Annual Report for 1997

NSF Science and Technology Center
for Computer Graphics and Scientific Visualization

Brown University

California Institute of Technology

Cornell University

University of North Carolina

University of Utah

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1. Executive Summary

The major goals of our STC are to establish a better scientific foundation for future computer graphics and to help create the basic framework for future interactive graphical and multimedia environments. As we move onto the next generation of computing systems, we will need to improve computational speeds for display, incorporate physical behavior into our models, extend the definitions of our models to incorporate manufacturing processes, move beyond the current generation of WIMP (windows, icons, menus, and pointing) user interfaces into post-WIMP user interfaces, scale our systems to handle more complex environments, reduce design cycle times, and store, manage, access, and transmit larger amounts of data. Finally, it is necessary to guarantee the validity and accuracy of our simulations according to each application's needs, particularly in medical, scientific, and engineering areas.

To achieve these goals, our comprehensive strategic plan is focused on four basic areas of computer graphics: modeling, rendering, user interfaces and high-performance architectures. We have made significant progress in each of these domains in the past year. Two basic applications have helped focus and direct these areas: scientific visualization and telecollaboration. The Center's research thus expands applications' capabilities while being focused in useful directions by the needs of these applications. The Center also works to improve standards efforts. Its broad knowledge of the state of the art of computer graphics continues to prove helpful in directing standards efforts towards good solutions while preventing premature standardization in open research areas.

The principal characteristic of our research is improvement in the accuracy and fidelity of models used in computer graphics. This goal requires generality in our representations and simulations. As contrasted with the previous two decades of computer graphics research, we are now focusing on experimental validation rather than simply "looking good." We have built test environments and models and are comparing simulations to measured physical behavior in order to determine the precise accuracy of current approaches. This traditional strategy of experimentally validating scientific hypotheses is necessary to establish the fundamental bases for future improvements in computer graphics technology. But this strategy is relatively new to the field of computer graphics and represents a significant shift in methodology.

A second characteristic is our focus on efficiency. The field is moving inexorably towards more complex environments and their increasing demands for interactivity and time-critical computing, especially for virtual environments, in which significant lag can cause motion sickness. Time-critical computing (or TCC) is the idea that an approximate result on time is better that a fully accurate result too late. Procedures for improving computational speeds and computing within a known length of time depend on predictability and on the determination of error bounds. Thus, the goals of accuracy and computational efficiency are intimately related, indeed inseparable. The drive for efficiency leads to both a better scientific foundation and a stronger framework for future applications.

Finally, while it is helpful to organize the research of the Center by dividing it into categories, a great deal of synergy and overlap exists between the various research areas. For example, user interface technology begins to affect modeling technology when scientists developing new modeling methods strive to develop techniques with more user-oriented parameters. Many of the high-performance architecture projects are driven by needs in scientific visualization

Our Center is distributed across five states and three time zones, has no single dedicated building, and operates as a virtual collaboratory aided by a custom communication infrastructure built on dedicated T-1 lines. Through collaborative efforts, shared research, common classes, and group discussions the Center continues to grow unified; even with little face-to-face physical contact, many of the participants in the Center have become true colleagues.

2. Research Accomplishments and Plans

2.A Modeling

A.1 Participants

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A.2 Recent Accomplishments and Plans

Modeling remains a key area of Center and computer graphics research. Advances in model representation and creation have driven research in rendering, interaction, visualization and performance while our advanced modeling and manufacture capabilities facilitate telecollaboration research. Our goals in modeling are to advance our abilities to create, modify, and represent increasingly complex and realistic models.

Sketch-N-Make

In the largest single collaboration in the Center, Brown, UNC, and Utah have developed a prototype *art-to-part* system [bloo98] that allows users to quickly design non-trivial, dimensioned, machined metal and plastic prismatic parts. These parts can then be automatically manufactured on a machining center with the aid only of a technician who prepares and loads the stock and cutting tools.

Over the past year, we both integrated and extended Brown's gestural UI framework to work effectively with Utah's Alpha_1 modeling system. In addition, we developed a family of stereotyped process plans, *process plan templates*, that work in concert with a restricted, but non-trivial class of mechanical parts -- prismatic parts with a single machining access direction. This combination allows high-level UI geometry to be transformed automatically into high level mechanical features that are placed within the context of an appropriate process plan template. These features may then be used to automatically derive computer numeric control (CNC) code that drives a machining center during manufacture.

Engineered Modeling

Large, complex design problems require new methods to create and organize the models. We have developed a distributed system for design, the DesignWeb, that integrates the Alpha_1 CAD system with the Internet world-wide-web, allowing for hierarchical representation and modification of a model. A web browser plug-in permits remote 3D viewing of geometry, while java applets allow editing of the design documents. This hierarchical, hyper-linked design document style scales with increasingly large models better than a linearly structured design document. This design style has been tested on to explore, record and design of ceramic composite alternatives for turbine blade design.

In a related project, we have applied software engineering ideas to design by creating new data structures for complex modeling [jaco98]. These structures perform similarly to object-oriented programming objects --- they define the interface between objects so that the interior details can remain hidden. These interface structures lend themselves to reusable design, collaborative design, and large-scale design.

Physically-Based Modeling

We have developed a high-level motion control mechanism, embodied in event- based "Response Graphs." Response Graphs allow the system's event responses to vary over the course of a simulation, providing support for complex and evolving behaviors. Multiple hierarchically-ordered response graphs are supported as well. The system chooses actions based not only on the most current event detected, but also on the entire history of events that occurred in the simulation up to that current simulation time. The event history data structure allows us to formulate general event predicates. This provides a more sophisticated decision-making mechanism for determining how to respond to events, and sequences of events.

Event predicates and actions will be an important part of our event handling system. The predicates are Boolean expressions based on the simulation's event history. Their values determine which actions are executed in response to future events. We allow the user to explicitly specify both the predicates and actions of the simulation. This provides significant control over the behavior of the simulation, with greater flexibility and predictability than previous systems. By enabling explicit predicates and actions in our event handling system we give the user explicit control over the behavior of the system in response to external events. By carefully specifying the appropriate combinations of detection routines, predicates and actions, the user has a better chance of obtaining a desired sequence of actions. To help develop methods for defining expressive motion of human figures, robust representations of dynamic contact between rigid and flexible objects, and simulations of instantaneous "impulses" when composite constrained objects collide with one another, we plan to create a PODE (piecewise ordinary differential equation solver) that utilizes general physically-based state machines. Additionally, our efforts in developmental modeling and artificial life test-beds will be aimed at methods to unify flexible, rigid, and fluid systems of objects.

Interactive Physically-Based Modeling

Many current modeling tools do not correspond to a physical action in the real world. We wish to take advantage of the intuition people possess about real-world activities. In this direction, we have created a surface modeling system that allows interactive application of forces, such as spring forces, to a model.

The model deforms in physically plausible ways. Constraints maintain portions of the model that are satisfactory and add another expressive means of designing shape. The combination of forces and constraints permits powerful, yet intuitive, tools for surface design.

Virtual Prototyping of Assemblies

Our development of a force-feedback environment for interacting with CAD models has progressed to the point where a designer can trace along, move [thom97], and grasp trimmed NURBS models [holl97]. In addition, we have developed methods for manipulating simple assemblies to test assembly motion [nahv98]. This work has spurred research on time-critical minimum distance computations, fast geometric interrogation algorithms, and 3D interaction. These operations provide the groundwork for a design system where complex assemblies can be designed and tested without having to resort to physical prototypes.

3-D Scan Conversion of Solid Models into Distance, Closest Point, and Color Volumes

We have completed the design and implementation of algorithms for 3-D scan converting Constructive Solid Geometry (CSG) models into distance, closest point and color volumes [bree98]. For a variety of volume graphics applications it is necessary to convert conventional geometric models into a volumetric representation. Volume graphics applications, such as 3-D model metamorphosis and offset surface generation, require volume models as input. Our particular applications utilize distance, color and closest point volumes. A distance volume is one where the shortest distance to the original scan-converted is stored at each voxel. A closest point volume stores the actual [X,Y,Z] location of the closest point on the original model to the voxel location. For each voxel, a color volume stores the color of the original model at the closest point from that voxel.

Generating Shaded Offset Surfaces from CSG Models

Once a distance volume is generated from a CSG model, an offset surface of the CSG model is easily generated by calculating the iso-surface at the offset value. Algorithms have been developed and implemented which shade these offset surfaces using the closest point and color volumes produced from the original CSG model. Our scan conversion technique provides more accurate volumetric representations than previous methods by evaluating the CSG model in object space before calculating the closest point. Additionally, the accuracy of our method is independent of the resolution of the final volume, allowing the user to define the time/accuracy trade-off.

Metamorphosis of 3-D Solid Models using Level-Set Methods

In collaboration with Dr. Ross Whitaker of the University of Tennessee - Knoxville, we have tested and refined methods for 3-D model metamorphosis (morphing) [whit98]. Here, one solid model is smoothly transformed into another using a level-sets model developed by Dr. Whitaker. The method has been refined and used to create two morphing sequences. Our method improves on previous methods because it requires little or no user input to produce a morphing sequence. Additionally, our method easily and naturally copes with changes of topology. A user may morph models of different topologies, with the level-set model naturally handling the change in topology during the morph. Level set models are active and automatically change one surface into another in a process which minimizes an energy functional on the surface. A user may provide additional input to direct the morph to evolve in a desired way, but no input, other than the initial and final models, is required to generate a "reasonable" result. We are unable at this time to smoothly change the surface color of the objects as their shape changes. In the coming year we will investigate methods for interpolating the surface color of the initial and final objects. While methods for shading the surface of offset surfaces have been developed, they are time-consuming and inappropriate for generating a sequence of images needed for animation. The major issue to be addressed is anti-aliasing of the relatively low-resolution color data that is generated in the scan conversion process.

Additionally, we plan to investigate methods for morphing the surface color while the object shape is also morphing.

Polyhedral Morphing Using Feature-Based Surface Decomposition

A different project morphs between two homeomorphic 3D non-simple polyhedral models [greg98b]. It allows the user to specify corresponding feature pairs on the polyhedra and a morphing trajectory between them with a simple and intuitive user interface. From this information we generate a new polyhedron which has the combined topology of the original two, and a trajectory for each vertex to travel during the morph. The user interface allows fine control over the resulting morph.

Appearance-Preserving Simplification

We have developed an appearance-preserving simplification algorithm that generates a low-polygon-count approximation of a model and also preserves the appearance [cohe98]. We convert the input surface to a representation that decouples the sampling of position, color, and curvature. The simplification algorithm employs a new texture deviation metric, which guarantees that these maps shift by no more than a user-specified number of pixels on the screen. We have applied our simplification technique to several large models, achieving significant amounts of simplification with little or no loss in rendering quality.

Model Extraction

One way to construct complex models is to acquire shape and reflectance information from images of real-world scenes and objects, as discussed under Rendering. To assure that gathered data is suitable for the intended applications, we will continue to use an MRI machine to create dynamic models via 3D scanning. We are establishing a teleological pipeline to gather high-resolution anatomical MR data, classify tissues, reduce artifacts, make geometric and dynamic models, and then visualize them [laid98b].

Mathematical Representations

To understand the complex requirements of modeling and explore more general mathematical approaches, we will develop new methods and modeling primitives and also use known mathematical methods in new computer graphics applications. This relates to projects at all sites of the Center, including:

- Differential geometry applied to computer graphics
- Wavelets and multiresolution representation of surfaces
- Representing and manipulating complex models of manifolds and/or torn surfaces
- Inverse methods for determining potential functions
- Mathematical methods for inverting the rendering equation
- Mathematics of image interpolation for use in model-less rendering
- Further work in correction of geometric perceptual distortions in images
- More general norms for measuring similarities between images

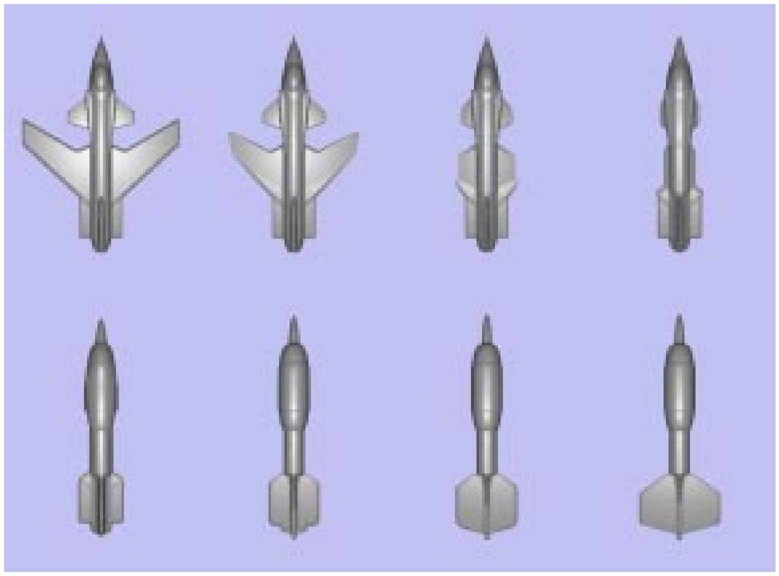

Figure 1: In collaboration with Dr. Ross Whitaker of the University of Tennessee-Knoxville, the Center is developing methods for automating 3-D model metamorphosis (morphing). These methods are based on level-sets libraries developed at Tennessee. Here we show a 3-D model of an X-29 jet transforming into a model of a dart.

Figure 2: Our appearance-preserving model simplification process reduces the number of polygons needed to display a model while maintaining the visual appearance. The ability to trade precision for rendering speed increases the complexity of the models we can work with.

2.B Rendering

B.1 Participants

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B.2 Recent Accomplishments and Plans

Since its inception, a primary goal of the center has been to develop physically based lighting models and perceptually based rendering procedures for computer graphics to produce synthetic images that are visually and measurably indistinguishable from real-world images. Another goal has been to develop rendering methods that generate images that are effective in communicating shape or structure. A third goal of the center has been to make the display of highly complex images more efficient, particularly using "image-based rendering" (IBR) techniques. Significant progress has been made on all these fronts within the center.

This collective research effort on rendering now spans most center sites and serves as one of the bases for our center-wide collaborative effort on telecollaboration.

B.2.1 Physically Based Rendering

If we can generate simulations that are guaranteed to be correct, they can then be used in a predictive manner. Physical simulation fidelity is a primary concern in order to use computer graphics algorithms for testing and developing printing technologies, photographic image capture, the design of display devices, and algorithmic development in image processing, robotics and machine vision. The center has articulated and refined a framework for global illumination research that subdivides the system into three parts: the local light reflection model [shir97], the energy transport simulation, and the visual display algorithms. The first two parts are physically based and the last is perceptually based. To verify the accuracy of the simulations, the center has assembled a sophisticated light measurement laboratory to test and compare the results of our simulations [patt97]. The results of this research have been presented in a special SIGGRAPH session in August 1997 [gree97]. This framework outlines an objective view of error that will allow physically-based techniques to become efficient enough to be useful in practice without sacrificing accuracy.

Light Reflection Measurement and Modeling

The bidirectional reflectance distribution function (BRDF) of a material describes how light is scattered at its surface. The accuracy, physical correctness, and computational efficiency of a representation of reflectance data will all contribute to the quality of the resulting images. In an ongoing effort to measure reflectance properties of surfaces, we have further calibrated and automated our custom-built gonioreflectometer. We have measured a set of materials and made the light source spectra, filter and lens transmission spectra, and full bidirectional reflectance distribution functions (BRDF's) available to the research community. We are now researching methods to speed up the reflectance measurement process, and we have developed a technique that is based on traditional cameras rather than a custom-built device [mars98]. Although we lose some accuracy in wavelength-based information, this image-based approach is significantly faster and provides many more data points. The results of the technique have been validated against traditional measurements.

Despite the dissemination of the measured data, there is a need for a representation of the scattering function of an arbitrary material. We have recently introduced a new class of primitive functions with non-linear parameters for representing light reflectance functions [lafo97]. The functions are reciprocal, energy conserving and expressive. They capture important phenomena such as off-specular reflection, increasing reflectance and retro-reflection. The resulting representation is simple, compact and uniform. It can be applied efficiently in analytical and Monte Carlo computations. The model is only about 30% slower than the ubiquitous Phong model and will be significant for simulating material behavior in real-time applications.

Acceleration

The majority of computation time in ray tracing and radiosity programs is spent executing a few small "kernel" routines. By collecting statistics as these kernel routines are executed for various data sets, we can observe patterns that will guide our optimization of the functions. We will then reorganize our programs and data structures so that they eliminate redundant computation, branch more efficiently, and avoid cache misses that slow down execution time. While many generalized algorithmic improvements have been made to these functions in the past, we can optimize them even further by tuning them to specific applications, data sets, and hardware platforms. These "local" speedups in kernels of our programs must be coordinated with efforts to take advantage of parallel computing, shared memory, and large on-chip cache.

