Digital Scene Simulationsm: The Synergy of Computer Technology and Human Creativity

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Invited Paper

Digital Scene Simulation is Digital Productions' philosophy for creating visual excellence in computer-generated imagery and simulation. The approach it advocates requires the use of powerful hardware, sophisticated software, and top creative talent. With a CRAY supercomputer at the heart of its computer network and its own proprietary image rendering and simulation software, Digital Productions is revolutionizing state-of-the-art computer graphics. At the forefront of computer graphics technology, Digital Productions is redefining traditional methods of visual communications and creating new forms of self-expression, instruction, and entertainment.

I. DIGITAL SCENE SIMULATION

A Digital Scene Simulation: A Philosophy

In 1982, Digital Productions revolutionized state-of-the-art computer graphics by dedicating a CRAY X-MP supercomputer to create computer-generated imagery and simulation. The company co-founders, John Whitney Jr. and Gary Demos, have long been associated with the field of computer simulation. Many years ago, they created a philosophy and a process they termed Digital Scene Simulation. Their innovations, applications, and emphasis on quality established visual standards for this young and burgeoning industry. The Digital Scene Simulation doctrine is comprised of three basic ingredients:

- the hardware: capable of producing high-quality, highresolution images;
- the software: capable of handling highly complex, fully detailed objects and scenes;
- the people: top creative talent to develop and take full advantage of the technology.

Digital Productions has attained the original objectives of Digital Scene Simulation. The computer network this com-

smDigital Scene Simulation is a service mark of Digital Productions, Los Angeles, CA, USA. pany is constructing, described in more detail on the following pages, is capable of quickly and efficiently producing motion picture animation and special effects of unsurpassed clarity and realism. The ability to produce large amounts of high-quality computer graphics on a short schedule is in much demand by the entertainment industry, making Digital Scene Simulation a viable medium with which artists can work.

The principles of Digital Scene Simulation have recently been extended to include qualitative, as well as quantitative, principles. Currently, the computer serves as an excellent productivity tool for the creative artist; it quickly calculates and displays high-quality images, allowing the artist to create a scene and experiment with different objects, placements, colors, textures, etc. The next step is to have the computer be the director's tool; it should be able to carry a story line and express theatrical characterizations. Digital Productions' current research has defined the following two new objectives for Digital Scene Simulation:

- dynamics: the study of movement and character interaction;
- characterization: the ability to portray the subtleties of character emotion, which involve the study of artificial intelligence, as well as human psychology and physiology.

Dynamic properties are currently represented mathematically, or algorithmically, in a computer. Objects of a scene are represented numerically; objects are designed on paper in three dimensions (3-D) using multiple views, coordinate points are digitized, or encoded, and the information is stored in computer data files.

Current research is investigating ways of keeping track of the relationships and interactions between an object and its environment. An *algorithmic database* is necessary for keeping track of objects and their behavior. Using artificial intelligence techniques for decision making, the *algorithmic behavior* of an object can be determined and realistically modeled for any given situation. The algorithms that specify the behavior of the objects and characters in scenes are determined by the director's script. The script specifies actions; the computer will have the intelligence to execute them.

Manuscript received July 11, 1983; revised July 27, 1983.

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The ultimate objectives are to use technology to portray both characters and characterizations realistically, and to enhance the creative achievements of artists and directors. "The great challenge," according to Whitney," is to simulate the mundane. It's the everyday street scene that we take totally for granted. That's the most difficult challenge we face in simulation. Once we've achieved that we can go ahead and create the surrealistic and the extraterrestrial scenes."

B. Digital Scene Simulation: The Implementation

Before examining the various hardware and software tools in use at Digital Productions, a brief discussion of the procedures needed to go from the artist's imagination...to the computer's memory...to the silver screen...is in order. Scenes, and the objects that comprise those scenes, begin as a concept on the drawing board of an art director or production designer.

Given a written script, a storyboard artist analyzes the scenes and draws visual descriptions of the key frames. Meanwhile, a production designer isolates the objects of a scene, whether they be spaceship, house, or human-like figure. Each object is designed in great detail, and an architectural plan is drafted that contains complete 3-D information.

An object is architecturally designed so that the surface shape of each of its parts is drawn as a set of polygons. These polygons are very significant. The more complex an object, the more polygons are created to describe its shape; hence, more computer storage is required, and more computation time is needed to render an object realistically.

