A Multi-Megavoxel Volumetric 3-D Display System for Distributed Collaboration

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***Abstract*-The increasing complexity of collaborative visualization tasks calls for new three-dimensional viewing modalities. In the case of mechanical computer-aided design (MCAD), for example, multiple design centers must be able to analyze and improve products comprised of multiple assemblies while seeking to minimize the costs of physical prototypes. One solution, a "virtual prototyping station," combines three-dimensional display technology with the ability to share data over a network. Actuality Systems, Inc. is constructing an autostereoscopic volumetric 3-D display which is being made compatible with several standard visualization packages. It creates volume-filling imagery that may be inspected 360 degrees around the display without the use of VR goggles. The display creates imagery comprised of at least 90 million volume pixels (voxels); the authors believe that this is the largest dot count for any volumetric display at the time of writing.**

I. Introduction

High-performance visualization plays a role in fields as diverse as geophysical imaging, product design, molecular visualization, and entertainment. For example, automotive engineers seek to speed the product development cycle and reduce its cost by exploiting visual information as much as possible before committing resources to the construction of physical prototypes. In the biochemical industries, some new pharmaceuticals are designed in a process which begins with a visual inspection of complex three-dimensional molecular structures. Some 3-D visualization scenarios require remote operation, *i.e.*, the individuals performing the analytical work of a certain task might not be at the same location as the task is carried out. One could, for example, imagine a specialized physician planning a surgical procedure at a location remote from that operation.

These tasks require a high-resolution, computer-generated, interactive, three-dimensional rendering which has the ability to be modified in real time. Specialized graphics workstations have been developed for those applications and are used to produce raytraced "2 1/2-D" renderings which appear on traditional CRTs. There is increasing activity in the field of three-dimensional display technology, whose practitioners seek to provide users with the ability to perceive true three-dimensionality. These solutions exist in many forms, such as multi-user visualization rooms, stereoscopic goggles, and volumetric displays, devices which create volume-filling imagery.

Actuality Systems, Inc. is preparing a volumetric 3-D display system for commercialization. The system is comprised of a high-resolution 3-D display, a customized graphics architecture, and a suite of software. This paper will describe the authors' 3-D display architecture, keeping an eye to parameters of particular interest to researchers in the field of virtual reality telecommunications, such as system bandwidth requirements, resolution, and compatibility with existing infrastructure.

II. Three-Dimensional Displays

A. Background

A number of publications summarize the field of three-dimensional displays in general [1, 2], including a particularly excellent review of autostereoscopic 3-D displays [3], which are displays that do not require the use of additional headwear. Most or all of the 3-D displays constructed to date create imagery that is perceived to be three-dimensional by exploiting certain visual cues for three-dimensionality. A review of these cues exists in [4], and can roughly be summarized as monocular and binocular cues. Monocular cues include texture gradients (*e.g.*, the visual texture of a receding wheat field) and motion parallax (objects which are farther from a viewer appear to move slower with head motion than near objects do.) Volumetric displays are particularly good sources of motion parallax, since viewers are given the ability to inspect the imagery from different angles. Binocular cues are sources of 3-D information from different left- and right-eye views; it is beyond the scope of this paper to describe these. They include positional disparity, phase disparity, orientation disparity, and spatial frequency disparity.

Three-dimensional displays can be broadly classified into families. A non-exhaustive list would include:

1) *Stereoscopic goggles:* A variety of goggle-based systems create binocular cues by providing different imagery to the viewer's left and right eyes. *Field-sequential goggles* do this by synchronizing left- and right-eye imagery presented by a CRT through liquid crystal shutters worn by the viewer. *Head-mounted displays* typically mount two small monitors on the user's head, directly presenting stereoscopic imagery to the eyes without any rapid shuttering.