Perception-Driven Global Illumination Computation

Because of the complex processing in the human visual system (e.g., visual adaptation, pattern masking), the visual system can be forgiving to larger errors in illumination computation. If we can compute a perceptually accurate solution instead of a physically accurate one, the computation time can be much less expensive.

As an initial effort we have developed a progressive path-tracer driven by perceptual error metric. Like a ray-tracer, path-tracing is a view-dependent image space algorithm devoting a very large amount of computational effort towards indirect illumination computation. Indirect illumination is known to be a smoother component of the total illumination function [greg98a]. We exploit this smoothness by computing this indirect illumination in a coarser image space and interpolate the resulting illumination over the full space. As the visual complexity of the scene increases we expect an order of magnitude improvement in computational speed.

We developed a model of visual masking [ferw97] that is useful in both image compression and assigning rendering parameters. In addition, we have developed a new visual model for realistic imaging based on a multiscale representation of pattern, luminance luminance, and color processing in the human visual system [patt98a]. We incorporated the model into a tone reproduction operator that maps the vast range of radiances found in real and synthetic scenes into the small fixed ranges available on conventional display devices such as CRT's and printers. The model allows the operator to address the two major problems in realistic tone reproduction: wide absolute range and high dynamic range scenes can be displayed; and the displayed images match our perceptions of the scenes at both threshold and suprathreshold levels to the degree possible given a particular display device. The model is general and can be usefully applied to image quality metrics, image compression methods, and perceptually-based image synthesis algorithms. Recently we have applied the model to the problem of cross-media reproduction of color appearance.

We believe even greater advances are possible by developing computational models of visual processing in three dimensions. One of the first projects we plan to undertake is to look at visual sensitivity to the geometric and photometric distortions that occur when an image is warped to a new viewpoint in image-based rendering schemes. By understanding how sensitive we are to these distortions under different conditions, we should be able to develop fast hybrid model-based/image-based renderers that only re-render objects when the warping distortions are greater than visual thresholds (see below).

B.2.2 Image Based Rendering (IBR)

In the pursuit of photorealism in conventional polygon-based computer graphics, models have become so complex that most of the polygons are smaller than one pixel in the final image. Formerly, when models were simple and the polygons were large, the ability to specify large, coherent regions with only three points was a considerable efficiency in bandwidth and computational requirements. It is time to rethink the graphics pipeline in terms of pixel algorithms.

We are investigating an alternative approach that represents complex 3D environments with sets of images. These images include information describing the depth of each pixel along with the color and other properties. We have developed algorithms for processing these depth-enhanced images to produce new images from viewpoints that were not included in the original image set. Thus, using a finite set of source images, we can produce new images from arbitrary viewpoints. We are also investigating an extension of the conventional pin-hole/planar-image camera model to cameras with smoothly varying centers of projection [rade98]. This representation allows us to rethink the form of the source images used for image-based rendering.

Captured images are a scalar representation of the scene and inherently contain both the diffuse (view independent) and specular (view dependent) components. We are developing a technique for image warping with view-dependent specular highlights. Our method requires a small number of input images with depth information captured at known viewpoints. It reproduces view-dependent lighting by fitting a simple reflectance model to objects in the input images.

Center work on the use of images for rendering also includes research on image-based impostors for architectural walkthroughs. We have taken advantage of the natural structure of buildings to extend previous work on cell and portal culling by replacing geometry visible through doors and windows with images. We have progressed from using simple textures [alia97] to using depth images warped with McMillan and Bishop's algorithm [raff98a]. Our current approach employs layered depth images to combat some of the artifacts of 3D warping [pope98]. A summary of these investigations will appear in [raff98b].

Using images to represent complex 3D environments will enable immersive systems for real places, enabling a new class of applications in entertainment, virtual tourism, telemedicine, telecollaboration, and teleoperation. From a practical perspective, using images implies a hybrid with a conventional graphics system. A process we call "post-rendering warping" [mark97a] allows the rendering rate and latency to be decoupled from the user's changing viewpoint. Just as the frame buffer decoupled screen refresh from image update, post-rendering warping decouples image update from viewpoint update. We expect that this approach will enable immersive 3D systems to be implemented over long distance networks and broadcast media, using inexpensive image warpers to interface to the network and to increase interactivity (see **Performance - Image-Based Rendering**).

There are many challenges to overcome before the potential advantages of this new approach to computer graphics are fully realized. First, we must develop algorithms and sensors for real-world data acquisition. We are currently testing an image-capture system that combines a laser range camera with a high-resolution color camera and registers the results to provide color depth images of real environments. Second, we need methods for compositing multiple source images from different viewpoints. The challenge is to produce a single output image with no artifacts left from occluded areas in one or more of the source images. Finally, we need new hardware architectures that are not designed exclusively for conventional triangle-based graphics. This may finally allow real time rendering on very simple hardware.

B.2.3 Non-Photorealistic Rendering (NPR)

The purpose of non-photorealistic rendering is to use computers to produce images that have the same merits as image drawn by human illustrators. Such renderings often prove superior to realistic images for applications where geometric structure or high-level ideas are communicated.

The JOT non-photorealistic renderer [mark97b] can help make comprehensible but simple pictures of complicated objects by employing an economy of line, deliberately trading accuracy and detail for speed. The JOT renderer uses a method for determining visible lines and surfaces which is a modification of Appel's hidden-line algorithm, with improvements that are based on the topology of singular maps of a surface into the plane. The system has been demonstrated with several non-photorealistic rendering styles, all of which operate on complex models at interactive frame rates.

Following up on our interactive NPR for polyhedral models, we have developed a system for interactive NPR for implicit models [brem98]. Like the polyhedral system, the renderer probabilistically locates silhouettes. Silhouettes are shaded based on analytic expressions for the cross-silhouette curvature.

We have also developed algorithms that simulate precise human technical illustrations [gooc98]. Human technical illustrators follow certain visual conventions that are unlike Phong shaded or wireframe renderings, and the drawings they produce are subjectively superior to conventional computer renderings. These illustration conventions were implemented in the Alpha_1 modeling system to create a new method of displaying and viewing complex NURBS models. In collaboration between Utah and Brown University, this new cool-to-warm shading and the metal shading were added to the JOT NPR program.

Figure 3: This figure illustrates how the multiscale visual model can be applied to the problem of displaying high dynamic range scenes on low dynamic range devices like CRT's and printers. The scene has a dynamic range of approximately 10,000:1 from highlights to shadows. The printed page has a dynamic range of less than 50:1. A typical linear mapping of the scene luminances produces the image shown on the left, which shows burnout and blackout in the bright and dark regions. Using a mapping based on the multiscale visual model produces the image on the right, which preserves detail across the full range of scene luminances and is much closer to our visual experience of the scene.

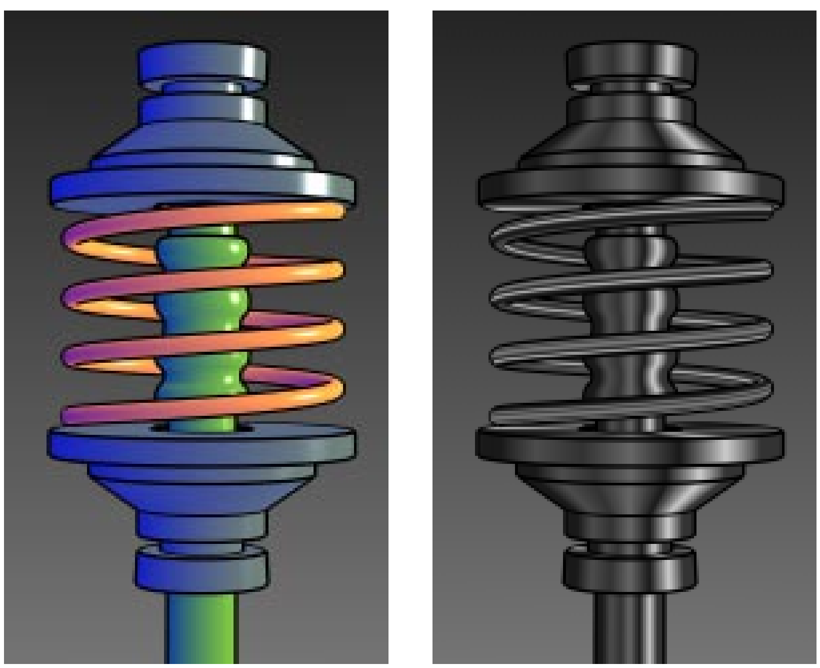

Figure 4: These images were automatically generated to resemble images drawn by an illustrator. The image on the left incorporates cool-to-warm shading with edge lines to emphasize its shape and distinguish features. Applying the non-photorealistic technique of alternating dark and light bands across the image on the right conveys its metallic material properties. Applying these illustration methods produces images that are closer to human-drawn illustrations than those generated by traditional computer graphics approaches.

2.C Interaction

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C.2 Recent Accomplishments and Plans

In a wide range of graphics applications, from geometric and mechanical modeling to scientific visualization to telemedicine, interaction is a throttling technology: if users could convey intent faster, the results would come faster. And because the cost of the user's time is steadily increasing relative to the cost of the computing hardware, making the user more efficient is of paramount importance. Our ten-year goal is to increase user fluency by developing novel interaction technologies, both hardware and software, in an array of application domains. In particular, we are interested in new interaction methods for geometric and mechanical modeling, scientific visualization, and other conventional graphics research areas, but also in experimenting with novel interaction software and hardware in more speculative domains like music editing, free-form shape creation, and telemedicine.

Gestural Modeling

Our original gestural-sketching system, Sketch, only supported conceptual modeling, with no support for specifying numerically precise models, such as those needed for MCAD. As part of the Sketch-n-Make system (**see Modeling - Sketch-N-Make**), we are extending Sketch to allow the specification of precise MCAD models, while still allowing rapid modeling. We have partly achieved this goal, but we feel that the modeling speed can still be improved. The initial results are promising --- we have developed a system [bloo98] in which certain classes of mechanical models can be built in a true art-to-part process, starting from a gesture-based construction of a model and ending with a metal piece with only minimal intervention by a technician.

We have also extended Sketch to allow multiple users to share a workspace, addressing the problems of contention -- who gets to pick up a piece when two users grab it at once, and who gets to edit an object when two users start editing at once? Such steps are essential for the Office of the Future collaboration project.

Finally, we have extended Sketch to allow preliminary multimodal input, so that a user at an ActiveDesk (or similar device) can interact with objects in both a 2D mode (as in the original Sketch) and in 3D, where the user wears stereo-goggles for a 3D view, can use a 3D-tracked device to position and orient an object, and a 3D-tracked pen to "paint" the object in space.

Gestural Interfaces

We have applied some of the ideas in our work on sketch-based modeling for 3D objects to create a system for gestural editing of musical scores [fors98a]. More than a simple "draw a note on the staff" model, our system takes variations on simple gestures to indicate various qualities, so that, for example, the size of a note indicates loudness, and spatial proximity of notes is used for grouping into chords. Because of the variability of input, the gesture-recognition component of the interface is richer, involving multiple recognizers each interpreting the input and comparing the likelihood of results. The resulting system is easy to use and intuitive.

Haptic Interfaces

We have implemented the first stages of a project to add force feedback to the X desktop [mill98]; this project is in particular distinguished from efforts of other researchers by the use of a 3 DOF force output device with a 2D GUI. Very preliminary pilot studies in the course of evaluation of the interface indicate that this direction has promise. One of the key aspects of this work is the use of haptics to do more than merely literally simulate the real world, in contrast to much other haptic work.

See also the **Modeling - Virtual Prototyping** section for a discussion of adding a haptic interface to a modeling environment.

Multimodal Interfaces

We plan to investigate the use of multimodal interfaces for 3D graphics applications. We plan to explore different combinations of inputs that include hand posture and gesture recognition, speech recognition, and handwriting recognition. We have two main goals for pursuing this research. The first goal is to provide the user with a natural and intuitive interface that resembles the way people communicate with others. The second goal is to use more than one mode of input to increase overall recognition accuracy of our interfaces.

Speech recognition

During the past year we have worked on computer speech recognition, speech production, and sound localization. We have developed an articulation-based recognizer based on factorial hidden Markov models and trained the system on measured data. We are now developing techniques to analyze and optimize the interaction of early and late processing components in recognition models, and investigating spatialized sound reproduction techniques for virtual environments. This work may, if sufficiently successful, be incorporated into our multi-modal VR interfaces research instead of the off-the-shelf speech system that we have been using until now.

In the coming year we will continue to work on our articulatory recognizer. Its performance will be evaluated relative to conventional systems, both in terms of recognition rate and ability to reject non-speech sounds.

Workbench

The responsive workbench offers a unique way for researchers to view and interact with scientific models and data. In the past year, our research in using the workbench for visualization has focused on interaction methodologies and metaphors that can better assist researchers in analyzing data. Working closely with NASA's Jet Propulsion Laboratory (JPL), we have begun developing an application to assist with trajectory planning and visualization for mission design, such as the upcoming NASA Genesis mission (launching in 2001). Interacting directly with end-users allows us to continually refine the interaction tools offered by the Workbench metaphor. Responding to users' comments we have also designed and implemented a preliminary, monocular version of the workbench using two angled display surfaces and plasma display panel technology. This new design offers increased working volume while using a much smaller footprint than the current workbench.

In future research, we will continue to design interaction tools and metaphors through our collaboration with JPL as well as to further evaluate the advantages of alternate virtual environment designs. We will continue to use our testbed applications like the JPL trajectory planner to evaluate new interaction toolkits as well as demonstrate the practical benefits of VR technology. Additionally, we will continue to examine the potential use of plasma display panels as a Virtual Reality medium.

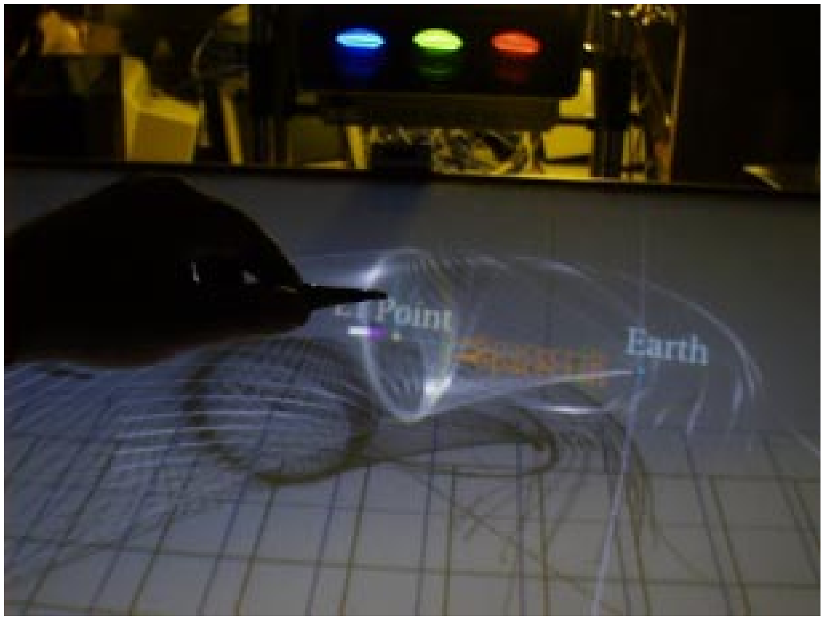

Figure 5: Center researchers are working with Dr. Martin Lo of the Jet Propulsion Laboratory, using the Responsive Workbench as an interactive visualization environment for time-dependent 3D orbits and trajectories. Here we show movement of the NASA Genesis spacecraft in an orbit around Lagrange point L1, for the year 2001 mission to return samples of the sun's corona.

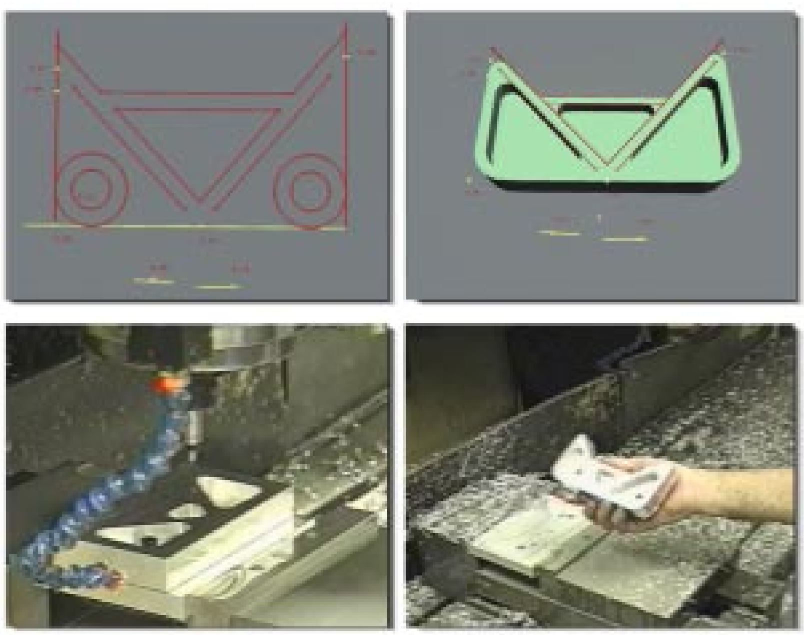

Figure 6: In the Sketch-n-Make system the user gesturally creates 2D construction geometry, extrudes a 3D model, and mills a block of metal to produce a final part, with the aid only of a technician who prepares and loads the metal stock and cutting tools.