These engineering diagrams are then encoded; i.e., coordinates on the drafting paper are translated into numbers with the aid of a digitizing tablet, and stored in a data file in the computer. From these data, the computer can construct a 3-D model and display it on a terminal screen. The people responsible for developing the architectural design and encoding it are known as drafter/encoders.

Sophisticated hardware/software systems enable the drafter/encoder to rotate and examine the object on the display screen and to make any necessary design modifications. The resulting image is called a *wire-frame*; it is a line drawing that looks like a wire mesh has been stretched over the surface of the object. This wire mesh is actually outlining the polygons that were created to describe the object's surface structure.

Next, the technical director realistically renders the encoded objects. The technical director uses Digital Productions' proprietary software to make the objects look like the creative artist's initial drawings. The technical director specifies material type, surface texture, placement of the light sources, color, etc. The computer realistically portrays the materials, whether they be metal, glass, wood, velvet, plastic, or chalk. Surfaces are made shiny or dull, smooth or textured. Highlights are reflected; shadows are cast. The physical properties of transparency, translucency, reflection, and refraction are applied. The artist and the technical director work closely together to ensure accuracy and realism.

The technical director is also responsible for animating the objects according to the specifications of the storyboard. Using wire-frame images, which require less data manipulation and allow faster drawing speeds, the technical director previews short motion segments in real time. The action commands being specified are visually checked for accuracy before the more costly and time-consuming final image rendering process.

Using a proprietary previewing package, the technical director tells the computer what the starting and destination key frames look like, what action is to occur, and the length of time over which the action is to take place. The programs compute the number of *in-between*, or intermediate, frames to be generated and automatically create the appropriate actions per frame.

In the final filming process, the computer calculates each frame using fully rendered objects to create visually realistic scenes. Action commands, already tested on the wire-frame images, are applied to the objects of the scene. Each frame can take 10–400 s to compute, depending on the complexity of the images. Output is directed to a film recorder. These film segments, once edited together and combined with live action footage, provide the special effects and animation that enthuse and entertain movie goers.

C. Digital Scene Simulation: Benefits Exceed Traditional Methods

Simulation offers many benefits over traditional methods of animation; it is an economic, creative tool that will further the objectives of the entertainment industry. High costs are limiting the use of traditional filmmaking techniques; labor costs will increase 30 percent in the next 2 years and production costs increased 126 percent between 1976 and 1980. There is a built-in economic need for new methodologies for making movies. Today's computer costs are competitive with Hollywood prices, and trends indicate that the computer costs will decrease over time.

Simulation enhances creativity. In traditional cinema, the cameraman and special effects artist are limited by the mechanics of moving a camera around miniature, specially designed models. The real world in which they must work is governed by gravity and the laws of physics. Using computer simulation techniques, artists and directors are free to create new worlds instead of recreating existing realities. Objects can be observed in 3-D space from any viewpoint. These creations can effortlessly defy gravity, turn inside out, go through solid objects, follow complex flight paths, or transform shape. Objects can be exploded and immediately put back together. The computer also encourages trial-and-error design; the creative artist and technical director can experiment with different surface textures, material types, and colors to achieve the desired effect.

Then again, simulation can be used to mimic our existing reality as well as create new realities. As such, the computer can improve the productivity of artists and directors. Digital Productions is currently working on intelligent programs to handle scenes according to the laws of physics and to assist in set design, lighting, and character behavior. By combining artificial intelligence techniques with simulation, Digital Productions hopes to leave the details of scene execution to the computer and the subtleties of design to the creative efforts of the artist.

Finally, simulation will contribute to new forms of entertainment for the general public. Aspects of the entertainment industry are already associated with high technology. The proliferation of personal computer games, video tapes, and video disks is encouraging a wide range of stimulating



Fig. 1. Digital Productions' computer facility overview.

home entertainment. A challenge for the future is to popularize the work Digital Productions is currently doing in a controlled laboratory environment on a supercomputer. New types of high-resolution, interactive, real-time movies and games will offer new methods of self-expression, communication, and amusement.

