a printer-plotter from the image

A unique graphics programming system has been implemented to generate the color displays. This system is designed to provide an environment familiar to vector graphics researchers while maintaining flexibility for a variety of experimental approaches to using the frame buffer. The data required for the generation of the black and white vector displays can also be used for the creation of color images. Specifically designed operators are provided for the creation of half tone color images, including commands for rendering dots, vectors, convex and concave polygons and run-length encoded scan lines.

For three-dimensional environments, an efficient hidden line and hidden surface algorithm has been developed and is available to all system users (7,10). The approach is based on a two-dimensional polygon clipper which recursively subdivides the image into polygon-shaped windows until the depth order is established. The method is sufficiently general to treat concave polygons with holes. A major advantage to this approach is that, since it retains the polygon information, it is equally valid for both hidden line and hidden surface display. Subroutines for smooth shading, edge smoothing, reflectance and shadowing are also available when more realistic images are desired (Figure 6).

#### Applications

The following is a brief synopsis of some of the major application projects currently under investigation. It is significant to note the diversity of the applications and their ability to use a variety of the graphic input and display routines. Since truly interactive graphics are not yet economical, our inter-disciplinary effort implies a potential cost-effectiveness for sophisticated graphics utilization. The graphics techniques have substantially enhanced the productivity and development of many of these projects even though, at their initiation, many of the routines were not fully developed.

### A. Structural Design

A series of critical problems in structural mechanics exploiting the natural symbiotic relationship between the highly effective, computation bound, finite element stress analysis technology on the one hand, and the visual, interactive, dynamic computer graphic technology on the other, are being investigated.

One project is concerned with finite element grid optimization. The finite element analysis method is a means for analyzing structural behavior by representing complex objects with a set of simple-shaped elements, i.e., triangles, quadrilaterals, etc. Structural equations are derived representing the contribution of each element to the total system response. Typically a dominant portion of the total cost for each analysis can be attributed to the input task of describing the structural geometry. Furthermore, badly chosen coarse element grids will not yield accurate solutions, but if large numbers of ele-ments are chosen, the input and computational times are excessive. A means must be found to reduce the input task and enhance the analytical solution techniques.

To accomplish this, the following approach is being used. The structure is first automatically subdivided into a mesh interactively



## Figure 6 - Color Graphic Displays

A color perspective image of a simulated house created using the extrusion system is shown in Figure 6a. Shadows are automatically generated using the hidden surface algorithm. A smooth-shaded, transparent object created with the serial section technique is shown in Figure 6b. (Doug Kay). The backgrounds of both figures were created by optical scanning techniques. selected by the analyst. The resulting gridwork is graphically displayed and revised as necessary (Figure 7a). When all loads, support conditions and strength information has been graphically input, a complete structural analysis is performed. The resulting stress distribution is then displayed in the form of iso-stress or iso-energy contours (Figure 7b). These contour lines are then used to create a more optimal gridwork.

Although the finite-element method is clearly an ideal approach for the analysis of arbitrary three-dimensional structures, its application has been hampered by the difficulty in generating the necessary digital descriptions of such structures. A second project involves developing a graphical method for the digitization, representation, and subdivision of arbitrary three-dimensional surfaces. This enables the rapid and accurate analysis of forms ranging from architectural shell structures to biological structures such as a human skull. The method uses the lofting techniques previously described, where the serial section contours are represented by B-splines and the surface is interpolated with Cardinal spline functions (12). The procedures used allow an accurate surface representation with only a small amount of data. The resulting surface can be interactively modified by the user until satisfactory results are obtained (Figure 4b).

### B. Animation

A key-frame animation system has been developed which accepts free-form line sketches, free-form images, or two-dimensional projections of complex three-dimensional environments (3). The key-frames are drawn by the artist using a digitizing tablet and displayed on either the black and white vector scope or the color halftone CRT. These two-dimensional images are combined using a multiplane cel animation technique to produce depth and motion illusions (Figure 8). The system allows real-time previewing by computing the in-between frames "on-



the-fly", thus providing the artist with instant playback of the animated sequence. All interaction is pictorial, enabling the artwork to be easily edited. Several artistic films are currently being produced.

#### C. Energy Conservation

Although for several years, it has been possible to simulate the dynamic thermal behavior of buildings, the use of such simulations has not been widespread for several reasons. First, the cost of analysis has been excessive since a large number of man hours are required to accurately describe the building geometry. Second, the input requirements for the available programs are so rigid and detailed that they can not be used at the preliminary design stage when much of the information is not yet available. Interactive computer graphics techniques can help alleviate both problems.