2.D Performance

D.1 Participants

Faculty

Alan Barr, Gary Bishop, Vernon Chi, Henry Fuchs, John Hughes, Anselmo Lastra, Lars Nyland, Peter Schroeder, Greg Welch

Staff

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Graduate Student

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Collaborators

Leonard McMillan, MIT Laboratory of Computer Science

D.2 Recent Accomplishments and Plans

Performance-related research in the Center concerns a set of enabling technologies that are essential to real-time graphics and visualization, ranging from input to rendering to display. We work on innovative tracking methods for handling user head and hand input, leverage UNC's high-speed graphics engines and other techniques from all the sites to render images faster and more effectively, and develop new 3D displays that provide the proper images to each eye of each user.

The importance of high performance in an interactive system is that it can provide transparency to the user. For example, using high quality rendering delivered by fast graphics engines, a scientist is not distracted by aliasing artifacts while interacting with molecules. With accurate tracking, a physician need not compensate for delayed display updates when moving a transducer during an ultrasound examination. And improving displays, increasing frame rates, reducing lag and accurately registering objects allows users to spend more time in a virtual environment without simulator sickness.

Tracking

Precise, unencumbered tracking of a user's head and hands over a room-sized working area continues to be an elusive goal in modern technology and the weak link in most virtual reality systems. Current commercial offerings based on magnetic technologies perform poorly around such ubiquitous, magnetically noisy computer components as CRTs, while optical-based products have a very small working volume and often need to maintain line-of-sight access between tracking cameras and illuminated beacon targets (LEDs). Recent commercial offerings include promising inertial-acoustic hybrids, but these also require the placement of acoustic "beacons" throughout the working area, and the accuracy is not yet sufficient for certain augmented reality applications in which the user's views of the local surroundings are augmented by synthetic data; e.g., location of a tumor in the patient's breast, or the removal path of a part from within a complicated piece of machinery.

For years UNC has been pursuing a variety of new approaches to head and hand tracking, principally with DARPA funding but also with Center support. Our latest system, the UNC HiBall tracker, is an optical tracker with a golf-ball sized tracking target that is either worn on the head or held in the hand. The target consists of a miniature cluster of six optical sensors looking out onto a specially outfitted room whose ceiling tiles have been embedded with infrared LEDs. The system, which is being used regularly in other graphics and visualization applications at UNC, operates anywhere in a large (20 x 20 foot) room, and exhibits resolution of under 1*mm* with 2KHz update rates and excellent stability. Furthermore, a recent change to a different mathematical model of human dynamics offers the promise of an order of magnitude greater position and orientation resolution during very slow movement, such as when a physician is using augmented reality to visualize a tumor in a patient.

The current HiBall system owes much of its existence to STC funding and a satisfying collaboration among UNC, Utah, Brown, and Caltech. The excellent results of the past years encourage us in our current efforts to develop systems that can operate with limited or no infrastructure, e.g., outdoors. First, our telecollaboration work on the Office of the Future has inspired some new ideas for tracking that make use of infrastructure that is already being used for graphics and visualization. For example, projectors and cameras used for dynamic scene capture and display could also be used for tracking participants. We have begun preliminary experiments and the results, while not complete, are very encouraging.

Graphics Systems

The Center uses the DARPA- and NSF-funded advanced computer graphics engine PixelFlow which, stored at UNC, was demonstrated at SIGGRAPH97 rendering over thirty million triangles per second. The Center-wide availability of such hardware, together with our infrastructure, enables us to undertake graphics and visualization projects that we would otherwise be unable to tackle. Our previous machine, Pixel-Planes 5, was used in a Utah/UNC collaboration to render complex models in real-time and in a Cornell/UNC collaboration to improve shading interpolation by using higher-order polynomial approximations.

PixelFlow is expected to provide the same synergistic advantages for Center-funded projects as did Pixel-Planes 5. It is also expected that the design of the successor to PixelFlow, ImageFlow, will be influenced by Center project needs, as was PixelFlow. ImageFlow, an NSF/DARPA funded grant, will be based on images as well as polygonal primitives.

Analog VLSI

Caltech has patented several algorithms that have eliminated barriers to analog VLSI system design. The goal is to create mass-producible low-power silicon structures for real-time graphics operations for modeling, rendering, tracking, model acquisition, and interaction that are several orders of magnitude faster and more reactive than today's digital systems. We are now ready for the design and construction of the first analog VLSI computer graphics system.

Image-Based Rendering

Image-based rendering is an important new approach to rapid rendering of highly realistic images (see **Rendering - Image-Based Rendering**). A typical image-based approach is to use cameras to collect real-world information, and then to use discrete reference images to create new views within a continuous range by interpolation, typically image warping. The advantage of image-based rendering over polygon rendering is the ability to display natural, real-world (as well as synthetic) scenes at rendering speeds that are independent of scene complexity.

The Center became an early leader in image-based rendering with the plenoptic modeling work of Leonard McMillan and Gary Bishop at UNC, and continues to pursue the field vigorously. In addition to developing both theory and algorithms, we are beginning work on ImageFlow, a hardware architecture that will display high-resolution, highly detailed views of natural and synthetic scenes at interactive rates using image-based rendering techniques.

A particularly exciting application of image-based rendering is post-rendering warp, which promises to speedup renderers originally generating only a few frames per second. The fundamental idea is to take the combination of image and z-buffer from the renderer and warp it to nearby user positions while waiting for the next image from the renderer. The current solution to the most serious problem of such image warping, namely gaps caused by newly unoccluded regions for which there is no information, is to use two range images rather than one, each warped to the current user location, and then merge them. To avoid doubling the burden on the original renderer, the two range images used are the last two generated by the renderer, and to avoid the problem of these having been generated for places far away from the user's current location, the renderer is asked to generate an image not for the current location, but for the location where the user is predicted to be at the next renderer's frame time. The results from the current software (non-real time) implementation of post-rendering warp are so startling that viewers typically have a hard time detecting the difference between post-rendering and standard per-frame rendering.

We are investigating an extension of the conventional pin-hole/planar-image camera model to include generalized cameras with multiple centers-of-projection [rade98]. This camera model provides information about the scene from more than the single vantage point available in traditional images. Each column or pixels in the extended image contains samples from a slightly different center of projection than the columns to its immediate left and right. We have demonstrated both acquisition and display of real-world scenes using this new image representation.

Another important part of IBR is obtaining depth for the image on a per-pixel basis. Many researchers have relied on vision techniques for obtaining depth. We, however, have a more active approach, that of using a laser range-scanner. At UNC a system has just been built, consisting of a range-"finder" camera, a scanning mirror and a panning unit. This allows us to take 25,000 range samples per second, or fifteen minutes for a very detailed measurement of an environment. We're currently investigating registration of the range-scanner data with color reference images. Preliminary results are promising and the real-time warping of these high-resolution images is possible on the PixelFlow Computer at UNC.

Despite promising results in image-based rendering, there is still considerable uncharted territory in this relatively new area. We plan to improve the current techniques used for real-world image acquisition via cameras. We will develop strategies to reduce and compress the potentially explosive number of images required to represent a complex scene: a scene with many rooms, and thus a high depth complexity, requires numerous views of each and every room.

Time-Critical Computation

An important issue in scene generation is the scheduling necessary to balance frame rate and image fidelity appropriately. We call the class of rendering and simulation techniques that addresses these issues time-critical computing; it enables an application to maintain an interactive frame rate by automatically reducing presentation quality, thus preserving interactivity at all times even in graphics environments with different performance characteristics. It relies on degradable algorithms to implement these trade-offs, a scheduler to decide dynamically which trade-off is most appropriate, and a predictor to estimate the performance of the selected trade-off. We have been investigating degradable algorithms for scan-conversion-bound rendering, for collision detection [john98b], and for rendering real-time motion blur [sche97]. We have also been studying performance measures, such as throughput and end-to-end lag, how to measure them, and how time-critical computing improves them [jaco97]. As further proof of the value of time-critical computation, we've developed a time-critical non-photorealistic renderer for implicit surfaces (see **Rendering - Non-Photorealistic Rendering**).

We will continue development of techniques for time-critical rendering that degrade visual characteristics of less perceptual importance to maintain performance, in such projects as the non-photorealistic rendering work done at Brown. We plan to incorporate the time-critical rendering techniques into a modular framework for time-critical applications using scheduling algorithms to budget time within real-time constraints. We will also continue work on frameless rendering to ascertain perceptually important contents of a scene and time-critical presentation of this crucial information.

Image Display Technologies

We have been pursuing two promising methods of image display for interactive 3D applications: video see-through HMDs and the stereo Multi-Viewer Display. The video see-through augmented reality device, designed in collaboration with the University of Utah specifically for surgical applications, is lightweight and open, and shows optically registered real and synthetic objects. It includes two video cameras for real-world capture and LCDs on which combined real-world and synthetic imagery can be displayed. The device features 2 separate, individually adjustable eye pods, each of which contains an LCD display and a miniature video camera. The pods provide a field of view of 24 degrees; the user can see "around" the pods. When the device is properly aligned and calibrated, the view around and the views inside the pods are registered. In 1997 and 1998, the device was used extensively by the augmented reality ultrasound/laparoscopic visualization group, mentioned in **Scientific Visualization - Augmented Reality for Image-guided Surgical Procedures**.

The Multi-Viewer Display is a multiple-viewer, immersive, interactive, large-screen environment. A new Multi-viewer display, called the "Office of the Future" [rask98b], was setup during 1997-1998. This is a multiple-viewer, immersive, interactive, large-screen environment. There are 3 main components of the system that were addressed: projection, rendering using image warping and tracking.

At the heart of the projection system is a TI Digital Light Projector(TM) (DLP) that can produce time-multiplexed stereo images for several users without flicker and at a high frame rate. The users wear shuttered glasses that separate the time-multiplexed color channels. Currently we can separate the three-color channels, providing a monochrome stereo view for one user and a single color monocular view for a second user. These results encourage us to extend this projector technology's capabilities to support dramatically higher frame rates, thereby supporting two or more simultaneously active users, each receiving the proper (and thus distinct) stereo image pair during each frame time.

The DLP is also used to create imperceptible structured light (also described in **Telecollaboration - Office of the Future**). The approach is a combination of time-division multiplexing and light cancellation techniques to hide the patterns in a rapid series of white-light projections. A binary pattern is projected for 700 microseconds and its inverse is projected for 700 microseconds in quick succession. The visually integrated image appears as a flat field but a synchronized video camera captures the pattern during the first 700 microseconds. The main challenge is to update the image frame projected by a projector at such high rates. This was demonstrated using a modified DLP hardware. Structured light can be used for depth extraction of display surfaces or to help create image-based models of the people in the environment, using active computer vision techniques.

The rendering method for the "Office of the Future" setup is different from that of the CAVE because the display surfaces are not necessarily planar or orthogonal to the projectors. Using a two-pass rendering technique [rask98a], we can pre-warp the projected images, so that they appear perspectively correct to a moving head-tracked user. This allows us to project light on everyday surfaces, such as walls, desks or other furniture in the office to create 2D or 3D images.

We are working on new ideas for tracking in Multi-Viewer applications, for correct image generation and user interaction. In particular, we are excited about the idea of using the Multi-Viewer (and Office of the Future) cameras not only for depth extraction, display calibration, and image-based modeling, but also for active and passive (vision-based) tracking. This approach is appealing in that tracking is performed with the same devices used for image/display sensing, and thus the system should be inherently self-consistent. This year we developed and implemented algorithms for tracking a pair of infrared light-emitting diodes

(LED’s) that were mounted on a video camera. This enabled us to capture tracked-camera video footage over most of the working area, with better noise and accuracy characteristics than our commercial magnetic tracker. This work should prove especially valuable as we go forward with our attempts to build full-color stereo displays accommodating multiple active users simultaneously.

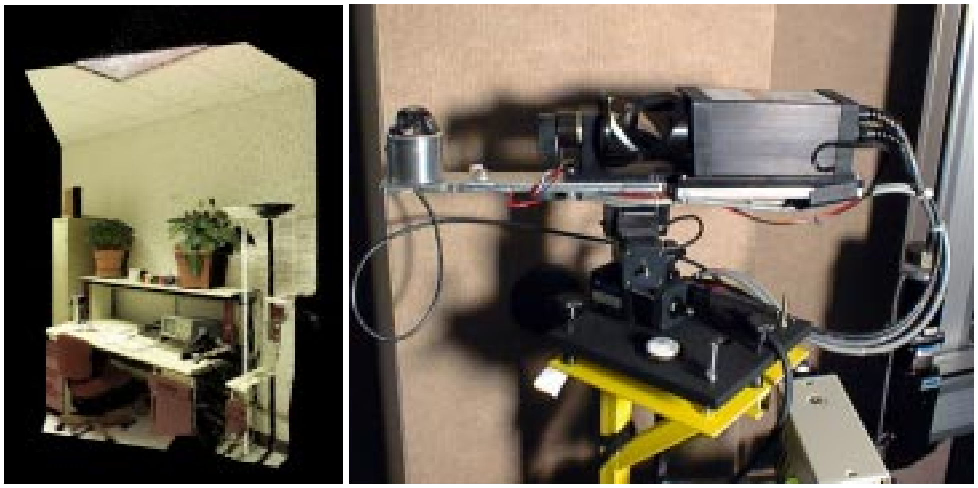

Figure 7: The left image is a warped photo composed of data from a laser range scanner. The viewpoint for the left image is moved to the right of the original viewpoint. All the pixels in the image are warped to the appropriate places to create the new view. The laser scanner is shown on the right.

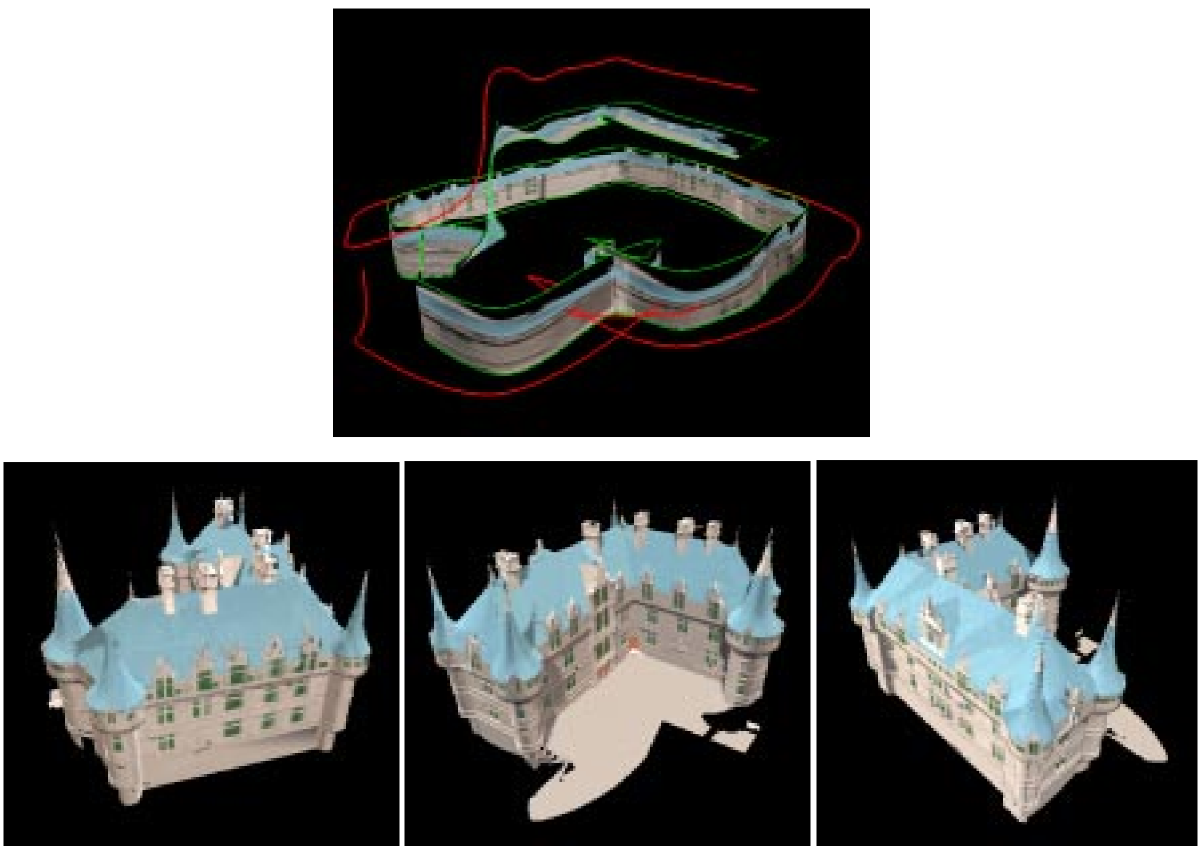

Figure 8: The multiple-center-of-project image (shown swept along the camera path at top) can reconstruct multiple views of an object, as shown in the three lower images.

