

## VOLUMETRIC VISUALIZATION OF 3D DATA

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### INTRODUCTION

In recent years, there has been a rapid growth in the ability to obtain detailed data on large complex structures in three dimensions. This development occurred first in the medical field, with CAT scans and now magnetic resonance imaging, and in seismological exploration. With the advances in supercomputing and computational fluid dynamics, and in experimental techniques in fluid dynamics, there is now the ability to produce similar large data fields representing 3D structures and phenomena in these disciplines.

These developments have produced a situation in which currently we have access to data which is too complex to be understood using the tools available for data reduction and presentation. Researchers in these areas are becoming limited by their ability to visualize and comprehend the 3D systems they are measuring and simulating.

### HISTORY

In response to this, there is growing activity in the area of visualization of 3D data. Some early work in this area was done by Harris et al. (1979) at the Mayo Clinic and Herman et al. (1984) at the University of Pennsylvania in the area of medical imaging. In 1983, Jaffey, Dutta, and Hesselink (1984) approached the subject from a different direction. They developed the "source-attenuation" model, and used holograms to visualize 3D subjects. More recently, there is stronger emphasis on interactive visualization, and concentration on techniques and systems for general use and commercial products (Goldwasser, 1985; Hunter, 1984).

Much of the recent activity is directed toward improving and extending the use of graphics techniques for interactive visualization of data based on surface representations. The groundwork for this was done by Herman et al. Work in this area is continuing both in academic groups (Herman at the University of Pennsylvania (Herman et al., 1984 and Fuchs at North Carolina (Fuchs et al., 1985), and in several commercial ventures (notably CEMAX)). Also, graphics projects at NASA, JPL, and aerospace corporations have been providing increasing support for visualization tasks based on conventional graphics concepts.

The more interesting projects involve departures from conventional graphics. By careful use of transparency, it is possible to produce images of 3D systems which provide true volumetric visualization, rather than surface projections. We have been working on this type of system for the past three years (Russell and Miles, 1987), concentrating on techniques which are efficient enough

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to be used interactively on existing computer systems. Pixar Corporation has recently been developing a package to support volumetric visualization, including an approach called Volume Rendering Technique, which they developed with Phillips Medical Systems and Dr. E. Fishman (1987) of Johns Hopkins University. This package is perhaps the most comprehensive image-based system commercially available at this time.

An approximation to volumetric imaging is also provided in PLOT3D, a graphics software system developed at JPL. This package includes a facility for producing nested transparent contour surfaces from a volumetric data base, which provides surprisingly good visualization of the data. Its primary limitations are data size (about 100,000 data points) and the number of contours it can support. Also, since this is a rather symbolic representation, it must be interpreted with care.

## VOLUMETRIC VS. 2 1/2D VISUALIZATION

Normal pictorial illustration (stills), and most widely used 3D graphics techniques are limited to providing 2 1/2D surface images. That is to say, along any line of sight there is only one object or surface visible. This usually produces pictures from which a rough idea of the three-dimensional structure of the original scene can be deduced. In contrast, X-ray images generally do not have a unique interpretation as projections of some three-dimensional subject, and even X-ray stereo pairs are insufficient to provide an unambiguous interpretation without a priori knowledge about the subject.

This is a computational constraint which applies not only to visual observation of pictures, but to interpretation of volumetric projections in general. Vision, however, is capable of limited volumetric perception and comprehension, if given adequate stimulus.

In order to achieve effective volumetric perception, it is necessary to present volumetric data in a form that vision is accustomed to dealing with. While cross sections are often useful for detailed study of internal features, it is difficult or impossible to fully comprehend the 3D structure of an object in this manner. Instead, data must be presented as we would see a real object. Natural visual processing transforms this information back into a mental structural model. Volumetric characteristics of the data are conveyed by making the projection TRANSPARENT, as implied in the earlier discussion.