II. DIGITAL PRODUCTIONS' SYSTEM ENVIRONMENT

A. Overview

Digital Productions houses a large computation facility featuring a full array of data entry, encoding, and movie previewing workstations. The CRAY X-MP/22300 dual CPU supercomputer is at the heart of this computer network. A VAX 11/782 dual processor serves both as a front-end computer to the CRAY and a stand-alone production system. Additional equipment includes several Ramtek color raster displays, a variety of precision encoding tables as well as vector display processors, several previewing stations, and the Digital Film Printer (DFP). The DFP is a uniquely configured film composition system consisting of two scanners and one film recorder. A CRAY I/O Subsystem (IOS) directly interfaces the CRAY to the DFP, high-performance color display systems, and on-line mass storage devices.

Fig. 1 illustrates the network facility currently in use. The following sections explain in more detail the functionality of the equipment.

B. The CRAY Network

The CRAY X-MP supercomputer is necessary for Digital Productions' unique and computationally intensive computer graphics application. According to John Whitney, Jr., company president, the big bottleneck in past computer graphics projects was the lack of available high-performance hardware and software. To achieve photographic reality—computer output that suspends disbelief—it was critical to achieve high scene complexity. Hence, the power of the CRAY became necessary.

The general-purpose computing capability of the CRAY was also required. A flexible system facilitates ease-of-use in an interactive environment and allows software changes to be made quickly and easily. Several languages are available on the CRAY, including Pascal, C, and FORTRAN. For portability, easy integration with other systems and powerful mathematical capabilities, FORTRAN '77 was chosen for Digital Productions' software development efforts. Overall, the CRAY permits code to be developed, compiled, edited, and debugged rapidly.

Computational speed and numeric accuracy are both necessary to achieve quality results. Some graphic algorithms, such as shadow computations, are extremely sensitive to numerical precision. Other algorithms are simpler to code if the logic does not have to worry about precision and does not have to scale values down to a certain number of bits. Object attributes, such as brightness, color, transparency, and texture mapping, are more appropriately manipulated with floating-point precision.

On the CRAY X-MP, floating-point arithmetic is faster than integer arithmetic; hence, speed and precision are both possible. The CRAY X-MP supercomputer is capable of performing in excess of 200 million floating-point calculations per second (megaflops). In fact, it can simultaneously perform 200 million floating-point multiplications and 200 million floating-point additions per second in ideal situations. In-system rates are typically 100 megaflops.

Digital Productions' proprietary software takes advantage of the CRAY's vector architecture, which significantly reduces computation time and improves throughput performance. Each one of the two CRAY CPU's has 8 vector registers, each of which has 64 words with a word length of 64 bits. When the CRAY performs a vector operation, results are computed once every clock period after the initial result is calculated; a clock period is 9.5 ns.

Vectorized code utilizes the 8 vector registers to feed operands into the vector functional units (floating-point add, multiply, reciprocal, and logical). A vector operation can occur when the same series of arithmetic operations are performed on consecutive values stored in pairs of vector registers. For example, the following FORTRAN DO LOOP can be executed as 6 vector operations: (1-3) load vector registers V_0 , V_1 , and V_2 with the values of the *B*, *C*, and *D* arrays, respectively, (4) multiply V_1 by V_2 , (5) add the result to V_0 , and (6) store the result.

4 DO 10 I = 1,64
10
$$A(I) = B(I) + C(I) * D(I).$$

Operations such as coordinate transformations, shading, and image merging are easily vectorized, whereas sorting algorithms common to a variety of classic hidden surface removal algorithms are not. An important activity at Digital Productions is the development of vector algorithms for hidden surface removal in extremely complex scenes; this will permit greater scene complexity and more film footage to be generated in a shorter time period.

Digital Productions' emphasis on speed and precision reflects the inherent problems in computer graphics to date. The computing requirements have been a limiting factor in the quality and quantity of computer generated scenes. With a supercomputer and serious attention to algorithm design, Digital Productions is making major strides in the advancement of this technology. The following facts and figures will explain and justify Digital Productions' requirements for a supercomputer.