2.E Scientific Visualization

E.1 Participants

Faculty

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E.2 Recent Accomplishments and Plans

The Center has wide-ranging accomplishments in scientific visualization that have significant impact on the fields of science, medicine [john98a], and engineering. Our strategy is two-fold: we conduct fundamental research in the field of scientific visualization and we apply the Center's skills in its four core research areas to scientific visualization projects, many of which involve scientists and engineers from outside the Center.

The Center has continued to increase its profile in Scientific Visualization by delivering invited talks and publishing papers in scientific visualization journals and conferences, such as the IEEE Transactions on Visualization and Computer Graphics and the annual IEEE Visualization conference. The Center will, once again, be one of the main exhibitors at the IEEE Visualization '98 Conference this year in Research Triangle Park, NC. The Center's research exhibit will include contributions from each of the five sites. Graduate students from each of the five sites will attend Visualization '98 and assist with the research booth. Five papers will be presented by Center sites at Visualization '98. Furthermore, one panel on Art and Scientific Visualization was organized by a Center faculty member and the Symposium on Vector Field Visualization was organized by another Center faculty.

Accomplishments for the past year in scientific visualization include a wide variety of research- and applications-oriented results.

Multiresolution Methods for Visualization and Computational Modeling (intersite collaboration between Caltech and Utah)

This inter-site collaboration examines the feasibility of applying advanced multiresolution geometric modeling, numerical simulation, and visualization approaches to advance the state-of-the-art of algorithms in this area. In preparation for numerical solvers, boundary surfaces must be extracted from volumetric datasets, whose origin ranges from volumetric imaging modalities to probability volumes generated from range sensors in reverse engineering applications. Standard marching cubes methods are inadequate for this purpose since they lead to meshes without a natural multiresolution structure and with severe problems from a numerical analysis point of view.

We have developed an algorithm ("MAPS: Multiresolution Adaptive Parameterization of Surfaces," which appeared at SIGGRAPH 1998), which can establish a smooth parameterization for arbitrary meshes [lee98]. This can subsequently be used for efficient resampling onto subdivision geometry with guaranteed error bounds. The algorithm can incorporate user or algorithm supplied constraints such as feature lines, for example. As a fundamental algorithms its applicability goes far beyond scientific visualization applications and covers, for example, morphing, animation, and range data reconstruction settings as well.

Interface Widgets for NASA

Continuing four years of work with NASA, we have abstracted the desktop and immersive environment interfaces we have developed into a library of interaction techniques. This library, comprising selection, manipulation, and navigation techniques is available to be integrated with other systems requiring similar 3D interaction solutions. For more information, see:
http://www.cs.brown.edu/research/graphics/research/widgetlib/.

Augmented Reality for Image-guided Surgical Procedures

The AR work at UNC focuses on visualization for image-guided surgical procedures. The research group focuses on two applications: ultrasound-guided needle biopsy and laparoscopic procedures. The tracking and head-mounted display technology is the same for both applications. The AR system has used the stereoscopic UNC/Utah video-see-through head-mount extensively during the past two years. With proper calibration and user-specific adjustment, it provides alignment between the videometric view inside the display and the direct optical view the user has around the display's "open-design" eye pods. The importance of this kind of alignment (without the awkward eye-offset characteristic of other video-see-through systems with head-mounted cameras) is a major result of this work. The research group has also improved the AR system by integrating new tracking devices and enhancing the features of the software, for example through new, automatic calibration techniques.

The medical AR group plans to construct a new video-see-through HMD, this time using commercial higher-resolution color displays, in preparation for human subject breast biopsy experiments to be conducted under separate funding from NIH (P01 led by Stephen M. Pizer). A number of further enhancements are planned for the system before that, such as porting to the SGI Reality Monster platform, fully integrating an optical tracking device, and parallelizing time-critical portions of the code.

Remote Microscope Control, with the Collaboratory for Microscopic Digital Anatomy (CMDA)

The Center has continued its participation in the research and development of a networked, interactive collaborative microscopy research environment, the Collaboratory for Microscopic Digital Anatomy (CMDA), with the National Center for Microscopy and Imaging Research (NCMIR) and the San Diego Supercomputer Center (SDSC). Recent activities have focused on the creation of visualization aids that greatly simplify the use of complex direct volume rendering systems, in particular the data-driven generation of transfer functions for such systems that emphasize boundary regions in biological data without significant user intervention. As well as being incorporated into the CMDA software, the work is to be presented at the upcoming ACM SIGGRAPH Volume Visualization Symposium.

During the fifth and final year of the CMDA grant the Center plans to integrate its recent research contributions into the operational CMDA software system. The use of Center-developed rendering tools and visualization aids by microscopy researchers will allow us to fully evaluate the effectiveness of these advanced techniques for EM tomography data and in a non-expert user environment. Such experience should allow us to improve these techniques and point the way towards new research challenges. In addition to integration and evaluation activities, we will be focusing our further research efforts on new direct volume rendering techniques, with the emphasis on bridging the gap between fast but approximate and slower but higher accuracy methods through the use of a metric-driven progressive refinement approach.

Scalar and Vector Field Visualization

The Center has continued to develop scalar and vector field visualization algorithms primarily aimed at large-scale scientific computing applications on unstructured grids. One application involves view-dependent isosurface extraction [livn98]. The idea is to only generate isosurfaces that are in the direct view of scientist. This leverages previous work on isosurface extraction in which we lowered the overall complexity of the search phase from $O(n)$ to $O(\sqrt{n}+k)$. Other researchers used our methods to find an optimal search complexity of $O(\log(n))$. The results of the new view-dependent isosurface extraction will be presented at the IEEE Visualization '98 Conference.

Painterly Visualization of Multi-valued Data

The display of multi-valued data in a single image is challenging. We have developed a new technique that borrows concepts from painting to effectively display many values simultaneously [laid98a]. By combining semi-iconic images, texture, and shapes in multiple layers we can effectively represent multidimensional data in a 2D image. We have presented examples on MRI data visualization [laid98b] and on airfoil flow simulation data.

Scalable Immersive Technologies for Scientific Visualization

In preparation for the new Center for Scientific Computing and Visualization at Brown University (funded through a NSF MRI grant), we have researched and selected a vendor for the Cave, the graphics machine, and the supercomputer. This facility will be operational in the coming year and will be used for research of user interfaces for scientific visualization in different work environments (the Cave, the responsive workbench, and traditional workstation).

Haptic Rendering and User Interaction with the NSF, ARO, and NASA

We are collaborating to develop graphical and haptic rendering methods for local visualization that can operate simultaneously with a global visualization method. A haptics-derived position locates a point in the simulation data much like a multi-dimensional computer mouse, but unlike a mouse, which is purely a positioning device, the haptic interface exerts forces or torques on the user that are mapped to provide quantitative information about the simulation data. This collaboration will draw upon the Center's visualization expertise in local and global visualization techniques, as well as on its significant experience in three-dimensional widgets.

Subdivision Surface Extraction

Our main focus so far has been on the geometric and fundamental infrastructure aspects of hierarchical mesh settings [zori97]. To move on to the PDE setting we are now developing the actual elliptic PDE solver framework for surfaces, which itself is a prelude to the full 3D solver setting. To this end we have now begun the pursuit of PDE structures on these surfaces. We are considering thin shell equations as needed in solid mechanics, for example. A first implementation is currently running and standard benchmark tests are being run to verify the accuracy of the methods. Depending on how successful this work will be, we hope to significantly expand this part of our overall effort to actively pursue other, more realistic applications.

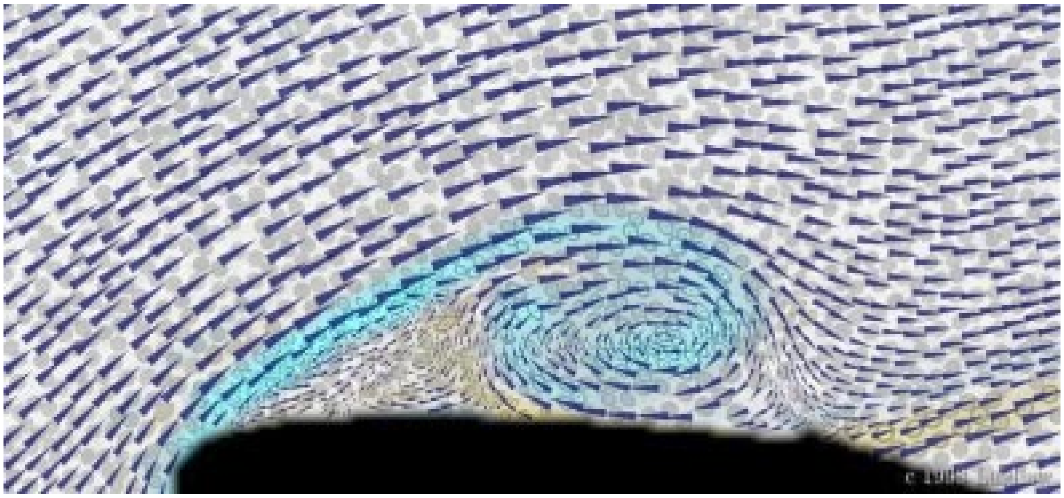

Figure 9: This image of 2D flow data over an airfoil simultaneously displays 2D velocity (2 values mapped to arrow direction and area), vorticity (1 value, mapped to color and texture on ellipse shapes), and deformation rate tensor (3 values, mapped to shape and orientation of ellipse shapes). The concepts of layering and semi-iconic representations borrowed from painting helped solve this challenging problem.

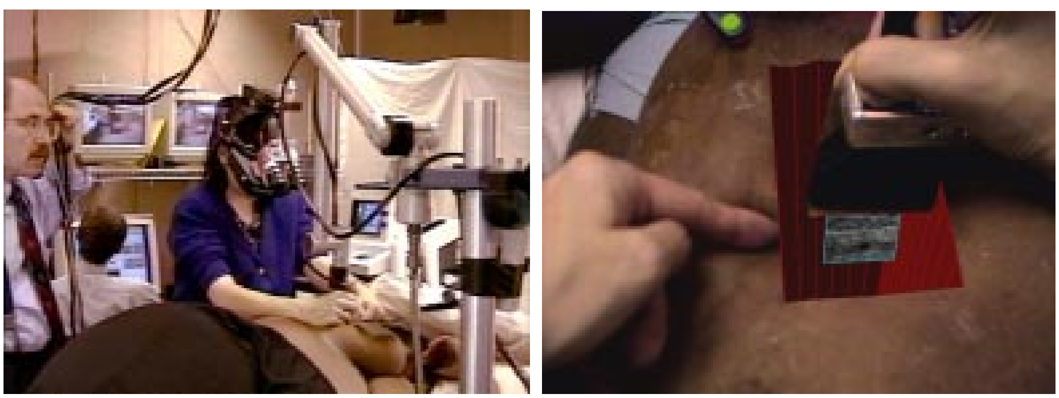

Figure 10: Surgical trial of augmented reality headset used in breast biopsy at the University of North Carolina at Chapel Hill. The surgeon, wearing the video see-through headset (left image) sees simultaneously the patient and the potential tumor inside the patient (right image), displayed by the computer using live, real-time, ultrasound data.

2.F Telecollaboration (a collaboration by all five Center sites)

F.1 Participants

Faculty

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Research Staff

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Graduate Students

Wei Chao Chen, Matthew Cutts, Eric Lafortune, Adam Lake, Aditi Majumder, Gopi Meenakshi, Ramesh Raskar, Lev Stesin, Nicholas Vallidis, Ruigang Yang

F.2 Recent Accomplishments and Plans

The Center's telecollaboration project is an ambitious collaborative effort by all the Center sites and ties together two-way, three-way, and four-way collaborative efforts funded from the Director's Reserve. The project also serves to test interactions between single-site research projects that support the Center's overall vision. This degree of research coordination would be impossible for the individual sites without the Center mode of funding. As a driving application, the telecollaboration effort requires fundamental, long-term research in all of the Center's core areas: modeling, rendering, interaction, and performance. The challenges include methods of scene construction and acquisition, reconstruction and display, and interaction techniques for virtual environments. Responses to these challenges have been discussed throughout the Research section.

The ultimate goal of the project is to enable distant collaborators to work together as if they were present in a common workspace. We foresee a virtual mechanical design environment in which technology mediates complex communications so well that the technology itself becomes transparent.

F.2.1 Office of the Future

The office of the future is the cornerstone of the center's telecollaboration research [rask98b]. The basic idea is to use real-time computer vision techniques to dynamically extract per-pixel depth and reflectance information for the visible surfaces in the office including walls, furniture, objects, and people, and then to either project images on the surfaces, render images of the surfaces, or interpret changes in the surfaces. In the first case, one could designate every-day (potentially irregular) real surfaces in the office to be used as spatially immersive display surfaces, and then project high-resolution graphics and text onto those surfaces. In the second case, one could transmit the dynamic image-based models over a network for display at a remote site. Finally, one could interpret dynamic changes in the surfaces for the purposes of tracking, interaction, or augmented reality applications.

To accomplish the simultaneous capture and display we envision an office of the future where the ceiling lights are replaced by computer controlled cameras and "smart" projectors that are used to capture dynamic image-based models with imperceptible structured light techniques, and to display high-resolution images on designated display surfaces. By doing both simultaneously on the designated display surfaces, one can dynamically adjust or auto-calibrate for geometric, intensity, and resolution variations resulting from irregular or changing display surfaces, or overlapped projector images.

Scene Acquisition

Our current approach to dynamic image-based modeling in the office of the future is to use an optimized structured light scheme that can capture per-pixel depth and reflectance at interactive rates. Our system implementation is not yet imperceptible, but we can demonstrate the approach in the laboratory. Our approach to rendering on the designated (potentially irregular) display surfaces is to employ a two-pass projective texture scheme to generate images that when projected onto the surfaces appear correct to a moving head-tracked observer. We have demonstrated an initial implementation of the overall vision, in an office-like setting, and preliminary demonstrations of our dynamic modeling and display techniques.

Scene acquisition in the office of the future project is currently done with perceptible light and current speed of depth extraction is roughly 5 frames per second. In the coming year we, along with Ruzena Bajcsy's GRASP Laboratory at the University of Pennsylvania, will endeavor to use imperceptible light and to increase the speed of the scene acquisition.

In the current office of the future, calibration of the cameras and light projectors has to be done largely by hand. A director's reserve project involving a collaboration between Brown, UNC, and Caltech, based on past collaboration on auto-calibration of the ceiling tracker, is working on auto-calibration of the cameras and lights in the office of the future, by placing a manifold structure on the light field.

The Camera Cluster

Another tool designed by the Center in an effort to advance telecollaboration is a wide-field-of-view, high-resolution video camera cluster. The device we have built uses twelve conventional cameras in a single cluster to construct an image with a 360 x 80 degree field of view, with twelve times the resolution of a single camera. The device is used to capture high-resolution images for 3D scene reconstruction as well as for conventional televideo systems.

The technical challenge in developing such a cluster lies in the difficulty of properly merging all the views into a seamless whole. This can only be achieved by optically arranging all the cameras to have the same center of projection. Achieving both the same center of projection and sufficient overlap to allow resampling without seams between the individual views has never been demonstrated to our knowledge. As with the HMD previously built, the multidisciplinary nature of the camera cluster means that we have to draw heavily on expertise at multiple sites.

Several other designs have been attempted for multiple cameras, wide angle field of view, including our own which used multiple cameras each focused on a single participant, but none have a true "common center point of projection" that this design has. This camera feature greatly enhances applications in videoconferencing since it allows multiple receivers to pan around very large and high-resolution images simultaneously.

Interaction

As discussed earlier (see **Interaction - Gestural Modeling**), Brown and Utah have worked together to extend Sketch to do mechanical computer aided design (MCAD) [bloo98], an important step towards seamless mechanical design.

We have prototyped other interaction techniques needed in the office of the future. We have built ErgoDesk [fors98b] on our ActiveDesk, a responsive workbench-like projection display that supports 2D direct-draw pen input in addition to 6 DOF input devices and stereo viewing. The ErgoDesk system uses this pen input along with multi-modal input and a stereo-on-demand display surface to seamlessly support transitions between a variety of 2D and 3D interaction techniques. We have also investigated techniques to support collaborative use of the Sketch system [lavi98b].

Research has begun on a system with an interface that combines voice and two handed 3D gestures using glove input to perform architectural layout and free form modeling. This is the beginning of a seamless interface tailored for immersive environments such as the Cave or the Office of the Future.