The requirements for volumetric perception are basically the same as for computed axial tomography. A set of projection images from many different viewpoints is computationally sufficient to reconstruct the internal details of a subject. Visual reconstruction has several added constraints: the images must be presented as an ordered sequence of closely spaced views, and they must be shown at a rate of at least 8 to 10 frames/sec. These constraints are dictated by the temporal character of visual perception.

For perception of volumetric structure (rather than surface structure), complex optical phenomena such as lighting and shading, specular (surface) reflections, and diffraction and diffusion are not useful. In fact, these effects generally make the basic structure of volumetric scenes more difficult to understand, overwhelming the viewer with fine details and optical distortions. Simple luminance and opacity are adequate for volumetric visualization.

## SYSTEM IMPLEMENTATION

We have developed a system at Princeton which implements this approach to volumetric visualization on a PC/AT (Russell and Miles, 1987). The algorithms upon which it is based are efficient enough to provide a usable off line visualization system on the AT (precomputed images take approximately 1 min/view for 2 million data points) and they are suitable for development into a real-time interactive visualization system using current state-of-the-art commercial hardware (AT&T Pixel Machine, for example).

The model for the system has the following characteristics.

1. Data consists of samples on any regular 3D lattice (e.g., simple cubic, face-centered cubic, hexagonal close packed).
2. The data elements are treated as nebulous, fuzzy regions localized around the sample coordinates. (i.e., no subvoxel definition—consistent with proper sampling technique).
3. Optical model includes luminance and opacity control at each data point, with the possibility of handling a light source (no refraction or specular reflection).
4. Views are computed directly from the data, without any intermediate representation. This reduces the risk of artifacts and avoids simplification of the data that may lead to the loss of features.
5. Perspective is not supported (this is subordinate to motion).

This combination of characteristics yields a model which is well-behaved and computationally efficient, with enough flexibility to provide a broad range of visual effects.

The implementation on the PC/AT operates in a two-step process. For a given data base, a sequence of views is computed, based on a selected set of optical characteristics onto which the data are mapped, and a viewpoint and axis of rotation for the data. Each image takes about 60 to 75 sec, for a typical data base of 2 million samples (e.g., 32x256x256 or 128x128x128), and we usually generate anywhere from 15 images (for a restricted range of views) to 120 images (for a full rotation of the data). The images are stored on a disk as they are generated. When a sequence is complete, the images are loaded by a second program for viewing. Up to 180 clipped images (176x176) may be loaded into 6 Mbytes of RAM on the PC/AT. They may then be viewed as a movie on a full-color, 8-bit greyscale display at frame rates up to 15 frames/sec. The viewpoint is controlled interactively using a mouse, within the precomputed range.

## EVALUATION

This method of visualization provides good comprehension for a range of subjects and optical characteristics. Its most significant advantage is that it is very robust. There is little or no preprocessing of the data, so there are generally no computational artifacts. Even data containing no distinct surfaces can be accurately visualized, since this method does not rely on surfaces as the

fundamental elements of a scene. The use of motion as the means of communicating structure allows all the data to be made visible through the use of transparency. This provides a high degree of confidence in the resulting visualization. It is also robust in the sense that an informative set of images can be produced using simple optical characteristics (luminance = data value, high transparency) with little or no a priori knowledge about the data itself.

The motion/transparency approach is most effective with scenes of moderate complexity (such as that shown in Fig. 1), that is, scenes whose structure can be largely comprehended as a whole. With very complex scenes, containing perhaps hundreds of detailed components (e.g., a video cassette recorder guts), this type of visualization suffers from showing too much information, which cannot be fully comprehended as a single entity.

## COMPLEXITY

The issue of complexity arises in visualization for two distinct reasons. The first is the visual limitation just mentioned. The mind is incapable of performing a complete internal reconstruction of a volumetric scene, as is done in a CAT scan, for example. We have observed that beyond a certain level of complexity in depth (apparently three to four layers of structure), the mind's ability to maintain a conceptual model of a scene begins to fail.