2) *Parallax displays:* As described in [3], "[p]arallax displays consist of a surface covered with display elements that can emit light of varying intensity in different directions." For example, a *parallax barrier display* such as that described in [5] creates 3-D imagery by using an electronically-controllable array of optical barriers to couple

CRT imagery for a series of viewing zones to the viewer's location. A control unit gathers knowledge about the viewer's position and dynamically arranges a series of light-blocking liquid crystal barriers to guide imagery to the appropriate eyes. This therefore provides motion parallax, since head position is used to derive the perceived imagery. However, this family of 3-D display generally has a limited viewing angle and a discretized manner of shifting between viewing zones. Another type of parallax display, the *lenticular sheet display,* uses an array of lenses which is placed over a CRT and steers image elements to several viewing zones.

3) *Volumetric displays*: As well-documented in [2], volumetric displays create 3-D imagery via the emission or relaying of illumination from well-defined regions in (x, y, z) space. Examples of volumetric displays include solid-state devices which create voxels (volume pixels) within a translucent substrate [6] and multiplanar volumetric displays [7, 8, 9] which typically build a 3-D volume from a time-multiplexed series of swiftly moving image surfaces. Human persistence of vision is employed to integrate these "image slices" into a three-dimensional whole. For example, [9] describes a system that creates volume-filling 3-D imagery by using lasers to illuminate a rotating diffuse screen. A sequence of radial image slices are visually integrated into the perception of a 3-D image.

4) *Electroholographic displays:* Researchers including a team at MIT [10] have created a holographic video display. Holographic "fringes" are created in real time in an acousto-optic modulator, whose image is scanned across an image plane in synchronization with the time-varying optical variations that travel along that modulator. Current research in this field includes efforts to reduce the bandwidth requirements for realistic imagery.

B. *The Ideal 3-D Display*

Although the display technology should be chosen to suit the application, we outline several desirable characteristics for 3-D displays that are intended for complex visualization tasks:

1) *Autostereoscopic.* If the display is intended to be used by multiple people simultaneously, it should produce three-dimensional imagery that is visible without the use of headwear. Users of stereoscopic goggles frequently complain of nausea after brief (15 minutes) periods of use. Also, it may be difficult to engage multiple people into sets of head-mounted units for presentations if they are not familiar with the technology. It may also be a benefit to eliminate the requirement of head-tracking devices, which would implicitly increase the number of simultaneous potential users.

2) *High image quality.* Although no formal metric has been accepted for the performance of 3-D displays, the following attributes are generally desirable: high resolution, large color gamut, and multi-user hidden surface removal.

3) *Ease of use.* The technology should be as easy to integrate into existing workflows as, for example, a laser printer.

Current 3-D display technologies vary widely when characterized along these dimensions. Electroholographic displays provide occlusion cues but at the time of writing produce relatively low-resolution imagery and require specialized optics. Head-mounted displays provide high-resolution full-color imagery, but they frequently lead to user discomfort. Volumetric displays provide imagery that may be seen from 360º at high resolution, but insufficient research has taken place in the creation of imagery with object occlusion.

III. ACTUALITY'S 3-D DISPLAY DEVELOPMENT

A. *3-D Display Development Background*

Actuality Systems, Inc. was founded to create high-resolution 3-D display systems that may be added easily to existing visualization processes. Initially, the chosen architecture was similar to that in [9], which creates 3-D imagery by scanning the output of a linear array of lasers onto a rotating diffuse projection screen. We constructed a prototype that created monochromatic (640 nm) imagery which occupied ~250 cm^3 at a resolution of 64 x 64 x 64. A standard personal computer provided data to the display through a custom ISA video card at a rate of 20 Hz. The imagery could be seen from nearly any angle and was updated interactively, and a joystick-controlled flight simulator was demonstrated of a helicopter over synthetic terrain. Fig. 1 illustrates a schematic rendering of DNA using this architecture.

Fig. 1. Photograph of 64 x 64 x 64 multiplanar display as described in [9].

A higher-performance and more scalable architecture was desired, so we changed direction and designed a comprehensive 3-D display system whose underlying principles were disclosed in the 1960s [7, 11] but whose enabling technology became available only recently. Additional research and development was required to improve those early architectures, particularly in terms of efficient line- and triangle-drawing algorithms, specialized graphics rendering electronics, and projection opto-mechanics.