- The amount of data that can be displayed on a Ramtek monitor is 1280 × 1024 picture elements (pixels) × 24 bits per pixel. This is approximately 32 million bits, or 4 million bytes (Mbytes), of data per frame. (Note: The color of a pixel is defined as a set of numbers; these numbers represent the intensities of the three primaries: red, green, and blue. Display monitors having 24 bits/pixel allocate 8 bits for each color specification.)
- High-resolution film recorders, necessary for quality 35mm film production work, have a resolution of 3000 × 4000 pixels × 30 bits/pixel. (A 30-bit pixel allocates 10 bits for each color specification.) This is 360 million bits, or 45 Mbytes, of data per frame.
- Assume it takes ten floating-point calculations to determine the value of each color per pixel. Since commercial motion pictures run at 24 frames per second, it takes 8.64 billion calculations to produce 1 s of film (24 frames/second × 10 instructions/color × (3000 × 4000 × 3 colors/frame) = 8 640 000 000 instructions per second of film).
- In actuality, various lighting and rendering algorithms require 1 to 10000 calculations per color. Therefore, it

takes anywhere from 864 million to 8.64 trillion arithmetic instructions to produce 1-s worth of motion graphics. The CRAY, capable of performing 200 million floating-point instructions per second, takes anywhere from 3 s to 10 h to generate 1 s of film. The entire image does not change in every frame, and programming shortcuts exist for reducing the number of calculations. Film recorders used to produce large-format 70-mm film have resolutions up to 4600×6000 pixels/frame $\times 30$ bits/pixel, which is approximately 100 Mbytes of data. Digital Productions has two or more film scanners operating simultaneously with its film recorder. This system scans, or digitizes, foreground and background images, merges them, and outputs them to the film recorder for printing on film. It can also scan and merge foreground, background, and several midground images with computer-generated special effects. For these applications, the amount of data being transferred per frame could be as high as 400 Mbytes.

The amount of data that needs to be computed and displayed is quite impressive, and it soon becomes evident that data bandwidth is a critical communications problem. It currently takes 20 s to transmit 3.5 Mbytes of image from the CRAY to the Ramtek via the front-end VAX. At this rate, it would take 10 min to send 1 frame (100 Mbytes) to a high-resolution film recorder.

To improve data communications, Digital Productions has a CRAY I/O Subsystem (IOS). The IOS allows high-bandwidth communication between the CRAY CPU and peripheral devices. High-Speed Channels (HSC's) and Low-Speed Channels (LSC's) connect the IOS to peripherals. The former run at 100 Mbytes/s; the latter run at 6 Mbytes/s. These speeds are exceptional when compared to DEC's UNIBUS (1.5 Mbytes/s), the DEC MASSBUS (2.0 Mbytes/s), or the IBM Block Multiplexer Channel (2.5 Mbytes/s).

The IOS consists of shared buffer memory storage and a set of three individual I/O Processors (IOP's). The IOS contains 64 Mbytes of buffer memory; this is four times the amount of memory resident in Digital Productions' CRAY. Each IOP has access to this buffer memory at 100 Mbytes/s. The IOP's each serve a specialized function; the configuration used at Digital Productions is described below. It should be noted that at most 4 IOP's can be contained in an IOS.

- The BIOP (Buffer I/O Processor), connected to the CRAY CPU via an HSC, manages the 64 Mbytes of buffer memory contained in the IOS. Data transfer is significantly improved; it takes 4 s to transfer an image between central memory and disk, but only 1/8 s to transfer an image between central memory and the IOS. The BIOP also interfaces to eight DD-29 high-density disk drives, each of which holds 600 Mbytes of data.
- The MIOP (Master I/O Processor) is the IOS controller; it is the central communications link. The MIOP is connected to the CRAY via an LSC. The MIOP functions as the CRAY console computer and monitors the CRAY's operation. It also performs CRAY diagnostic functions.
- The XIOP (Graphics I/O Processor) was custom-built for Digital Productions' unique application. It contains three HSC's for attaching graphic devices directly to the CRAY, including frame buffers, precision film scanners, and film



Plate 1. CRAY Temple—front view. This Temple was one of the first objects designed and encoded at Digital Productions to publicize the sophisticated software being developed on the CRAY supercomputer, acquired in April 1982. This computer generated image demonstrates such real-world properties as highlighting, shadowing, and light diffusion. Digital Scene Simulationsm by Digital Productions, Los Angeles, CA © Copyright 1983. All rights reserved.



Plate 2. Fuji Balls. These colorful balls are patterned after Japanese ornaments known as Fuji balls. Digital Scene Simulationsm by Digital Productions, Los Angeles, CA © Copyright 1983. All rights reserved.

recorders. The XIOP is also connected to two high-speed tape drives. Interfacing the CRAY directly to peripheral devices via the IOS HSC's dramatically reduces transmission time. The in-system transfer rate for 400 Mbytes of data, including overhead processing time required by system software, is approximately 12 s.