In the office environment 3D gestures alone will not suffice for all interaction needs; in some cases 2D (pen based) gestures are better fits for some jobs. We will also continue to improve our 2D gestural interfaces, hopefully merging the benefits of 3D and 2D gestures in one environment.

Discussion

We will continue to pursue our goal of giving distance collaborators a compelling sense of common presence in a virtual space, in the limit "making it as real as being there." We will improve the sense of presence in the Office of the Future, especially in the area of scene acquisition, as well as improving our interaction techniques in that environment.

Figure 11: Conceptual sketch for the Office of the Future environment. We have completed and presented preliminary work on displaying images on irregular surfaces and on scene acquisition. This effort is intended to bring immersive and flexible telecollaboration tools into ordinary rooms.

Figure 12: The "Camera Cluster" is an optical device which uses multiple cameras to create a very high resolution, full 360 degree image with a common center of projection. It is especially useful for video conferencing and other applications, such as surround video or movies, where a strong feeling of "presence" is desired. The device was created and developed by UNC's Microelectronic Systems Laboratory in the Computer Science Department and the mechanical structure was designed and built by the University of Utah.

3. Education and Human Resources

The Center runs a wide range of programs to develop human resources in science and engineering. Our emphasis over the past year has been on our programs for women and minority groups. Throughout the Center, from K-12 outreach to undergraduate education to graduate programs and post- docs, we are taking actions aimed at bringing underrepresented groups into the field of computer science. Some of these efforts may affect the Center directly while others will more fully benefit future students and research groups.

3.A Achievements

A.1 Graduate Programs

Center graduate students see and interact with one another in the all-site televideo seminar. In addition, they have the opportunity to meet in person in Center graduate student workshops. Incoming students have cited the Center as a reason for applying to Center university graduate programs and exposure to the Center often leads undergraduates to consider graduate school at one of the other Center sites. This exposure has also lead graduates to consider jobs with the Center; this year David Laidlaw, who received his Ph.D. at Caltech, was hired as tenure track faculty at Brown.

All-Site Graduate Televideo Seminar

The Center is in the fifth year of its pioneering all-site televideo seminar, attended and taught by all five sites. The seminar is offered for credit at three of the sites and is attended by approximately 70 students/year, having reached almost 400 students since its inception. A unique feature of the Center graduate experience, this seminar provides access to information and people well beyond the scope of any single university. Graduate students also use the televideo system as part of a research lab without walls to discuss collaborative work. Lecture titles and abstracts for the 1997-8 academic year seminar can be found at:

`http://www.cs.brown.edu/stc/education/course97-98/home.html`

All-Site Graduate Student Workshops

The Center's popular graduate student workshops are in their third year, with participants from each of the sites gathering at a different Center location each time. Nearly 80 graduate students have participated. Agendas, presentation abstracts, images and references, and student commentary from the latest workshop are available at:

`http://www.cs.utah.edu/~dejohnso/workshop/talks/home.html`

Many students compare the experience favorably with a full-fledged graphics conference and feel that they have gained a better understanding not only of the work of their distributed Center colleagues, but of the field in general. The chance to visit other Center sites and see different approaches to graphics research is felt to be particularly rewarding.

Women's Televideo Roundtable on Computer Science Graduate School and Careers.

See description in Undergraduate Programs, Section A.2.1.

A.2 Undergraduate Programs

Undergraduate education at all sites (with the exception of UNC, which has no undergraduate computer science program) is directly influenced by the Center. Students take innovative undergraduate courses inspired by Center research, such as a *3D Photography* course at Caltech. This year, with support from the Teaching and Interdisciplinary Education (TIDE) program, several undergraduates wrote some of the software used in this class, exposing them to the latest research techniques and principles related to computer vision and surface reconstruction.

Undergraduates at most Center sites have been co-authors on published papers. Nate Robins, a Center undergraduate at the University of Utah exemplifies the close ties between Center research and education. Nate gave a course at SIGGRAPH last year and this year worked with Center faculty to implement openGL for Windows and to conduct research into the pros and cons of different shadow algorithms. He is now continuing his studies as a graduate student at another Center site, Cornell.

All-Site Graduate Televideo Seminar

Although technically a graduate course, this seminar is taken by almost as many undergraduates as graduates. See Graduate Programs, Section A.1

Undergraduate Research Programs

Through Center-funded undergraduate research positions and programs such as the NSF Research Experience for Undergraduates (REU), the Caltech Summer Undergraduate Research Fellowship (SURF), and the Teaching and Interdisciplinary Education (TIDE) program, undergraduates pursue serious research agendas. Since the Center’s inception in 1991, more than two hundred fifty undergraduates have worked in the Center’s labs, more than a third of them supported with Center funds. This year, six Center students received REUs for work ranging from real-time rendering systems to free-form sketching to the creation of frameworks for interactive educational applets.

A.2.1 Undergraduate Programs for Underrepresented Groups

Women and underrepresented minorities often arrive at high school or college with an interest in science and computing but become discouraged from pursuing those subjects and choose to focus in other areas. The Center’s programs for underrepresented groups are designed to spark interest and identify interested candidates early on and provide the necessary support to help them feel at home in science courses and research labs.

The Utah ACCESS Program

Started in 1990 by a Center faculty member, the ACCESS program has introduced over 120 young women to university-level research in science and technology (20 each year) by providing both academic and social support systems. During an eight-week summer course before their initial year at the University of Utah, ACCESS students get a feel for research by tackling real-world problems in a mentored setting that includes instruction, laboratory work, and team work on assigned problems. Supported by a $2,500 stipend during the academic year, ACCESS students are placed in a science, engineering, or medical research lab. The large majority continues to work in research labs throughout their undergraduate careers. This year one of the ACCESS graduates will be beginning a doctoral program at Cornell.

`http://www.cs.utah.edu/~jshepher/access/access.html`

Undergraduate Research Access

For the past two years the Center has followed up the pre-freshman architecture program component of the Cornell Summer Session for Design Professions (see Career Explorations in Architecture in section A3) during the academic year. The Cornell site's "Undergraduate Research Access" program provides extended opportunities for students to gain exposure to computer science and architectural design research in the Center. The students involved are primarily minority female students, but have included males and non-minority females as well. Here the emphasis is on mentoring and developing long-term career interest in computer graphics, primarily through contact with older students and opportunities to explore high-end modeling and rendering tools. Sessions led by former Center Director Don Greenberg have described how technology is changing architectural education and professional practice, and talks by graduate students have introduced students to research software not available in university computer labs. Some students have spent additional time both during the semester and in the summers learning software and supplementing their own design projects.

Our goal is to mentor the students and instill in them greater confidence that they can undertake careers in computer graphics. This job has been enhanced by the enrollment last year of minority student Corey Toler in our graduate degree program. Corey first came to the lab as a high school student participating in the summer program. She pursued independent study and summer modeling work in the lab over her college career and has now completed a very successful first year of graduate study. Corey serves as an excellent mentor for other women and minority students.

Underrepresented Groups' Televideo Roundtables on Computer Science Graduate School and Careers

The Center is taking further advantage of its televideo system by hosting a series of roundtable discussions with speakers and audiences from different sites of the Center. The first talk, with four female faculty and a Ph.D. student speaker (representing four of the five sites), had over 50 undergraduate and graduate participants from all sites, including members of the ACCESS Program. This roundtable was designed to help students understand the options open to them in both academia and industry and to extend their network of female colleagues. Roscoe Giles, a member of the Center's External Advisory Group, hosted our first minority roundtable, a discussion among technical students of color. Dr. Giles shared his own experiences with the group and sparked lively debate. More roundtables are being planned for this year.

Research in Center Labs for Students from Historically Black Colleges

The Center has begun a new initiative to create alliances with historically black colleges. Last fall, the Chair of Morehouse's Computer Science department, along with Morehouse's Director of Educational Technology, visited the Brown site for three days. This summer the Center hosted Seleon Lendor from Morehouse College. He worked with the Exploratories Group at Brown for four weeks and is continuing to work on projects with the Center this fall from Morehouse.

A.2.2 Undergraduate Interactive Materials Development

The Center is augmenting its intensive local hands-on outreach programs with materials development efforts. This strategy lets us build on the entire Center's outreach and educational experiences and leverage them to greatly expand our influence.

Interactive Tools for the Classroom of the Future

The Center has worked for several years on an ambitious education outreach project called Interactive Tools for the Classroom of the Future. In this project a post-doc, graduate student, and undergraduates worked together to develop visualization and physical simulation tools for science education, using a fully interactive 3D environment including object behaviors derived from the laws of physics. Based at the Cornell site, this project has drawn on Center software resources from several other sites, including UNC's OBB-Tree collision library and Brown's VRAPP library. One year of this project was funded by EHR, and funding for ongoing development is being sought. This project and related activities have involved ten material-creators and impacted hundreds of students. Dr. Waldemar Celes presented his work on the project at the Brazilian Symposium on Computer Graphics and Image Processing in October 1997.

Exploratories

Exploratories are a computer-based combination of an exploratorium and a laboratory—a constructivist way of teaching and learning using two- and three-dimensional, explorable worlds in which objects have behaviors and users can interact with models of concepts and phenomena. Exploratories leverage the joint forces of computer graphics and interaction to provide efficient, powerful learning experiences that would be impractical, if not impossible, to attain with traditional means.

To facilitate widespread use, the exploratories are written in Java and embedded within a hypertext (HTML) framework that facilitates both independent and guided use. Teachers may incorporate individual exploratories into existing curricula, while students may find guidance to additional resources, including related exploratories.

The Exploratory project is three-pronged research effort to advance the state of the art in designing and implementing interactive exploratories. The three research prongs are: Content Creation, Authoring Tools, and a Design Strategy Handbook

Current exploratories incorporate a range of computer graphics subject matter taught in the Center, including linear interpolation for animation, wavelets, filter and image processing operations, color perception, matrix math for graphics, scene graphs, and more. The interactive materials are appropriate for a range of educational levels, from high school to the graduate level, but emphasize undergraduate-level courses. Applet production is going on at several sites and applets are being integrated into the Center's introductory graphics programming courses.

`http://www.cs.brown.edu/exploratory/`

Past efforts have met with success beyond the Center. Our applets have won awards from Sun and "best of" web sites and have been used in other universities and featured in local high school exhibitions. Internationally, our applets have been used in an exhibition on color perception at Uppsala University and by teachers as far away as Australia.

A.3 Pre-College Programs

Opportunities offered by the Center have brought our researchers in contact with large numbers of K- 12 students and teachers. Connections have been created with groups that historically have had little interaction with university researchers and research labs. The pre-college programs are designed to contribute to the Center goal of drawing more students into computer science and computer graphics. Emphasis is increasingly on programs that encourage underrepresented groups, such as women and minorities, to participate. The experiences gained in intensive, hands-on workshops are being distilled into interactive materials that can potentially be used by thousands of students and teachers.

The Utah High School Computing Institute (HSCI)

Now in its eighth year, the five-week HSCI was started by a Center co-PI and continues to provide an important regional service for 30-40 high school students each year (almost 350 since the program began) from across the entire state of Utah, including many rural areas. Just as some students are disadvantaged by race or gender, others struggle with geographic destiny—they are simply too far away from centers of academic excellence to grasp a fast-changing field like computer science or to be exposed to a nationally recognized research lab. In addition to the summer activities in programming, computer graphics, artificial intelligence, and Web design, year-round workshops and an increasing number of Web connections keep students involved long after the initial summer program. See:

`http://www.cs.brown.edu/stc/outrea/utahhsci.html`

Students who take the program often continue on in the field of computer science. As a case in point, Chad Barb was influenced by his experience in the HSCI to stay at the University of Utah instead of going to college out of state; he is now working with Center faculty researching interfaces to modeling and design.

The Summer Workshop in Computer Graphics and 3D Modeling/The Greenhouse

For five summers, the Center ran an intensive three-week workshop for high school teachers within commuting distance of Brown University, with over 50 teachers attending. The emphasis has shifted this past year to materials development. See

`http://www.cs.brown.edu/stc/outrea/greenhouse/home.html`

This year one of our teachers, Jim Rusconi, won a $10,000 grant from CESAME (The Center for the Enhancement of Science and Math Education), an organization funded by the NSF and Northeastern University. The grant will help fund the continuing construction of the interactive biology Web site that Jim started while participating in our Workshop. The Web site will be expanded to include models for Chemistry, Math, Physics, as well as Biology. It will have sections for both student and teacher use and will be translated into Portuguese, Spanish and French.

Career Explorations in Architecture

During the current year the Center has continued its long-term involvement with the Cornell Summer Session for Design Professions. This summer career exploration program brings approximately 80 to 100 high school juniors and seniors to Cornell for six weeks. The program also serves as an intensive orientation experience for incoming Cornell freshmen in cooperation with the College's Office of Minority Educational Affairs.

The Center does not run the summer session, but over the past six years Center PI Donald Greenberg has given lectures and additional evening technical sessions, broken into small groups to permit one-on-one interactions and questions. These sessions include demonstrations of modeling, architectural sketching, 3D scanning, digital photography, and rendering. Dr. Greenberg also leads discussions about careers in graphics and animation, opportunities in college and graduate school, and recommendations for course choices.

Beginning with Children

The Cornell site has initiated a cooperative relationship with the Beginning with Children School in Williamsburg, Brooklyn. This is a public school designated by the New York City Board of Education as a model elementary demonstration school. Twenty inner-city children from the school recently visited Cornell and its graphics lab. We plan to coordinate further visits and to assist teachers at the school with integrating computer software into the elementary science curriculum, initially using off-the-shelf tools.

Special Activities

Center participants speak at numerous events and try to take advantage of opportunities to reach out to students who might not otherwise have a chance to learn about the field. For example, this year Dr. David Breen participated in Career Day at Camino Grove Elementary School in Arcadia, CA. He discussed computer animation research and production with the students, whose ethnic breakdown is 60% Asian, 30% white and 10% Hispanic.

A.3.1 Pre-College Programs for Underrepresented Groups

The Artemis Project

The Artemis Project, a five-week summer leadership program designed and led by female undergraduates, has just completed its third year. This summer's enrollment was 11 participants. In addition to the intensive five-week summer session, last year's Artemis Project met one Saturday a month for the entire school year. The Project is directed toward inner-city public school girls about to enter the ninth grade (a time when, research indicates, many girls lose interest in science). The Artemis goals are to enhance self-confidence, introduce participants to a university setting, and build leadership skills through hands-on experience with computers and discussion of important issues relevant to the lives of women and girls. Artemis is now funded entirely by the Center and by $3,000 to $4,000 yearly in gifts-in-kind from local companies (including lunches for each day of the program). Artemis participants meet with Brown's PI and with a range of faculty in Brown's CS department. This year we hired a student who had attended the program in 1997 to act as a teaching assistant and mentor for new Artemis girls. See:

`http://www.cs.brown.edu/stc/outrea/greenhouse/artemis/home.html`

A Bridge Course for Introductory Computer Science (Pre-College/Undergraduate)

This year marked the completion of the second Bridge Course to welcome incoming first-year minority students into computer science. These intensive four-week-long in-residence summer program provides a supportive environment and teaches skills that increase the likelihood of the students taking and enjoying introductory computer science courses. This year's program was led by two minority female undergraduates and included instruction in HTML, JavaScript, and Unix. Participants heard lectures from the Center PIs as well as a range of faculty members in Brown's Computer Science department. The program is designed to convey the excitement of several areas of computer science, and also to show how basic knowledge in computer science can be applied to a wide range of other endeavors in academia and industry. The course is administered in conjunction with Brown University's Summer Studies Program through which the students also receive tutoring in mathematics.

Cornell Summer Session for Design Professions

See Pre-College Programs, Section A.3.

Computer and Computational Sciences Program at Caltech

Caltech Computer Graphics Lab participated in the 6th Annual Computer and Computational Sciences Program, which is organized by the Center for Advanced Computing Research at Caltech. The Lab hosted about 25 minority high school students from around LA County for part of an afternoon. The purpose of the Program is to give minority high school students first-hand exposure to "cutting-edge" research in science and mathematics, which is enhanced by advanced applications of computers. Computer Graphics and Computer Animation technology was presented and discussed.

A.4 Opening the Lab Doors—Center Lab Tours, Talks, and Demonstrations

As a nationally funded organization, the Center takes pride in its open-door policy for all interested groups, from academics to industry to local schools.

Tours and demonstrations of work in the Center's research labs (and of the interlinking televideo system) continue to expose large numbers of visitors to the state of the art in computer graphics. Each site hosts several hundred visitors a year with UNC hosting over 700 each year.

The UNC site focuses its outreach efforts on tours, devoting at least one day a month to tours and demonstrations (the equivalent of running a yearly full-time three-week outreach program). Virtually everyone working in the lab, from the site PI to undergraduates, contributes to this demanding and unusually strong commitment to the public.

A.5 Museum Programs

The Center installed and has continued to support a Web browsing kiosk and a Web server for the Sciencenter in Ithaca. This community-based science museum has garnered national attention for innovative exhibits, community outreach, and extraordinary volunteer commitments.