In addition to the visual/conceptual limitation, there is an optical constraint which limits the degree of complexity which is practically acceptable. There is a tradeoff between the amount of transparency used (which affects the visibility of embedded structures) and the amount of contrast available in small features. This is directly related to signal-to-noise (S/N) ratio. Vision does not have particularly large S/N ratio, so fine details quickly lose definition as transparency is increased. This is also a limiting factor in CAT scans, but the devices used have much higher S/N ratios, so much lower contrast can be tolerated in CAT-scan source images than is detectable visually.

These considerations provide strong motivation to develop means of reducing and controlling the level of complexity in volumetric visualization.

## THE ROLE OF BINOCULAR VISION

From a very early point in our investigation of visualization, it was clear that stereo pairs were inadequate as illustration of volumetric scenes. Once we had a working visualization system based on motion, it was easy to see how much more comprehensive this approach is than static stereo viewing. For some time, we assumed that adding stereopsis to the motion-based system would not be worthwhile, since static experiments suggested that stereopsis would not work well on precisely those scenes where some improvement was needed. Specifically, scenes with extensive volumetric content and high complexity, such as medical data, generally have low contrast and few clearly defined, unique features on which stereopsis can operate. For scenes which are visualized with low transparency, which provides more distinct features, stereopsis is not really needed since these scenes are generally quite easily understood with only the motion-based visualization.

When we actually were able to try out stereo and motion together, the results were somewhat surprising. With scenes of medical data with moderate to high transparency, static stereo viewing is relatively ineffective, as expected. However, when motion and stereo viewing are used together, the stereopsis provides noticeable enhancement to the visual perception of the structure over motion alone. There is apparently some interaction between the visual mechanisms which use stereo and motion to deduce structure. The combined effectiveness suggests that stereopsis is facilitated by information made available by motion, which perhaps allows better feature matching between images, resulting in more and better disparity measurements.

This strong interaction between stereopsis and motion perception means that stereopsis must be considered as an important part of any visualization system. Though motion is very powerful alone, considerable enhancement is possible through the use of binocular vision.

## CONCLUSIONS

This approach to visualization, using transparency and motion in an image-based system, has significant advantages over systems based on solid rendering or graphical modeling. Most significant are the broader range of volumetric structure which can be visually represented and the robustness and freedom from artifact which volumetric visualization provides. A comprehensive visualization facility should certainly include the ability to perform both image-based and graphical rendering, and in the future these techniques should be increasingly integrated to allow both graphical and image-based components in a single visualization.

Computers are now becoming available which will be capable of performing visualization tasks interactively. This will dramatically change the way in which visualization is used, particularly for very complex subjects. As interactive visualization becomes more practical, the current emphasis on development of techniques for data reduction and rendering should be supplanted by the need for means of controlling and interacting with the visualization process. As the potential degrees of freedom for controlling a visualization increase with the complexity and size of scenes, the design of effective control mechanisms will be a difficult endeavor.

Some simple control mechanisms, such as clipping, spatial editing tools, and 3D cursors, are relatively easy to implement. However, for complex data, control mechanisms should parallel the way in which structures are decomposed and manipulated conceptually. This means providing the capability to specify the structural components of a scene and control their visual characteristics by referring to them as objects. Automated or computer-aided object segmentation is required to make this practical, but for the purpose of interactive control of visualizations, the accuracy and reliability of segmentations need not be as high as it must for conventional, noninteractive visualization.

Additionally, it may be useful to be able to produce geometric distortions of data in order to push obstructing objects out of the way without separating them altogether from the region of interest. The net effect would be to produce the equivalent of an exploded view for structures of nondiscrete components. This would be particularly useful in medical applications. If information about connectivity and stiffness can be incorporated into the process, this could make the visualization system even more useful in surgical training or preoperative planning environments, where the mechanical properties of tissue structures is very important.

Advanced modes of interaction will become more and more important as volumetric display is applied to more ambitious problems of data interpretation.