Ramtek has designed a high-speed interface to connect its frame buffers, with resolution $1280 \times 1024 \times 20$ (7 bits for Red, 7 bits for Green, and 6 bits for Blue) to the IOS. Information can be written to the displays at the full channel speed. It takes 1/8 s to write a full screen of data. Since displays are refreshed at a rate of 30 frames/s, the CRAY is almost keeping up with real time. If an alternate resolution were used (such as TV resolution of 512 × 640 pixels), then displays could be used for real-time playback.

A CRAY-1S can generate 4 min of film per month, where the average frame complexity is 250 000 polygons. It is possible to produce 45 min of simulation per year.

To meet expanding work loads and improve production time overhead, Digital Productions has installed and is using a new supercomputer, a dual processor CRAY X-MP. Each of the individual processors is faster than a single CRAY-1 because of a faster clock; the Cray X-MP has a clock period of 9.5 ns, while the CRAY-1 has a 12.5-ns clock cycle. The processors communicate through a set of shared registers, including semaphores for interprocessor synchronization.

Both processors also share all of memory. The CRAY X-MP memory has approximately four times the bandwidth of the CRAY-1S memory. The CRAY X-MP also has improvements in the vector floating-point processor which allows *chaining*, i.e., two floating-point operations can be easily run simultaneously.

The CRAY X-MP has increased performance by a factor of 3. This increased processor power will be utilized for more workstations and terminal displays, and for generating more scenes of greater complexity.

Digital Productions' productivity has increased three-fold, and it will be possible to generate 12 min of film per month, or 144 min per year. That is equivalent to two full-length feature films. Using traditional techniques, Disney animators produce, on the average, one film every two years.

C. VAX 11/782 Front-End Station

Digital Productions uses a VAX 11/782 dual processor computer as a front-end station to the CRAY. The DEC machine was chosen because it is a user-friendly performance machine and provides users with excellent tools for local program development. The VAX is also an industry standard for computer graphics; it interfaces with a wide range of graphics devices and can run most available graphics software packages.

The communications software that allows the VAX user to talk to the CRAY was developed by Digital Productions. Digital Productions wrote its own multiuser interactive front-end station to support interactive programming and to drive its graphics devices in a fast and efficient manner.

D. Encoding Workstations

As described earlier, the objects of a scene are sketched on an artist's drawing board and then architecturally detailed before ever making it to film. Once an object is architecturally designed and drafted, it is entered into the computer at an encoding workstation.

An encoding workstation is a well-tuned hardware/ software system, configured by Digital Productions' engineers and analysts. A workstation consists of a precision encoding table and an Evans & Sutherland PS300 vector display processor; each station is connected to the VAX. The software, developed by Digital Productions, is responsible for data storage, manipulation, and verification.

Architectural drawings of objects are taped down on large 42 \times 60-in encoding tables. Man and machine then work together to enter object information into the computer's memory. Point by point, the drafter/encoder enters the x, y, z coordinates of the vertices of the polygons that describe an object's surface structure. Software routines accept this information, store it in object data files, and provide immediate feedback by drawing the polygons on the vector display screen.

To use the encoding workstation, the drafter/encoder places a transparent disk-shaped input cursor over his hand-drawn schematic. At the center of the cursor is a cross-hair, which he aligns with each vertex on the object's polygonally designed surface. When the coordinates are ready to be entered, he pushes a button on the cursor. The electronics in the encoding table calculate the location of the cross-hair and transmit the associated coordinate values to the computer. Precision encoding tables can gather data with an accuracy of 1/1000th of an inch.

The encoding program also lets the user scale and rotate the encoded objects on the vector display. Additional features provide shortcuts to enter geometric shapes, such as cones and cubes, to mirror symmetrical objects, to add details to objects, to smooth surfaces, and to draw curves and manifolds. Correction routines detect and correct any misalignments of polygons. Verification routines flag inconsistencies and errors in data entry.

A drafter/encoder can also examine objects on a raster display; a rendering program on the VAX 11/782 lets him display a solid looking version for more enhanced visual verification. The drafter/encoder can position the object, select colors, define surface materials, shade surfaces, and add light sources.