A system allowing the graphic creation of complex three-dimensional building descriptions has been interfaced with multi-zone thermal analysis routines. Combinations of primitive volumes are used to specify the building shell. The composition of each of the wall sections of the building are interactively specified and assigned to the appropriate planes (Figure 9). Windows and doors may be precisely located on any of the walls of the building. All of the required thermophysical characteristics of the building shell are automatically computed and used for the thermal analysis routines. The graphic procedures for defining the residential building have proven to be very flexible and efficient to use.

#### D. Agricultural Tractor Accident Prevention

Agricultural wheel tractors frequently operate on potentially hazardous terrain where overturning or other types of accidents occur. Up to 1000 deaths in the United States occur each year as the result of tractor accidents, of which two-thirds are the result of tractor overturns. The prevention of overturns, or at



## Figure 7 - Structural Analysis

Display of finite element grid interactively created by the analyst is shown in Figure 7a. Only the perimeter contours were specified. The mesh, including the node numbering system was automatically created and serves as input for the analytical routines. After the stress analysis, isocontour lines are displayed and can be used to generate a more optimal finite element mesh (Programby Bob Haber and Mark Shephard).





# Figure 8 - Animation

Figure 8a shows a key-frame line drawing of a princess kissing a frog. Editing options at the artists' disposal are shown in the menu. A painted background scene for a multi-ccl environment is depicted in Figure 8b. (Program NEREUS by Marc Levoy, artwork by Jose Gelabert).



Figure 9 - Energy Conservation

A composite wall section is interactively built up from a stored library of materials and the thermal characteristics are automatically computed (Figure 9a). The wall sections have been assigned to each plane and windows and doors have been attached to the thermal enclosure of the private residence shown in Figure 9b (Program GLAS by Rich Rogers).



Figure 10 - Tractor Simulation

The figures are graphic displays of a tractor approaching a roadside bank and turning over. The tractor motion is predicted and displayed using a dynamic simulation model. Interactive graphic routines allow the tractor to be viewed from any vantage point (Program by Peter Atherton).

least properly designed rollover protective structures, will help protect the tractor operators. The general objectives of this research project are to develop dynamic computer simulations of agricultural tractor accidents to examine the many parameters of tractor design and terrain that influence accidents, in order to improve the safety and reliability of vehicles. To effectively comprehend the tractor motion, the mathematical simulation model has been combined with dynamic graphic display capability (Figure 10). The researcher can actually see the vehicle turn over, and visually as well as mathematically locate the actual point of impact. These graphic displays are being used, not only to study tractor dynamics and motion during accidents, but to develop an understanding of appropriate tractor operator actions to prevent accidents.

#### Commentary

This paper has briefly described the input and display procedures, the operating configuration, and some of the research projects currently under investigation at Cornell's Program of Computer Graphics. Based on our two and one-half year experience, several statements can be made:

1. Almost all programming has been implemented using FORTRAN IV under the **RSX-11M** multiuser operating system. Although FORTRAN has enabled us to interface with many analytical routines in the published literature, a higher level language, with recursive and interruptable capabilities, would prove to be much more flexible for the coding and debugging of interactive graphics software.

2. The mini-computer environment has proven to be generally satisfactory. By using efficient matrix inversion techniques, the normal limitations on problem size can be overcome. Relatively large scale numerical problems have been successfully analyzed in structural mechanics, optimization and energy analyses. The time requirements are not excessive. The major restrictions arise from the 16 bit word size limiting the amount of core storage available to a single task (32k) and the precision available for certain display calculations.

3. Both dynamic vector displays and color raster displays demand substantial amounts of data throughput; a requirement which can severely hamper a multi-user environment. By using independent display processors (the PDP 11/34 and the E & S picture processor, Figure 1) the total system resources can be more effectively utilized.

4. A graphics software package has been developed to generate images on the storage tube terminals. This package simulates the commands and hardware capabilities of the fast vector display. Not only has this enhanced productivity, particularly in the development of new graphics programs, but it can provide remote users with more powerful graphic display capabities.

5. Each application project relies on graphic input using either the dynamic display, the color display, or both. These projects have been developed by programmers with expertise in their own field but with only limited experience in graphics. Our ability to provide these researchers with a comprehensive set of graphic utilities that can be easily interfaced to their analysis programs has proven invaluable.

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