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Figure 1.— Vortex rings resulting from the Crow instability. Navier-Stokes simulation data provided by Dr. Micheal Shelley, Princeton University.



# **FINAL PROGRAM**

**Spatial Displays and Spatial Instruments:  
A Symposium and Workshop  
Sponsored by the  
National Aeronautics and Space Administration  
and the  
University of California, Berkeley**

**August 31 – September 3, 1987  
Asilomar, California**

## **August 31**

2:00–5:00 pm	Check-in and Orientation
4:00–5:00 pm	Reception
6:00 pm	Dinner
7:00–8:00 pm	Welcomes D. Nagel Chief: Aerospace Human Factors Ames Research Center
	Conference Purpose Pictorial Communication S. R. Ellis Ames Research Center
	The Role of Pictorial Communication in Aerospace M. W. McGreevy Ames Research Center
	Conference Logistics, etc. M. Moultray and S. R. Ellis

## **September 1**

7:30–8:20 am	Breakfast
8:20–12:30 pm	Invited Paper Session 1 Chairman: S. R. Ellis

## SPATIAL PERCEPTION

- 8:30 am            “Perspectives on Perspective”  
Professor R. L. Gregory  
University of Bristol Medical School  
Introduction by S. R. Ellis  
  
5-min discussion
- 9:05 am            “Visual Realism in Boeing Simulators”  
C. Kraft  
Formerly Boeing Commercial Aircraft Company  
Introduction by J. Cutting  
  
5-min discussion
- 9:40 am            10-min Coffee Break

## SPATIAL ORIENTATION

- 9:50 am            “Perception of Egocentric Visual Direction”  
Professor I. Howard  
York University  
Introduction by H. Mittelstaedt  
  
5-min discussion
- 10:25 am           “Egocentric Direction in Simulators”  
T. Furness  
Wright-Patterson Air Force Base  
Introduction by S. Fisher  
  
5-min discussion

## PICTURE PERCEPTION

- 11:00 am           “Picture Perception and Virtual Space”  
Professor H. A. Sedgwick  
SUNY College of Optometry  
Introduction by J. Perrone  
  
5-min discussion
- 11:35 am           “The Design of Pictorial Displays”  
Professor S. Roscoe  
New Mexico State University  
Introduction by J. Hartzell  
  
5-min discussion

12:20–1:30 pm      Lunch Break

1:30–5:50 pm      Contributed Paper Session  
Chairman: M. Kaiser

#### SPATIAL PERCEPTION

1:30 pm      “Spatial Factors Influencing Stereopsis  
and Fusion”  
Professor C. Schor  
U.C. Berkeley

1:50 pm      “Scaling Stereoscopic Space”  
Professor J. Foley  
U.C. Santa Barbara

2:10 pm      “Paradoxical Monocular Stereopsis and  
Perspective Vergence”  
Professor J. T. Enright  
Scripps Institution of Oceanography

2:30 pm      “The Perception of Three  
Dimensionality Across Continuous  
Surfaces”  
Professor K. Stevens  
University of Oregon

2:50 pm      “Perceiving Environmental Properties  
From Motion Information: Minimal  
Conditions”  
Professor D. Proffitt  
University of Virginia  
and  
M. Kaiser  
Ames Research Center

#### SPATIAL ORIENTATION

3:10 pm      “Memory Distortions of Visual  
Displays”  
Professor B. Tversky  
Stanford University