E. Previewing Stations

Real-time vector display systems are used for previewing objects and scene motion. Interactive Machines Inc.'s (IMI) workstations feature fast drawing speeds, high-resolution images, and high levels of interactivity. These stations are connected to the VAX via ETHERNET and achieve an in-system transfer rate of 125 kbytes/s.

Digital Productions developed an interactive software system for specifying and previewing motion. The user specifies the objects that will appear together in a picture frame and their relationship to one another, i.e., which objects move in conjunction with other objects. The user also designs the starting and destination key frames, specifies the number of frames in the sequence, and defines the movement and acceleration of each object. The previewing software interpolates the in-between frames and displays the resulting movement in real time on one of the vector displays. It also creates a file of movie instructions for Digital Productions' image rendering software, DP3D, used to generate the final film sequence. In addition to specifying the movement of objects in time, Digital Productions has developed additional languages for defining the movements of parts of an object. These command/control languages allow the technical director to do such things as turn spaceship engine exhausts on and off, flash the lights of an LED display, or spin propellers.

F. Special-Purpose Front-End Software

There are a variety of user-friendly interactive front-end languages for DP3D, Digital Productions' proprietary image rendering software. These include a general-purpose language for specifying object attributes and placement; a simulation language based on mathematical models of physical phenomena; a special-purpose system for defining human-like body descriptions and movements; and a system for modeling geological and meteorological objects, such as mountain strata, billowy clouds, and planets.

The general-purpose front-end language to DP3D allows an individual with little programming experience to specify the placement and characteristics of objects in a scene. Its simplicity lets the user dynamically change the attributes, size, and location of objects and immediately view them.

A physical simulation language provides another method of supplying information to DP3D. Given objects and a mathematical model of physical events that define the way the elements of a system interact, it simulates the changes to the state of the system over time. For example, a bouncing ball is affected by gravity and the slope and surface texture of the terrain it contacts. The simulation language supports differential equations, and models discrete events (changes occurring at specific time intervals), continuous events (changes occurring continuously), and a combination of the two. It outputs a file of movie instructions for DP3D.

LABAN provides yet another alternative for inputting information to DP3D; it is based on Labanotation, a dance notation language. Labanotation, a system for recording body movement, was developed in 1928 by Rudolf von Laban. It is based on spatial, anatomical, and dynamic movement principles. The notation is used by choreographers, anthropologists, physiotherapists, etc., to represent and animate movement.

LABAN accepts the definition and movement description of a human-like body, i.e., any jointed figure with any number of appendages. It assembles the figure according to the instructions in a body description file; the description includes the location of limbs and joints, initial orientations, and allowable movements. LABAN then analyzes and interprets a list of movements the figure is to execute. LABAN produces a movie file for DP3D.

GEOVIEW, a recently developed in-house software package, can simulate geological and meteorological objects. It is based on the recently published mathematical algorithms of Mandelbrot and Carpenter that produce fractals, i.e., random surfaces. To generate realistic looking scenes, Digital Productions has discovered a way to control the shapes of fractals so the known properties of such natural phenomena as mountains, craters, rocks, and clouds can be modeled with a high degree of accuracy.

G. DP3D Image Rendering Software

At the heart of its software system is Digital Productions' unique DP3D package, a library of sophisticated imagerendering and simulation routines. DP3D is tailored to the CRAY's architecture and runs under the CRAY Operating System (COS). The code is vectorized and optimized, which significantly reduces its computation time and improves its performance. DP3D also contains a set of routines that "virtualizes" the CRAY architecture so large amounts of data can be easily manipulated.

The software models the laws of physics and lighting from the physical world. DP3D models such natural phenomena as perspective, highlighting, shadowing, microfaceting, reflection, refraction, multiple light sources, volumetric transparency, translucency, surface texture, texture mapping, and complex model coloration techniques. DP3D will soon be able to project a ray of light through a transparent medium and have it follow the laws of physics appropriate to the index of refraction, as well as the opacity, translucency, specularity, and internal structures of a transparent medium.

DP3D represents an on-going software development effort. More enhancements will be added; imaging capabilities will increase and execution speeds will decrease. These enhancements will be gained by man-years of careful assembly language and Fortran coding and efficient graphics algorithms. DP3D can produce images of up to 250 000 polygons in 100 s on the CRAY-15; it can display 1 million polygons within only 6 min of computer time. The CRAY X-MP will work 4 times faster and will be able to support even more complex images.