The Internet connection has now become an integral part of the exhibits and special events programming of the Sciencenter. For special events such as a day-long program on the recent NASA Mars mission, a special page was developed to facilitate visitor access to the latest photographs as soon as they were made available. Live chat sessions have been set up to link visitors at the Sciencenter with the launch site of a NASA-sponsored SCIFER upper atmosphere test rocket in Alaska, through collaboration with Professor Paul Kintner of Cornell's Space, Plasma, and Atmospheric Studies research team.

The Internet connection has also spawned significant outreach programs within the Sciencenter. The YouthAlive! Program has centered much of its outreach to disadvantaged youth in Ithaca on internet-based activities, including Web page development. Inspiration from that program has provided the motivation for an all-volunteer Alliance Program for Tompkins County youth from ages 12-19. With support from area radio stations, newspapers, and diverse other businesses including a limousine company, the Alliance Program has involved 30 at-risk teens in two programs which got started via the Sciencenter Internet connection. The participants write, illustrate, and publish interactive stories as part of a family reading project, and have initiated a "Net Chat Consortium" to provide audio feeds from selected public events, including Hilary Clinton's recent visit to the Greater Ithaca Activities Center and two community meetings hosted by Congressman Maurice Hinchey. Both programs provide valuable training to the participating youth, as well as increased their self-confidence through participation in live news events.

A local Internet provider has now offered to provide dialup lines and server space for the Alliance web pages, and Center personnel have, in a volunteer capacity, helped to assure the continuation and formalization of the Sciencenter's Internet connection through the auspices of the Ithaca City School District.

`http://www.sciencenter.org`

3.B Plans

We are continuing to refine and improve the education and outreach programs discussed above.

In our efforts to expand the programs targeted to women and minorities, the Center has designed a large-scale effort that will impact hundreds of mostly minority students. The Center program will work with newly established computer labs in the Pasadena public school system (which otherwise would have only

Microsoft Office installed) to provide basic software programs and training that will enable students to generate visualizations and output mathematical and scientific equations in publishable form. The Pasadena public school system is approximately 78% black and Hispanic; thus the Center's efforts will predominantly impact underrepresented minority teenage students. Additionally, resources will be focused on female-only training sessions.

4. Outreach and Knowledge Transfer

The computer graphics industry continues to hire a significant number of Center students, many for key positions. This is a highly effective form of technology transfer and our students are among the most sought-after in the industry. Many tools and techniques developed in Center laboratories have emerged in commercially available products, including products influenced by Center research in physically based modeling, computer-aided design, radiosity, virtual reality techniques, geometric modeling and 3D user interface widgets.

While working in industry, Center students frequently return to their schools to recruit new employees.

4.A Industry and Government Research Relationships

The Center has maintained research relationships with many U.S. hardware and software companies. Current relationships include Alias|Wavefront, ANS, Autodesk, HP, ITD, IVEX, Microsoft, and Sun. Center labs have received equipment grants from HP, IBM, Intel, Kodak, Lucent, SGI, Sun, and Tanner Research.

The Center continued to work closely with HP: PI Don Greenberg spends regular sabbaticals with the company, Dr. Peter Schroeder, along with two of his graduate students, spent this summer working at HP Labs in Palo Alto, and HP has purchased licenses for the PixelFlow graphics supercomputer. Two prototypes of the machine have been constructed (one was unveiled at SIGGRAPH 97) and both are in use. The machine at UNC is used in the nanoManipulator project and for simulation purposes by Cornell. PixelFlow provides unprecedented graphics performance, displaying over 43 million Phong-shaded full-color polygons per second. PixelFlow licenses have also been purchased by Integrated Device Technologies (IDT).

The Center is building a close relationship with IBM through the new Brown University Scientific Computing and Visualization Center, created with a one million dollar NSF MRI grant. The new visualization facility features a Cave visualization environment driven by an IBM supercomputer with scalable graphics hardware designed especially for immersive environments.

Dr. Peter Schroeder jointly developed MAPS (Multiresolution Adaptive Parameterization of Surfaces) with Lucent Technologies. They have filed a joint patent application and had a joint paper at SIGGRAPH.

Advanced Networks and Services (ANS), which played a leading role in the growth of the Internet in the early 1990's, has identified telecollaboration as a principal driving application area because of its critical high-bandwidth and low latency demands. In recognition of the leadership role that the Center has taken in different areas of telecollaboration, ANS has verbally agreed to provide three years of funding for multiple Center research projects in telecollaboration. Initially ANS plans to augment NSF funding for the UNC, Utah, and Brown sites of the STC to pursue their collaborative effort on immersive telecollaboration environments for mechanical design. Other partners who will be funded by ANS include former Brown Graphics Group members Professors Steven Feiner at Columbia and Randy Pausch at CMU, UNC Ph.D. Professor Ulrich Neumann at USC, Professor Tom DeFanti at UIC, and Professor Michael Zyda at the Naval Postgraduate School.

Center researchers are working in advisory or consulting capacities with a number of companies, including the Center for Complex Systems and Visualization, Bremen, Germany; the Fraunhofer Center for Research in Computer Graphics, Providence, RI; Lightscape Technologies Inc., San Jose, CA; Mixed Realities, Yokohama, Japan; Raycer Graphics, Palo Alto, CA; and Wholly Light Graphics, Jerusalem, Israel. A Center PI also holds positions on the technical advisory boards of Raycer Graphics and

Microsoft Research. In addition, a former Center Director is Chairman of the Board of Numinous Technologies, Seattle, WA, and on the Boards of Turbine Entertainment, Westwood, MA and Fraunhofer Center for Research in Computer Graphics (CRCG).

Both the Center and the Fraunhofer Center for Research in Computer Graphics (CRCG) are working on large-scale telecollaboration projects. The CRCG has supplied the Center with a Barco Baron stereoscopic/rear-projection table so that the Center can take part in the Virtual Table consortium. The VT consortium, which includes CRCG, has members from the United States, Germany and Portugal. The goal of the VT consortium is to study how long distance telecollaboration can be done using the Barco Baron. The consortium will leverage CRCG's high speed ATM connection with Fraunhofer IGD in Darmstadt, Germany.

Center members are part of a MURI grant to develop the mathematical infrastructure for robust virtual engineering. The primary goal of this interdisciplinary grant is to develop mathematical and computational methods to integrate diverse approaches to modeling and simulating systems of rigid, flexible, fluid, and heterogeneous interacting objects. This MURI program proposal includes collaborative relationships with AFOSR and among the university researchers and DoD personnel.

Center PIs have served on several government boards, including the NRC's Computer Science and Telecommunications Board, DARPA's Information Science and Technology Study Group, the Blue Ribbon ERC Panel, the NSF CISE Advisory Committee, and the advisory committee on Data and Visualization Corridors for the DOE ASCII Program.

4.B Academic Outreach and Education

Center research is presented each year at multiple conferences. At this year's SIGGRAPH (the premier computer graphics conference) all of the Center labs were featured in an historical exhibition of visual images from the most important research groups in computer graphics. All the Center PIs, a co-PI, and a Center research staff member were featured in the SIGGRAPH exhibit of the world's top graphics researchers. Center members ran two courses, participated in two courses, were on four panels and six paper sessions and presented a technical sketch. In addition, the Center has four slides in the technical slide set. In the past year, we integrated our Sketch system (a video paper at SIGGRAPH 96) with Columbia's Repo 3D system. A video showcasing this integration was shown as part of Blair MacIntyre's Repo 3D paper presentation at SIGGRAPH 98. Since Repo-3D is a distributed 3D graphics library without rapid object creation functionality and Sketch uses a novel gestural interface that enables the rapid creation of 3D geometry, using Sketch was a perfect way to demonstrate Repo-3D.

Center PIs keynoted several conferences this year including IFIP in Budapest, Hungary, Eurographics in Lisbon, Portugal, and Multi-Media Computing and Networking (MMCN) in San Jose, CA. Center members had a strong presence at the Image Based Rendering (IBR) Workshop in Palo Alto, CA. Considered by many to be the next major wave in graphics (comparable to the shift from vector to raster graphics, even), the field of image based rendering is being defined with strong influence from the Center. In this invitation-only conference with only 17 speakers, over 35% were currently or had recently worked at Center sites or had received PhDs from Center schools.

This fall the Cornell site has undertaken a major new initiative in undergraduate teaching that is impacting students from a range of disciplines. Center faculty have developed two new courses, both of which are oversubscribed and are receiving very enthusiastic receptions. Twenty undergraduate computer science and electrical engineering majors are taking the new "Advanced Computer Graphics: Realistic Image Synthesis" course taught by Donald Greenberg, Kenneth Torrance, and the research staff of the Program of Computer Graphics. Ten undergraduate architecture and fine arts students have enrolled in the inaugural *Design Studio for the 21st Century* course. The course will introduce new paradigms for the conceptual development, modeling, and rendering of architectural design. Tools are based on sketching routines, digitizing drafting tables, projection displays, and the ability to interactively modify and walk-through virtual environments. Donald Greenberg is also continuing to teach his successful *Imaging and the Electronic Age* course in the Business school, which draws undergraduate students as well as students in the MBA program.

In addition to innovative work in undergraduate and graduate education, three of the five Center PIs are now members of the National Academy of Engineering.

4.C International activities

Center researcher Peter Schroeder organized a Hierarchical Methods Workshop at Dagstuhl, Germany, and has an active collaboration with Dr. Leif Kobbelt of the University of Erlangen, Germany in the area of subdivision surfaces. Dr. James Arvo actively collaborates with Dr. Kevin Novins of the University of Otago, New Zealand. The Caltech Computer Graphics Lab hosted Gilles Debunne, a Ph.D. student from the iMAGIS Lab of Grenoble, France this summer. His visit began a joint project in physically-based modeling. The Caltech site also hosted Dr. Ruediger Westermann from the University of Erlangen, Germany this summer. Joint work in volume rendering was conducted during his stay. Dr. Rich Riesenfeld worked with Dr. Tom Lyche on multivariate splines in geometric design, both by travelling to Oslo and by hosting Dr. Lyche at Utah. Utah continues to work with Dr. Gershon Elber from the Technion-Israel Institute of Technology in Haifa, Israel. David Johnson presented a paper at the International Conference for Robotics and Automation '98 in Leuven, Belgium to an international crowd of roboticists and engineers. Dr. Waldemar Celes presented a paper, "Act: An easy-to-use and dynamically extensible 3D graphics library", at the Brazilian Symposium on Computer Graphics and Images Processing in October of 1997. The paper was based on his postdoctoral studies with the Center as described in section A.2.2. The Center collaboration with the Fraunhofer CRCG is discussed in section 4.A.

4.D Software Distribution

In keeping with our philosophy of sharing knowledge, we have made software and educational resources available over the Internet. These range from programming environments for scientific visualization to VR libraries to the exact dimensions and material properties of the "Cornell Box." Space precludes a full listing but all the Center's on-line software can be accessed from:

`http://www.cs.brown.edu/stc/outrea/community.html#software`

4.E Plans

E.1 Technology Transfer and Industrial Linkage

When the Center was founded in 1991, industry funding in computer graphics for university research collaborations and donations of equipment and software were far larger than today. The Center is striving to adjust to the new climate by proactively strengthening industry and government ties. The Center will continue to pursue new industry collaborations focused on research, licensing, technology transfer, and exchange of personnel.

5. Shared Experimental Facilities

The Center structure allows sharing of unique facilities and resources among the sites and with the graphics community. These shared facilities have often provided a basis for collaborative work between Center sites.

Advanced Manufacturing Lab

Utah's advanced manufacturing lab (AML) has been involved in several collaborative projects. In the Sketch-N-Make project (see **Modeling - Sketch-N-Make**), the lab was used as a test facility for validating the sketching approach. In the Camera Cluster project, the AML was used as a rapid prototyping facility. Without access to this facility, this project might not have been even attempted.

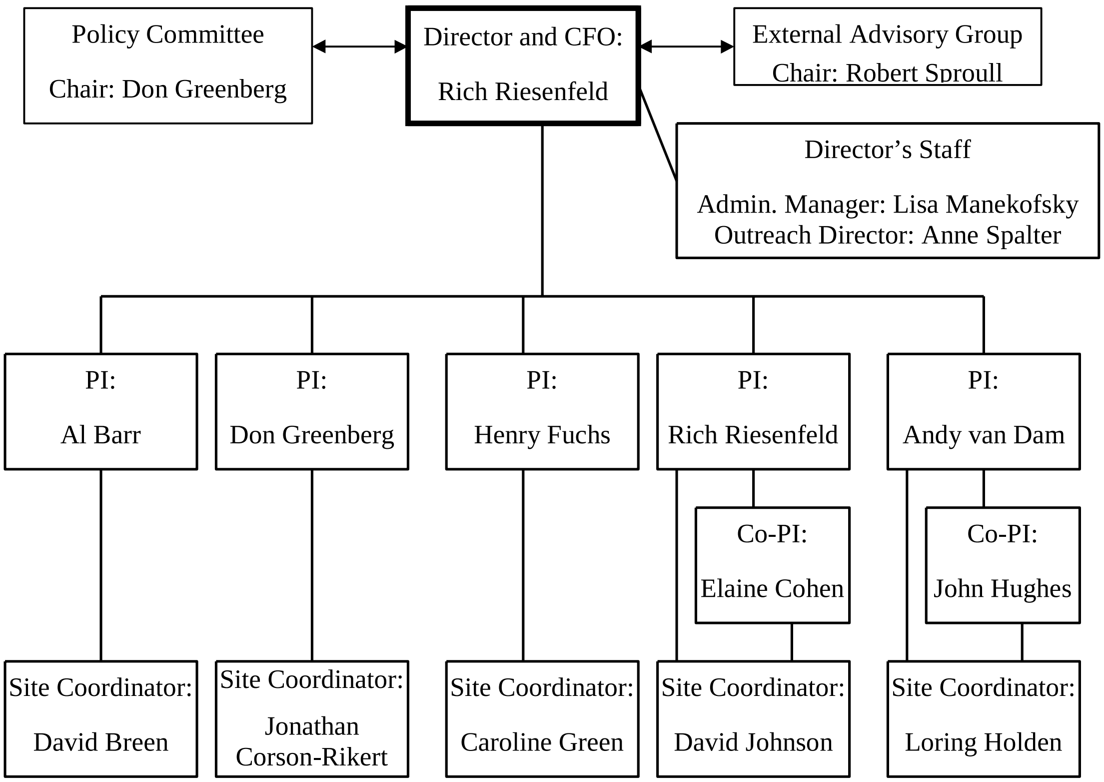
The Cornell Light Measurement Lab

We have measured a set of materials and made the light source spectra, filter and lens transmission spectra, and full bidirectional reflectance distribution functions (BRDF's) available to the research community. They represent a valuable resource for developing and validating reflectance models and rendering techniques. The data and some rendered images can be found at

http://www.graphics.cornell.edu/online/measurements/

6. Administration and Management

6.A Organization Chart



There have been no changes in the Center's organizational structure during this reporting period. However, there has been a rotation of personnel in senior positions. The most significant change is the transfer of Directorship from Andy van Dam to Rich Riesenfeld. The Center's Management Plan states "the Director shall not serve for more than five years, three years being a more typical term of office". Andy van Dam had served as Center Director since July 1995 and he chose to step down at the end of his third year in order to allow the next (and last) Director a full three years in office. The Center Policy Committee met and unanimously voted that Rich Riesenfeld should be the next Director (effective August 1, 1998). Andy van Dam will serve in an advisory capacity to the new Director throughout the transition period. As the PI at the Center's prime site (the University of Utah), Riesenfeld has held a key role throughout the Center's life and we expect an extremely smooth transition. Continuity in Center management will be ensured by the fact that our Administrative Manager (Lisa Manekofsky) and our Outreach Director (Anne Spalter) will stay on in their current positions (which they have held since 1995).

The other major change is in the position of Chair of the Policy Committee. The Policy Committee is a governing board, composed of the five Center Principal Investigators. The membership of the Committee has not changed but the position of Chair has rotated from Henry Fuchs to Don Greenberg.

6.B Director's Narrative

Scientifically and otherwise the past year has been an eventful one for the Center. In the spring of 1997 then-Director Andy van Dam was orchestrating the Center's mandated renewal process, approval of which would grant the Center funding for a full eleven years. A substantial Center-wide commitment of effort yielded a strong renewal proposal. Further months of preparation culminated in approximately seventy Center personnel and several crates of sensitive equipment converging on Utah to stage the two day site visit, with some of these resources arriving up to two weeks prior to the event. A large and distinguished group of jurors convened to judge the merits of the case. Our efforts were rewarded. The Center received high compliments for its structural development and continuing robust research program. A strong and unanimously favorable recommendation for our renewal emerged from the process resulting in renewed funding.