3:30 pm      20-min Coffee Break

## PICTURE PERCEPTION

- 3:50 pm      “The Effect of Changes in Viewpoint  
on the Pictorial Perceptions of Spatial  
Layout and Orientation Relative to the  
Observer”  
Professor B. Goldstein  
University of Pittsburgh
- 4:10 pm      “Cinematic Efficacy, or What the Visual  
System Did Not Evolve to Do”  
Professor J. Cutting  
Cornell University
- 4:30 pm      “Congruence Under Motion as a Basis  
for the Perceived Geometrical Structure  
of Forms and Spaces”  
Professor J. Lappin  
Vanderbilt University  
and  
Dr. T. Wason  
ALLOTECH
- 4:50 pm      “A Theoretical Analysis of the  
Recognition of Pictorial Displays”  
Professor I. Biederman  
SUNY Buffalo
- 5:10 pm      “Spatial Displays and Spatial  
Instruments from the Graphics Design  
Perspective”  
A. Marcus  
Aaron Marcus Associates
- 5:30 pm      “Interactive Displays in Medical Art”  
Professor D. McConathy  
University of Illinois
- 6:00–7:30 pm      Dinner

8:00–10:00 pm

Poster Sessions and Informal Discussion

“Synthetic Perspective Optical Flow: Influence on Pilot Control Tasks”

T. Bennett, W. Johnson, and J. Perrone

Ames Research Center

and

A. Phatak

Analytical Mechanics Associates

Ames Research Center

“Visual Enhancements and Control in Telerobotics”

W. S. Kim, F. Tendrick, and Professor L. Stark

U.C. Berkeley

“Visual Slant Underestimation”

J. Perrone and P. Wenderoth

Ames Research Center and University of Sydney

“Optical and Gravitational Information in the Perception of Eye Level”

Professor A. Stoper and M. Cohen

Ames Research Center

“Interactive Spatial Instruments for Proximity Operations” (video)

Professor A. Grunwald and S. R. Ellis

Ames Research Center

“Exocentric Direction Judgements Based on Pictorial and Real-World Layouts” (video)

S. R. Ellis, Professor A. Grunwald, and S. Smith

Ames Research Center

“Criteria for the Successful Representation of Information”

Professor M. Hagen

Boston University

“Development of a Stereo 3-D Pictorial Primary Flight Display” (video)

M. Nataupsky

Langley Research Center

and

T. Turner, H. Lane, and L. Crittenden

Research Triangle Institute

“Representational Structure for Evaluation of  
Human/Robotic System Control”

K. Corker

BBN Laboratories Incorporated

“Adaptation to Non-Zero Disarrangement of the  
Visual Field”

Professor R. Welch and M. Cohen

Ames Research Center

“Theoretical Issues in the Development of a 2-D and  
3-D Computer-Aided Designer Support System”

J. Hartzell

Ames Research Center

“Telepresence in Dataspace” (video)

S. Fisher

Ames Research Center

“The Photo-Colorimetric Space as a Medium for the  
Representation of Spatial Data”

K. F. Kraiss and H. Widdel

Forschungsinstitut für Anthropotechnik

“The Role of Attensity in Spatial Perception”

M. Companion

Lockheed-Georgia Company

“Achieving a Concrete ‘UP’: Embodiment of Spatial  
Relationships in a Head-Mounted Display System”  
(video)

W. Robinett

Ames Research Center

“Requirements and Features of a Synesthetic  
Supermedium”

Professor R. Mallar

ATARI Computer

Arstechnica: Center for Art and Technology

University of Massachusetts

“Helmet Mounted Displays—Spatial Orientation  
Problems”

S. Hart

Ames Research Center

“How to Reinforce Perception of Depth in Single Two-Dimensional Pictures”

S. Nagata

NHK Science and Technical Research Laboratory

“Direction of Movement Effects Under Transformed Visual-Motor Mappings”

H. Cunningham and Professor M. Pavel

Stanford University

“Efficiency of Graphical Perception” (video)

Y. Gu, Professor G. Legge, and A. Luebker

University of Minnesota

“Applications of Human Factors for Cartography and Geography”

Professor George F. McCleary

University of Kansas

“Interactive Digital Video Interface to an Atlas of Histology”

Michael D. Doyle

University of Illinois, Urbana-Champaign

## September 2

7:30–8:30 am Breakfast

8:30–12:00 am Invited Paper Session 2  
Chairman: S. R. Ellis

### MANIPULATIVE CONTROL

8:35 am “Visuo-Motor Plasticity and Time Lags”  
R. Held and N. Durlach  
MIT  
Introduction by D. Fadden