Because DP3D is a general-purpose imaging package, it is capable of producing a medley of different visual styles. This feature is of interest to anyone requiring high-quality imaging capabilities. It not only has application in motion picture and television entertainment, but in military, industrial, and scientific/research imaging and simulation.

Digital Productions ultimately plans to license its software, as well as continue to market its high-quality imaging capabilities as a service. The software was conceived and designed to potentially integrate into other CRAY sites with minimal impact on existing databases and user analytical methodologies. There are no other systems currently available that are capable of supporting this level of complexity and quality.

H. Ramtek Displays

All objects have a number of attributes associated with them: color, texture, material type, transparency, reflectivity, etc. The technical director applies these attributes to the encoded object and views the fully rendered image on high-resolution Ramtek color raster displays. The production designer and technical director get immediate feedback; they can dynamically experiment with a variety of different attributes or make changes where warranted. The Ramtek 9400 and 9460 have resolutions of 1280 × 1024 pixels × 24 bits/pixel. Also in-house are Ramtek 9050 displays, which have resolutions of 512 × 512 × 11.

In conjunction with Digital Productions, Ramtek is developing a new high-quality graphics output display system and high-speed interface that will allow it to accept data directly from the CRAY IOS. The new architecture will allow the color screen to be updated in 1/8th of a second. Digital Productions will be able to support up to 48 displays on the CRAY.

Also developed in conjunction with Ramtek is a precision film recorder. The recorder has a resolution of 2048×2560 pixels \times 30 bits per pixel and is used in 35-mm production work. Images are photographed at a rate of 10 s per full color frame.

I. Digital Film Printer

The Digital Film Printer (DFP) is an integrated system composed of two film scanners and a film recorder. The DFP electronically scans, digitizes, and merges images with computer-generated special effects, and writes the composite picture out to its film recorder. The DFP can handle 35-mm film (3000×4000 resolution) or 70-mm VistaVision (4600×6000). Connected to the CRAY via the IOS, it is capable of recording 1 color pixel every 600 ns, or a complete frame every 10 to 15 s.

The DFP offers a dramatic breakthrough in quality, speed, and cost savings. It allows correction for generation color degradation and assures minimal generation loss, thereby enhancing image appearance and sharpness. Its cost/performance ratio is well below traditional methods, due to fast turn-around, low labor overhead, and decreased postproduction expenses.

Traditional photography uses a technique for film compositing known as blue-screen matting. This method merges two film strips, a foreground and a background image, using a mechanical optical printer. The foreground film has a blue background matte into which the background image is printed.

The operating ease and speed of the DFP radically alters current filming practices. The DFP can complete 1 min of blue-screen compositing in 6 h, whereas a mechanical optical printer takes 2 weeks to complete the process. Current compositing techniques require many intermediate processing steps to merge the images of two films; these involve the creation of color separations, negative prints, and positive prints. In fact, a total of 15 different films are necessary to make 1 composite. If more than 2 films are to be overlayed, time and materials increase dramatically.

A 2-week wait to view the results of a composite shot also requires that the cast, crew, and stage props remain on location. Using the DFP, post-production can be concurrent with principal photography, thus shortening post-production and expediting the picture into release. Important composites can be viewed daily while cast and crew are assembled. Sets do not have to be held.

The DFP can accept and process subtle variations in matte colors over time. It also releases the special effects team from the tedious limitations of manually operated mechanical optical printers, thereby giving feature films script and directorial freedom.

Unique capabilities of the DFP allow the special effects team to set optimum exposure, gamma, and color correction characteristics for each shot. This is done using analytic programs which graphically represent measured characteristics of the frame. The DFP can apply nonlinear corrections for various inherent film and CRT color distortions which have never been possible with existing film or video processes. This improved information on critical exposure levels means fewer errors, thereby avoiding costly reshoots.

Generation loss has been another limitation in opticals. The quality of reproduction with the DFP eliminates the need to use a larger film format than required for the effects being generated. VistaVision format is a part of the system and available when extremely high quality is desired. Digital signal processing is less susceptible to noise such as film grain and color aberrations and can be adjusted to reduce their effects.

III. THE FUTURE OF COMPUTER SIMULATION

Many of the imaging problems inherent in computer simulation have been solved. The mathematics exists for describing such physical properties as highlights, reflections, friction, gravity, etc.