However, most of the Center's request for substantial additional funding for upgrading a woefully out of date networking infrastructure was not considered within the renewal request. Rather, it was suggested that we compete for this separately in an equipment and infrastructure program like the MRI program. We accepted the advice and followed up the renewal effort with a proposal to the MRI program. Under the leadership of the previous Director this too won approval and resulted in a $1.3M award for complementary equipment funding with a 1 October 1998 start date.

The Center worked hard and was rewarded for its efforts and accomplishments. In addition, we benefited from the opportunity to pause and collectively observe our own accomplishments. While site visits can be exhausting, they can also be invigorating -- with the new personal connections that were made there, new ideas and projects have emerged. Those who participated learned something important about the Center and what it was capable of. Televideo is not yet a replacement for working shoulder to shoulder, for challenging each other's ideas eye to eye, and for breaking bread across the dinner table at day's end. In making an impression on the jury we also made an impression on ourselves.

Fundamental research has always been a cornerstone of Center efforts. SIGGRAPH is always an important time for the Center, a time of high visibility for our work and leadership in the field. Once again the STC was represented in flattering numbers and importance with regard to paper authors, panel members, and tutorial lecturers. Moreover, this year was the 25th Anniversary for SIGGRAPH, and many retrospectives were featured. All of the STC PIs and many of its senior investigators were recognized for their leadership in establishing the field of computer graphics in a prominent photographic exhibit whose final home will be the Computer Museum. This underscored the fact that the Center consists of individuals who have pursued their research programs with persistent, long-term strategies. It was a time for the Center members to feel proud for their acknowledged seminal contributions during the last 25 years and to feel pleased with the role of the Center in providing compatible long-term support for their work. Of the more than 60 SIGGRAPH individuals featured for pioneering work in the entire field of computer graphics, only three were to women. Two of the three women cited, Mary Whitton and Elaine Cohen, are senior investigators in the Center. Such personnel resources as these two successful women are invaluable for our efforts to understand relevant discouraging subtleties in the field and to help to formulate strategies to effect positive change in the field with respect to opportunities for women and other underrepresented groups.

In addition to providing role models at the highest levels, the Center has continued its many programs aimed at increasing the flow of women and minorities into the field of computer science. This summer we had a boisterous group of 8th grade girls participating in the Artemis program at Brown who impressed Center faculty with their energy and career plans, as well as a dedicated group of incoming minority freshmen in the Bridge program and Cornell Summer Session. We also started a new alliance between the Center and Morehouse College, which included a Morehouse student working in the Brown site's graphics lab for four weeks this summer. Beginning this spring, the Caltech site will be starting a large-scale Center-funded outreach effort in Pasadena's largely minority public school system.

As a distributed team, the Center has continued its efforts to strengthen internal ties. At our annual STC SIGGRAPH reception there was a genuine esprit de corps -- a sense of common purpose, friendship, and fate that has taken years to nurture. In many ways we have become the Center that was only a dream in Don Greenberg's mind nearly a decade ago. During the reception, with 175 Center members present, Director Andy van Dam announced his resignation. He had done a great deal to bring the Center to this high point in its history, and we all acknowledged his outstanding leadership and level of commitment.

I feel highly privileged to follow Don Greenberg and Andy van Dam, who have demonstrated such exceptional capabilities as previous Directors. We had always envisaged that three directors would span the life of the STC, and so it has become my turn to be at the helm. We have worked smoothly through the transition. In fact, the Administrative Manager for the Center, Lisa Manekofsky, remains in her role, working from her office at Brown, as does Anne Morgan-Spalter, the Outreach Coordinator. I think this is an example of how the Center has developed, and how the network infrastructure serves to transcend the distances. As the timely receipt of this report indicates, so far this experiment in geographically distributed staffing has been comfortable and successful.

The research focus of the Center has remained telecollaboration, a joint project that extends over all sites. It is a good theme for the Center in that it highlights and draws on our diverse, complementary strengths to pursue a highly challenging problem requiring long-term, sustained research. This project largely represents work that we all believe could not occur without the framework of the Center.

This year the bulk of the research funding within the Center was distributed from the Director's Reserve for specific projects that were chosen from a suite of internally generated proposals. Since the distribution of the Director's Reserve affected both our tenures Andy and I decided to work together to make the funding decisions jointly, incorporating feedback from external reviewers. Again, the quality of the proposals was exceptional, and the fundable projects vastly outstripped the funding available. Subject to adequate funding and progress, we intend that sustained funding for these projects will be available for two years.

As I assume the role of Director I intend to concentrate on two major challenges, namely, making a greater impact on the community, and securing adequate follow-on funding. Heretofore the STC has been primarily challenged with internal issues. How should the STC be structured? How should it disburse its research funds? What function should its internal lecture series serve? How can we facilitate collaboration across sites? At this point I feel that the Center is functioning well internally, and we should give priority to making a larger impact on the community beyond the boundaries of the Center. I believe that we are at the proper stage of organizational maturity to appropriately pursue this goal. It will take further definition and focus to effectively develop an agenda in this direction.

The Center has made extraordinary internal progress. I have taken some space in this narrative to communicate this. We have come to know each other at new levels of working intimacy, and we are realistic in how we proceed in our collaborations. Together with love of the field and ultimate mutual professional respect, learning experiences and working friendships have brought us a long way. Through large NSF and personal investments, we have built an effective and powerful organization. We shall seek resources for further research support beyond the maximum eleven years of funding provided by the STC program. I plan to give this quest priority. The adopted Center theme of telecollaboration will be a significant strength in this pursuit. The theme is timely, important, and requires the broad creative and technical resources of the STC team.

Finally, I would like to reiterate that I was handed a ship that is on course and moving forward with a full head of steam, a clear tribute to my predecessors in this role. Don Greenberg and Andy van Dam have done outstanding work to bring the STC to this stage of success. I hope to do justice to their efforts in continuing this fine tradition.

6.C Center Advisors - the External Advisory Group

- Dr. Norman Badler, Professor, CIS and Director

  University of Pennsylvania Center for Human Modeling and Simulation

- Dr. Ingrid Carlbom, Head of Image Synthesis and Recognition Research Department

  Bell Laboratories, Lucent Technologies

- Dr. Donald Gaubatz, Consultant/Investor

  Multimedia/ATM Networking, Microprocessor Report Editorial Board

- Dr. Roscoe Giles, Associate Professor

  Boston University Department of Electrical and Computer Engineering

  Director, Center for Computational Science, Boston University

- Dr. Evelyn Hu, Professor

  University of California Department of Electrical and Computer Engineering

  Director, NSF STC for Quantized Electronic Structures (QUEST)

- Dr. Robert Sproull, VP & Fellow

  Sun Microsystems Laboratories

- Dr. James J. Thomas, Chief Scientist

  Information Sciences Department, Pacific Northwest National Laboratory

- Dr. Michael Wozny, Professor

  Department of Electrical & Computer Systems Engineering, Rensselaer Polytechnic Institute

7. Budget

The budgetary information follows this page.

8. Appendicies

8.A Publications

These are the publications from the current reporting period (October 1, 1997 - September 30, 1998) as well as articles for which complete publication information was not available at the time of the last Center report (the May 1997 renewal proposal). The ten most significant Center publications are marked with an asterisk (*).

Publications benefitting from primary Center support:

[alia97] Daniel G. Aliaga and Anselmo A. Lastra. "Architectural walkthroughs using portal textures," IEEE Visualization '97, pp. 355-362, Oct 19-24, 1997.

*[bloo98] M. Bloomenthal, R.C. Zeleznik, R. Fish, L.S. Holden, A.S. Forsberg, R. Riesenfeld, M. Cutts, S. Drake, H. Fuchs, and E. Cohen, “Sketch-N-Make: Automated Machining of CAD Sketches,” to appear in Proceedings of the 1998 ASME 8th Computers In Engineering Conference, 1998.

[bree98] David Breen, Sean Mauch, and Ross Whitaker, “3D Scan Conversion of CSG Models into Distance Volumes,” to appear in the Proceedings of the 1998 Symposium on Volume Visualization, October 1998.

[brem98] D.J. Bremer and J.F. Hughes, “Rapid Approximate Silhouette Rendering of Implicit Surfaces,” Proceedings of Implicit Surfaces ’98, June 1998, pp. 155-164.

[cele97] Waldemar Celes and Jonathan Corson-Rikert, “Act: An Easy-to-use and Dynamically Extensible 3D Graphics Library,” Proceedings, Brazilian Symposium on Computer Graphics and Image Processing, Campos do Jordao, SP -Brazil, October, 1997.

[cohe98] J. Cohen, M. Olano, and D. Manocha, “Appearance-Preserving Simplification,” Computer Graphics Proceedings, Annual Conference Series, 1998, ACM SIGGRAPH, pp. 115-122.

[cout97] Richard Coutts and Donald P. Greenberg, “Rendering with Streamlines,” Visual Proceedings, Computer Graphics Annual Conference Series, 1997, ACM SIGGRAPH, page 188.

[elbe97] G. Elber and R. Fish, “5-Axis Freeform Surface Milling using Piecewise Ruled Surface Approximation,” Journal of Manufacturing Science and Engineering, 1997.

[ferw97] James A. Ferwerda, Sumanta N. Pattanaik, Peter Shirley, and Donald P. Greenberg, “A Model of Visual Masking for Computer Graphics,” Computer Graphics Proceedings, Annual Conference Series, 1997, ACM SIGGRAPH, pp. 143-152.

[fors98a] Andrew Forsberg, Mark Dieterich, and Robert Zeleznik, “The Music Notepad,” to appear in Proceedings of UIST ’98, ACM SIGGRAPH.

[fors98b] A.S. Forsberg, J.J. LaViola, Jr., and R.C. Zeleznik, “ErgoDesk: A Framework for Two- and Three-Dimensional Interaction at the ActiveDesk,” Proceedings of the Second International Immersive Projection Technology Workshop, Ames, Iowa, May 11-12, 1998.

*[fors97] A.S. Forsberg, J.J. LaViola, Jr., M. Markosian, and R.C. Zeleznik, “Seamless Interaction in Virtual Reality,” IEEE Computer Graphics and Applications, Vol. 17, No. 6, November/December 1997.

*[gooc98] A. Gooch, B. Gooch, P. Shirley, and E. Cohen, “A Non-photorealistic Lighting Model for Automatic Technical Illustration," Computer Graphics Proceedings, Annual Conference Series, 1998, ACM SIGGRAPH, pp. 447-452.

*[gree97] Donald P. Greenberg, Kenneth Torrance, Peter Shirley, James Arvo, James Ferwerda, Sumanta Pattanaik, Eric Lafortune, Bruce Walter, Sing-Choong Foo, and Ben Trumbore, “A Framework for Realistic Image Synthesis,” Computer Graphics Proceedings, Annual Conference Series, 1997, ACM SIGGRAPH, pp. 477-494.

[greg98a] Gene Greger, Peter Shirley, Philip M. Hubbard, and Donald P. Greenberg, “The Irradiance Volume,” IEEE Computer Graphics and Applications, 18(2):32-43, March 1998.

[greg98b] A. Gregory, A. State, M. Lin, D. Manocha and M. Livingston, “Feature-based Surface Decomposition for Correspondence and Morphing between Polyhedra The Irradiance Volume,” Proc. of Computer Animation, 1998, to appear.

[heir98a] Alan Heirich, “Analysis of Scalable Algorithms for Dynamic Load Balancing and Mapping with Applications to Photo-realistic Rendering,” Caltech CS Technical Report CS-TR-98-10.

[heir98b] Alan Heirich and James Arvo, “A Competitive Analysis of Load Balancing Strategies for Parallel Ray Tracing,” Journal of Supercomputing, Vol. 12, No. 1/2, April 1998, pp. 57-68, 1998.

[heir97a] Alan Heirich and James Arvo, “Parallel Rendering with an Actor Model,” Proceedings of the 6th Eurographics Workshop on Programming Paradigms in Graphics, September 1997, pp. 115-125.

[heir97b] Alan Heirich and James Arvo, “Scalable Monte Carlo Image Synthesis,” Parallel Computing, Vol. 23, No. 7, July 1997, pp. 845-859.

[holl97] J. Hollerbach, E. Cohen, W. Thompson, R. Freier, D. Johnson, A. Nahvi, D. Nelson, T. Thompson II, and S. Jacobsen, “Haptic Interfacing for Virtual Prototyping of Mechanical CAD Designs,” Proceedings of Design for Manufacturing Symposium, (Sacramento, CA), ASME, September, 1997.

*[jaco98] Timothy Jacobs and Elaine Cohen, “Aggregation and Controlled Interaction: Automated Mechanisms for Managing Design Complexity,” Proceedings of ASME Design Engineering Technical Conference in Design Theory and Methodology, September, 1998.

[jaco97] Marco C. Jacobs, Mark A. Livingston, and Andrei State, "Managing Latency in Complex Augmented Reality Systems," Proceedings of 1997 Symposium on Interactive 3D Graphics (Providence, Rhode Island, April 27-30, 1997), pp. 49-54.

[john98a] C. Johnson, “Computer Visualization in Medicine,” to appear in National Forum, 1998.

[john98b] D.E. Johnson and E. Cohen, “A Framework For Efficient Minimum Distance Computations,” in Proceedings of the International Conference on Robotics and Automation, (Leuven, Belgium), IEEE, May 1998, pp. 3678-3684.

[klin97] G. Klinker, K. Ahlers, D. Breen, P.-Y. Chevalier, C. Crampton, D. Greer, D. Koller, A. Kramer, E. Rose, M. Tuceryan and R. Whitaker, “Confluence of Computer Vision and Interactive Graphics for Augmented Reality,” Presence: Teleoperations and Virtual Environments, Vol. 6, No. 4,August 1997, pp. 433-451.

[koll97] D. Koller, G. Klinker, E. Rose, D. Breen, R. Whitaker and M. Tuceryan, “Real-time Vision-based Camera Tracking for Augmented Reality Applications,” Proceedings of

the ACM Symposium on Virtual Reality Software and Technology (VRST-97), September 1997, pp. 87-94.

[lafo97] Eric P. F. Lafortune, Sing-Choong Foo, Kenneth E. Torrance, and Donald P. Greenberg, "Non-linear Approximation of Reflectance Functions," Computer Graphics Proceedings, Annual Conference Series, 1997, ACM SIGGRAPH, pp. 117-126.

[laid98a] David H. Laidlaw, Eric T. Ahrens, David Kremers, Matthew J. Avalos, Carol Readhead, and Russell E. Jacobs, "Visualizing Diffusion Tensor Images of the Mouse Spinal Cord," to be published in the Proceedings of the Visualization '98 Conference, October 1998.

*[laid98b] David H. Laidlaw, Kurt W. Fleischer and Alan H. Barr, "Partial-volume Bayesian Classification of Material Mixtures in MR Volume Data using Voxel Histograms," IEEE Transactions on Medical Imaging, Vol. 17, No. 1, Feb. 1998, pp. 74-86.

[lavi98a] J. LaViola, A. Forsberg, and R. Zeleznik, "Jot: A Framework for Interface Research," IBM interVisions Online, #11, February, 1998.

[lavi98b] J. LaViola, L. Holden, A. Forsberg, D. Bhuphaibool, and R. Zeleznik, "Collaborative Conceptual Modeling Using the SKETCH Framework," Proceedings of the IASTED International Conference on Computer Graphics and Imaging, June 1998, pp 154-158.

*[lee98] Aaron W.F. Lee, Wim Sweldens, Peter Schroeder, Lawrence Cowsar and David Dobkin, "MAPS: Multiresolution Adaptive Reparameterization of Surfaces," Computer Graphics Proceedings, Annual Conference Series, 1998, ACM SIGGRAPH, pp. 95-104.

[livn98] Y. Livnat and C. Hansen, "View Dependent Isosurface Extraction," to appear in Proceedings of IEEE Visualization '98, October, 1998.

[mark97b] Lee Markosian, Michael A. Kowalski, Samuel J. Trychin, Lubomir D. Bourdev, Daniel Goldstein, and John F. Hughes, "Real-Time Nonphotorealistic Rendering," Computer Graphics Proceedings, Annual Conference Series, 1997, ACM SIGGRAPH, pp. 415-420.

[mark97a] William R. Mark, Leonard McMillan, and Gary Bishop, "Post-Rendering Warping," Proceedings of 1997 Symposium on Interactive 3D Graphics (Providence, Rhode Island, April 27-30, 1997), pp. 7-16.

[meen98] Gopi Meenakshi and Dinesh Manocha, “A Unified Approach for Simplifying Polygonal and Spline Models,” To appear in the Proceedings of IEEE Visualization ’98, October, 1998.

[mill98] Timothy Miller and Robert Zeleznik, “An Insidious Haptic Invasion: Adding Force Feedback to the X Desktop,” to appear in Proceedings of UIST ’98, ACM SIGGRAPH.

[nahv98] A. Nahvi, D.D. Nelson, J.M. Hollerbach, and D.E. Johnson, “Haptic Manipulation of Virtual Mechanisms from Mechanical CAD Designs," Proceedings of the IEEE International Conference on Robotics & Automation, Leuven, Belgium, May 16-21, 1998, pp. 375-380.