5-min discussion

9:10 am “Displays and Controls for the Space Shuttle Arm”  
G. M. McKinnon  
CAE Electronics Ltd.  
Introduction by B. Bridgeman

5-min discussion

9:45 am 10-min Coffee Break

## VESTIBULAR ASPECTS

- 9:55 am                    “Theories of Visual-Vestibular Interaction”  
C. Oman  
MIT  
Introduction by R. Haines  
  
5-min discussion
- 10:40 am                    “Vestibular Realism in Simulators”  
J. Sinacori  
Consulting engineer  
Carmel, California  
Introduction by E. Palmer  
  
5-min discussion

## COMPUTER GRAPHICS

- 11:15 am                    “Graphics Hardware and Software: Coming Attractions”  
F. Baskett  
Silicon Graphics Inc.  
Introduction by (to be determined)  
  
5-min discussion
- 11:50 am                    “The Making of the Mechanical Universe”  
J. F. Blinn  
JPL Graphics Laboratory  
Introduction by M. Kaiser  
  
5-min discussion
- 12:30–1:45 pm            Luncheon  
Speaker: J. P. Allen  
Space Industries Inc.  
(former Shuttle astronaut)  
“The Challenges of Flying the Manned Maneuvering Unit in Earth Orbit”
- 1:50-5:30 pm              Contributed Papers  
Chairman: A. Grunwald

## MANIPULATIVE CONTROL

- 1:50 pm                    “Two Modes of Visual Representation”  
Professor B. Bridgeman  
U.C. Santa Cruz



- 2:10 pm            "Perception-Action Relationships Reconsidered"  
Professor W. Shebilske  
Texas A&M University
- 2:30 pm            "A Computer Graphics System for Visualizing  
Spacecraft in Orbit"  
D. Eyles  
Charles Draper Laboratories
- 2:50 pm            "Displays for Telemanipulations"  
B. Hannaford, M. Salganicoff, and A. Bejczy  
Jet Propulsion Laboratory
- 3:10 pm            "Experience in Teleoperation of Land Vehicles"  
D. McGovern  
Sandia National Laboratories
- 3:30 pm            "Spatial Displays and Pilot Control: Where Do We  
Go From Here?"  
D. Fadden, R. Braune, and J. Wiedemann  
Boeing Commercial Airplane Company
- 3:50 pm            20 min Coffee Break

#### VESTIBULAR ASPECTS

- 4:10 pm            "Determinants of Space Perception in  
Weightlessness"  
Professor H. Mittelstaedt  
Max Planck Institut für Verhaltensphysiologie
- 4:30 pm            "Voluntary Presetting of the Vestibular Ocular Reflex  
Permits Gaze Stabilization Despite Perturbation of  
Fast Head Movements"  
Professor W. Zangemeister  
Neurologische Klinik der Universität  
Hamburg

## COMPUTER GRAPHICS

4:50 pm                    “Wide Angle Display Developments by Computer Graphics”  
W. A. Fetter  
Siroco

5:10 pm                    “Visualizing Space Filling Data”  
G. Russell  
Princeton University

6:00–8:00 pm            BBQ on Asilomar Terrace

### September 3

7:30–8:30 am            Breakfast

8:30–9:00 am            Summary Session  
Summary: L. Stark/U.C. Berkeley  
Thanks to all  
Checkout

10:00 am                Leave for tours of Ames Research Center

11:30 am                Arrive Ames Research Center

11:30–12:30 pm        Lunch at Ames Cafeteria (not included in conference fee)

12:30–2:30 pm        Open House at Aerospace Human Factors Division and possibly Vestibular Research Facility

2:35 pm                Leave for Return to Asilomar

4:00–4:15 pm           Arrive Monterey Airport/Asilomar Conference Center