Today's problem centers around storytelling. Today's automated methods model traditional techniques; keyframes are drawn, corresponding to scenes of a storyboard. The technical director must devote his total concentration to specifying the details of color, movement, texture, etc. There is a limit to the complexities with which a human can deal, which limits the quality that can be achieved in storytelling.

Within several years, Digital Productions foresees the computer being used as a creativity tool by film directors. The director will specify object descriptions and interactions, and the computer will animate the scenes, as well as the objects within the scenes, realistically. Sophisticated software, with built-in heuristics determined by experts in artificial intelligence, will account for character behavior, action, and reaction to real-world events. The effects of physical properties, including gravity, friction, and acceleration, can be modeled and relationships can be assigned to encoded objects. This algorithmic behavior can then be simulated where appropriate without further specification. Various conditions and responses can be stored in an intelligent, or algorithmic, database; automated decision-making techniques will be able to make the appropriate choices.

An algorithmic database would keep track of objects and their behaviors. The algorithmic behavior of an object will be automatically determined and realistically modeled for the given situation. Algorithmic behavior and algorithmic databases will automate many of the details with which a director or animator is involved. The script becomes the algorithm.

The most difficult problem will be the creation of believable human figures and human interaction. Currently, exaggerated expressions can be modeled, but subtle facial features cannot. The personality, persona, or psyche of a character must be accurately portrayed and penetrated to achieve total realism.

Expert directors have pursued the use of subtle behavior in developing characters and stories. Those who have mastered the art have worked up characterizations, i.e., behavioral studies, including attitude, expression, tone of voice, and speed of movement. Disney pioneered this technique with animated figures, and his characterizations of such personalities as Pinnochio and Snow White have touched audiences worldwide.



Plate 3. Moonscape. Science fiction scenes are rendered with total realism by Digital Productions. The planet in the background is artistically rendered with soft colors blended together in a rainbow effect to represent clouds. The beautifully imaginative terrain is modeled using a proprietary fractal package which produces random surface textures. These techniques are used to synthesize imaginary objects. Digital Scene Simulation^{5m} by Digital Productions, Los Angeles, CA © Copyright 1983. All rights reserved.



Plate 4. The CRAY-1, a self-portrait. This creative imaging concept uses the CRAY to simulate the CRAY. Digital Scene Simulation^{5m} by Digital Productions, Los Angeles, CA © Copyright 1983. All rights reserved.

Eventually, more complex, psychological behavior will also be modeled. A driver will know to stop his car at red traffic lights; a person will know how to walk, run, and jump; a baby will know how to cry. Lighting will be automatic; the intelligent system will know the difference between daylight, moonlight, and room lights.

Digital Productions has already started investigating current directing methodologies and has started designing programs for automating much of the processes. Database management, artificial intelligence, psychology, physiology, kinesiology, physics, and natural language processing are being studied. The future of interactive input techniques, both in computer graphics and digital sound, are being examined. Pre-production to post-production procedures are being scrutinized.

Digital Productions is creating new realities and exploring new areas of simulated visualization. Research activities, combined with the power of the CRAY X-MP supercomputer, will open new and exciting forms of entertainment, artistic freedom, and communication. Ultimately, computer graphics will be used to conjure up images that can express ideas and events better than words.

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Plate 1. CRAY Temple—front view. This Temple was one of the first objects designed and encoded at Digital Productions to publicize the sophisticated software being developed on the CRAY supercomputer, acquired in April 1982. This computer generated image demonstrates such real-world properties as highlighting, shadowing, and light diffusion. Digital Scene Simulationsm by Digital Productions, Los Angeles, CA © Copyright 1983. All rights reserved.

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Plate 2. Fuji Balls. These colorful balls are patterned after Japanese ornaments known as Fuji balls. Digital Scene Simulationsm by Digital Productions, Los Angeles, CA © Copyright 1983. All rights reserved.

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Plate 3. Moonscape. Science fiction scenes are rendered with total realism by Digital Productions. The planet in the background is artistically rendered with soft colors blended together in a rainbow effect to represent clouds. The beautifully imaginative terrain is modeled using a proprietary fractal package which produces random surface textures. These techniques are used to synthesize imaginary objects. Digital Scene Simulationsm by Digital Productions, Los Angeles, CA © Copyright 1983. All rights reserved.



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