*[olan98] Marc Olano and Anselmo Lastra, “A Shading Language on Graphics Hardware: The PixelFlow Shading System,” Computer Graphics Proceedings, Annual Conference Series, 1998, ACM SIGGRAPH, pp. 159-168.

*[patt98a] Sumanta N. Pattanaik, James A. Ferwerda, Mark D. Fairchild, and Donald P. Greenberg, “A Multiscale Model of Aadaptation and Spatial Vision for Realistic Image Display,” Computer Graphics Proceedings, Annual Conference Series, 1998, ACM SIGGRAPH, pp. 287-298.

[patt98b] Sumanta N. Pattanaik and Kenneth E. Torrance, “Light Measurement Using the Photometrics PXL1300L CCD Camera,” Technical report PCG-98-1, Program of Computer Graphics, Cornell University, May 1998.

[patt97] Sumanta N. Pattanaik, James A. Ferwerda, Kenneth E. Torrance, and Donald P. Greenberg, “Validation of Global Illumination Solutions through CCD Camera Measurements,” Proceedings of the Fifth Color Imaging Conference, Society for Imaging Science and Technology, pages 250-253, November 1997.

[pope98] Voicu Popescu, Anselmo Lastra, Daniel Aliaga, Manuel de Oliveira Neto. "Efficient warping for Architectural walkthroughs using layered depth images," IEEE Visualization 98, to appear.

[rade98] Paul Rademacher and Gary Bishop, “Multiple-Center-of-Projection Images”, Computer Graphics Proceedings, Annual Conference Series, 1998, ACM SIGGRAPH, pp. 199-206.

[raff98a] Matthew Rafferty, Daniel Aliaga, Anselmo Lastra. "3D image warping in architectural walkthroughs." VRAIS 98, pp. 228-233, March 14-18, 1998.

[raff98b] Matthew Rafferty, Daniel Aliaga, Voicu Popescu, Anselmo Lastra, "Images for accelerating architectural walkthroughs," IEEE Computer Graphics and Applications, to appear December 1998.

[rama98] Ravi Ramamoorthi, “Creating Generative Models From Range Images,” Caltech CS Technical Report CS-TR-98-05, 1998.

[rama97] Ravi Ramamoorthi and Alan H. Barr, “Fast Construction of Accurate Quaternion Splines,” Computer Graphics Proceedings, Annual Conference Series, 1997, ACM SIGGRAPH, pp. 287-292.

[rask98a] Ramesh Raskar, Matt Cutts, Greg Welch, and Wolfgang Stuerzlinger, “Efficient Image Generation for Multiprojector and Multisurface Display Surfaces,” 9th EuroGraphics Rendering Workshop (1998).

*[rask98b] Ramesh Raskar, Greg Welch, Matt Cutts, Adam Lake, Lev Stesin, and Henry Fuchs, “The Office of the Future: A Unified Approach to Image-Based Modeling and Spatially Immersive Displays,” Computer Graphics Proceedings, Annual Conference Series, 1998, ACM SIGGRAPH, pp. 179-188.

[rask98c] Ramesh Raskar, Greg Welch, and Henry Fuchs, “Spatially Augmented Reality,” First IEEE International Workshop on Augmented Reality, San Francisco, 1998.

[sche97] Ellen J. Scher Zagier, "A Human's Eye View: Motion Blur and Frameless Rendering," ACM Crossroads `97.

[shir97] P. Shirley, H. Hu, B. Smits, and E. Lafortune, “A Practitioners' Assessment of Light Reflection Models," Pacific Graphics 97, pp. 40-49.

[sloa98] Peter-Pike J. Sloan, David M. Weinstein, and J. Dean Brederson, “Importance Driven Texture Coordinate Optimization,” to appear in Eurographics ’98, September 1998.

[thom97] T.V. Thompson II, D.D. Nelson, E. Cohen, and J. M. Hollerbach, “Maneuverable NURBS models within a haptic virtual environment,” 6th Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, DSC-Vol. 61, (Dallas, TX), Nov. 15-21, 1997, pp. 37-44.

[walt97a] Bruce Walter, Philip M. Hubbard, Peter Shirley, and Donald P. Greenberg, “Global Illumination using Local Linear Density Estimation,” ACM Transactions on Graphics, 16(3):217-259, July 1997.

[walt97b] Bruce Walter, Gün Alppay, Eric Lafortune, Sebastian Fernandez, and Donald P. Greenberg, “Fitting Virtual Lights for Non-Diffuse Walkthroughs,” Computer Graphics Proceedings, Annual Conference Series, 1997, ACM SIGGRAPH, pp. 45-48.

[whit98] Ross Whitaker and David Breen, “Level-set Models for the Deformation of Solid Objects,” Proceedings of the 3rd International Workshop on Implicit Surfaces, Eurographics Association, June 1998, pp. 19-35.

[zori97a] Denis Zorin, “Stationary Subdivision and Multiresolution Surface Representations,” Caltech CS Technical Report CS-TR-97-32, 1997.

[zori97] Denis Zorin, Peter Schroeder, and Wim Sweldens, “Interactive Multiresolution Mesh Editing,” Computer Graphics Proceedings, Annual Conference Series, 1997, ACM SIGGRAPH, pp. 259-268.

Publications benefitting from partial Center support:

[mars98] Stephen M. Marschner. *Inverse rendering for computer graphics.* PhD thesis, Cornell University, 1998.

[mars97a] Stephen R. Marschner, “Texture Maps from Photographs of Scanned 3d Surfaces,” Technical report PCG-97-1, Program of Computer Graphics, Cornell University, April 1997.

[mars97b] Stephen R. Marschner and Donald P. Greenberg, “Inverse Lighting for Photography,” Proceedings of the Fifth Color Imaging Conference, Society for Imaging Science and Technology, November 1997.

[moll97] Tomas Möller and Ben Trumbore, “Fast, Minimum Storage Ray-triangle Intersection,” Journal of Graphics Tools, 2(1):21-28, 1997.

[peng98] Liang Peng, “Dichromatic Based Photographic Modification,” Proceedings of the Sixth Color Imaging Conference, Society for Imaging Science and Technology, November 1998.

[peng97] Liang Peng, Eric Lafortune, and Donald P. Greenberg, “Use of Computer Graphic Simulation to Explain Color Histogram Structure,” Proceedings of the Fifth Color Imaging Conference, Society for Imaging Science and Technology, November 1997.

8.B Patent Applications:

Henry Fuchs, Greg Welch, Gary Bishop and Mark Livingston: Dynamic Generation of Imperceptible Structured Light for Tracking & Acquisition of Three-Dimensional Scene Geometry and Surface Characteristics in Interactive Three-Dimensional Computer Graphics Architecture

Peter Schroeder with Lucent Technologies for MAPS: Multiresolution Adaptive Parameterization of Surfaces

8.C Graduates During the Reporting Period

DEGREE:	PLACEMENT:
Ph.D.	
Weihai Chen	industry
Alan Heirich	industry
Chi-Chang Ho	industry
Subodh Kumar	academia
Steve Marschner	industry
T. Marc Olano	industry
Liang Peng	industry
Han-Wei Shen	government
Margaret Sturgill	industry
Bruce Walter	academia
Xiaohong Zhu	industry
Denis Zorin	academia
M.S.	
Gun Alppay	industry
Lubomir Bourdev	industry
David Bremer	industry
Dennis Brown	industry
Richard Coutts	industry
Matthew Cutts	academia
Myles Harthun	industry
Andrew Kunz	industry
Brian Frank Los	industry
Joseph LaViola	academia
Michael Malone	industry
Moreno Piccolotto	academia
Ravi Ramamoorthi	academia
Lev Stesin	industry

Jennifer Stewart	industry

Postdoctoral Associates

Sumant Pattanaik	academia
Ruediger Westermann	academia

8.D List of Center Participants (Faculty Level and Equivalent)

Receiving Center Support:

James Arvo

Alan Barr

Gary Bishop

David Breen

Elaine Cohen

Thomas Doeppner

Sam Drake

Henry Fuchs

Donald P. Greenberg

Chuck Hansen

John Hughes

Christopher R. Johnson

Richard F. Riesenfeld

Peter Schroeder

Peter Shirley

Brian Smits

Kenneth E. Torrance

Andy van Dam

Greg Welch

Affiliated (not receiving Center support):

Frederick P. Brooks, Jr.

Nick England

Mathieu Desbrun

Mark Fairchild - visiting professor from Rochester Institute of Technology 8/97-8/98

Anselmo Lastra

David Laidlaw

Dinesh Manocha

Brent Seales

Ruediger Westermann

Mary Whitton

User of Shared Center Facilities:

John Hollerbach

Robin McCloud

Lars Nyland

Steven M. Pizer

Nancy Pollard

Jon Schmidt

Russell Taylor

William Thompson

8.E Biographical Information for New Investigators

Mathieu Desbrun

Postdoctoral Associate

Multi-Res Modeling Group

Computer Science Department

California Institute of Technology

Education

Ph.D., Computer Science, National Polytechnic Institute of Grenoble, France, 1997.

M.Eng, Computer Science and Applied Mathematics, University of Grenoble, 1994.

Mathiew Desbrun's current research interests include physically-based animation for deformable bodies, modeling and sculpting with implicit surfaces, and multi-resolution models. He also supervises the progress on the Responsive Workbench at Caltech.

Selected Publications

* Mathieu Desbrun and Marie-Paul Cani-Gascuel, "Active Implicit Surface for Animation," Proceedings of Graphics Interface '98

* Marie-Paul Cani-Gascuel and Mathieu Desbrun, "Animation of Deformable Models Using Implicit Surfaces," IEEE Transactions on Visualization and Computer Graphics, Vol. 3, No. 1, 1997

* Mathieu Desbrun, Nicolas Tsingos and Marie-Paul Gascuel, "Adaptive Sampling of Implicit Surfaces for Interactive Modeling and Animation," Computer Graphics Forum, Vol. 15, No. 5, 1996.

* Mathieu Desbrun, Nicolas Tsingos and Marie-Paul Gascuel, "Animating Soft Substances with Implicit Surfaces," Proceedings of SIGGRAPH 1995.

Nancy S. Pollard

Assistant Professor

Computer Science Department

Brown University

Education

Ph.D., Massachusetts Institute of Technology, 1994.

M.S., Massachusetts Institute of Technology, 1989.

B.S., University of Houston, 1986.

Experience

Assistant Professor, Brown University, July 1998-present.

Postdoctoral researcher, Georgia Institute of Technology, Oct. 1996-June 1998.

Engineer/Consultant, Decision Architects, Cambridge, MA Jan. 1994-Sept. 1996.

Research Assistant, MIT Artificial Intelligence Labs, Oct. 1986 - Jan. 1994.

Awards Received

National Science Foundation Postdoctoral Research Associates in Computational Science and Engineering, 1997

Professional Activities

* Program Committee for the 1998 IEEE Robotics and Automation Conference

* Session Chair for the 1997 IEEE Robotics and Automation Conference

* Reviewer, IEEE Transaction on Visualization and Computer Graphics, IEEE Computer Graphics and Applications, IEEE Transactions on Robotics and Automation, Journal of Robotic Systems, IEEE International Conference on Robotics and Automation.

Selected Recent Publications

* Nancy S. Pollard, “Quality Preserving Algorithms for Grasp Synthesis from Prototypes,” IEEE Transactions on Robotics and Automation (to appear).

* Nancy S. Pollard and Jessica K. Hodgins, “Adapting Behaviors to New Environments, Characters, and Tasks,” The Tenth Yale Workshop on Adaptive and Learning Systems, Yale University, New Haven, CT, June 10-12, 1998.

* Jessica K. Hodgins and Nancy S. Pollard, “Adapting Existing Simulations for New Characters,” ACM SIggraph ‘97 Proceedings, Los Angeles, CA, 1997.

* Nancy S. Pollard, “Parallel Algorithms for Synthesis of Whole-Hand Grasps,” Proceedings of the IEEE International Conference on Robotics and Automation, Albuquerque, NM, 1997.

* Nancy S. Pollard, “Synthesizing Grasps from Generalized Prototypes,” Proceedings of the IEEE International Conference on Robotics and Automation, Minneapolis, MN, 1996.

Brian Smits

Assistant Research Professor

Department of Computer Science

University of Utah

Education

Ph.D., Computer Science, Cornell University, Ithaca, NY, 1994.

B.A., Computer Science/Mathematics, University of Oregon, Eugene, OR, 1990.

Experience

Assistant Research Professor, Dept. of Computer Science, University of Utah 1998-

Post Doctoral Associate, Dept. of Computer Science, University of Utah 1997-1998

Software Engineer, Lightscape Technologies, 1994-1997.

Recent Research Accomplishments:

Professor Smits has worked in the areas of both physically based and perceptually based rendering.

Selected Publications

* Peter Shirley, Helen Hu, Brian Smits, Eric Lafortune, “Light Reflection Models for Realistic Computer Graphics,” Pacific Graphics 1997 (invited paper).

* Brian Smits, Jim Arvo, Don Greenberg, “A Clustering Algorithm for Radiosity in Complex Environments,” Computer Graphics (Proceedings of SIGGRAPH) 28(4) August 1994.

* Jim Arvo, Ken Torrance, Brian Smits, “A Framework for the Analysis of Error in Global Illumination Algorithms,” Computer Graphics (Proceedings of SIGGRAPH) 28(4) August 1994.

* Dani Lischinski, Brian Smits, Don Greenberg, “Bounds and Error Estimates for Radiosity,” Computer Graphics (Proceedings of SIGGRAPH) 28(4) August 1994.

* Chris Schoeneman, Julie Dorsey, Brian Smits, Jim Arvo, Don Greenberg, “Painting with Light” Computer Graphics (Proceedings of SIGGRAPH) 27(4) August 1993.

* Brian Smits, Jim Arvo, David Salesin, “An Importance-Driven Radiosity Algorithm,” Computer Graphics (Proceedings of SIGGRAPH), 26(4) July 1992.

* Brian Smits, Gary Meyer, “Newton’s Colors: Simulating Interference Phenomena in Realistic Image Synthesis,” Eurographics Rendering Workshop Rennes, France 1990.

8.F Awards and Honors

SIGGRAPH '98:

The 25th SIGGRAPH conference, held in July 1998, featured exhibits and events celebrating the history of SIGGRAPH and computer graphics. The Center's PIs and labs were featured in the following:

** A Visual Tribute to Computer Graphics Laboratories 1971-1998*

Twelve laboratories were presented in this exhibit, including all five Center labs.

** Portraits in Computer Graphics*

Photographic portraits of eighty noteworthy individuals in the field of computer graphics were exhibited at the conference. Included were portraits of all five Center Pis, Center co-PI Elaine Cohen, and Center Faculty Mary Whitton and Ken Torrence.

* *Seminal Graphics: Pioneering Efforts that Shaped the Field*

This special ACM Publication highlighted the most influential papers in the field of computer graphics over the past 25 years. It included four papers from Center PIs: Al Barr's paper, "Global and Local Deformations of Solid Primitives". Don Greenberg's papers, "Modeling the Interaction of Light Between Diffuse Surfaces", and "A Progressive Refinement Approach to Fast Radiosity Image Generation", and Henry Fuchs' paper, "Distributing a Visible Surface Algorithm Over Multiple Processors."

** Trading Cards*

SIGGRAPH 98 produced a set of trading cards featuring award winners, art, and hardware from the past 25 years. Four of the five Center PIs (Al Barr, Don Greenberg, Henry Fuchs, and Andy van Dam) were featured on trading cards.

** Digital Campfire*

The great stories and legends of computer graphics told by the luminaries in the field. Andy van Dam was invited to speak during the "Interactivists" session.

Other Awards and Honors

Faculty:

Henry Fuchs was inducted into NAE (the National Academy of Engineering)

Don Greenberg was awarded the Association of Collegiate Schools of Architecture (ASCA) Creative Achievement Award on March 14, 1998.

Chris Johnson was a finalist for the Smithsonian Computerworld Innovation Award. He also received the Presidential Teaching Scholar Award from the University of Utah.

Peter Shirley received the College of Engineering Distinguished Teaching Award from the University of Utah.

Students:

Matthew Cutts was awarded a Link Foundation Fellowship.

Joseph Laviola received an IBM fellowship.

Matt Lerner received an IBM fellowship.

Lee Markosian received an Intel fellowship.

Mark Meyer received a Charles Lee Powell Foundation Fellowship.

Ramesh Raskar was awarded a Link Foundation Fellowship.

8.G Summary of External Advisory Group Meetings

While the Center does hold an External Advisory Group (EAG) meeting each year, the most recent meeting did not fall within the reporting period for this report (October 1997 through September 1998). The last EAG meeting was held on May 1, 1997, at which time the advisory group provided input on the Center's draft renewal proposal and plans for our (then) upcoming renewal site visit. Our next EAG meeting is scheduled for December 10, 1998.

8.H Continuing and Pending Support

Continuing and Pending Support pages follow this page.