B. Design and Results

At the time of writing, the authors are completing the construction of a rotating-screen 3-D display capable of providing imagery comprised of at least 90 million voxels. As illustrated in Fig. 2, a high-speed 2-D projector (1) images a time series of approximately 4,000 – 10,000 frames per second onto a diffuse projection screen (3) which rotates at 600 rpm. A series of three mirrors (2) relay the imagery to the rotating screen in a manner that ensures accurate focus regardless of the screen's angle.

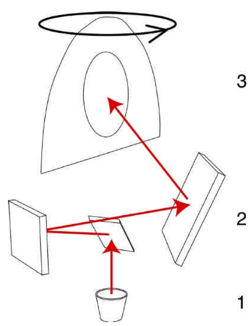

Fig. 2. Schematic illustration of 3-D display principle. A fast projector (1) illuminates a rotating projection surface (3) via several relay mirrors (2) which rotate with the screen. The projector and control electronics are fixed.

If the screen rotates at or above 600 rpm, persistence of vision fuses the sequence of 2-D images ("image slices") into a concrete 3-D image. Because the screen sweeps through a series of points within an actual volume, the imagery is volumetric, and furthermore may be inspected from 360º around the display. No headwear is required, and all focus (accommodation) and parallax cues are correct.

The prototype's projector is based on the Texas Instruments™ Digital Light Processing™ technology, which utilizes a MEMS-based reflective array to create single-bit-depth frames at approximately 4 kHz. Each frame has a resolution of roughly 768 x 768, and the volume is comprised of between 200 and 500 frames, resulting in an image of at least 90 million voxels. The projection system is creates red, green, and blue image components, yielding a 3-bit (8-color) display. The projection system is unique, incorporating aspects such as a rotating triplet lens assembly. An analysis of the system reveals that novel algorithms must be employed in order to create voxels at any specified (x, y, z) coordinate. That is the role of Actuality's proprietary rasterization algorithms which convert arbitrary 3-D images (*e.g.* an MCAD illustration of an engine block) into a sequence of image slices. At the time of writing, the authors believe that this is the highest resolution 3-D display constructed to date.

A customized graphics architecture was designed, built, and tested; its chief purpose is running the rasterization code and interfacing to the user's PC. As illustrated in Fig. 3, the graphics system is composed of several blocks. 3-D data, usually in the form of geometric or volume data, arrive from the user's PC over an Ultra SCSI interface to the display prototype. The "raster engine" rasterizes the data, converting the 3-D scene descriptions into a series of projector illumination patterns which are routed into 6 Gbits of DDR SDRAM. This graphics memory is organized as 1 Gbit x 3 x 2 (3 colors, double-buffered), and bandwidth from the raster engine to the graphics memory peaks at 133 MByte/s.

The sequence of 2-D bitmaps drives three T.I. DMD™ projector components in precise synchronization to the position of the projection screen. Although the projector bandwidth is currently limited to 3 x 400 MByte/s, the authors' architecture is capable of 3 x 800 MByte/s to allow for higher-performance projectors. Note that the display's resolution in the plane of the projection screen is determined by the projector resolution, in this case a 768 x 768 region of an XGA-resolution projector. However, the number of radially-disposed slices comprising the 3-D image is determined by the frame rate of the projector system. It is possible therefore to trade radial resolution for refresh rate. A photograph of the raster engine is shown in Fig. 4.

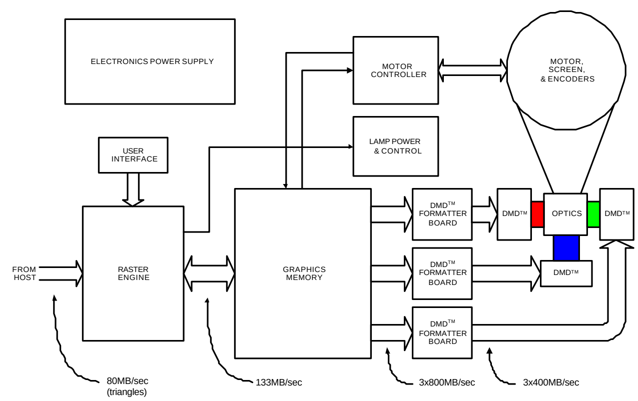

Fig. 3. System electronics.

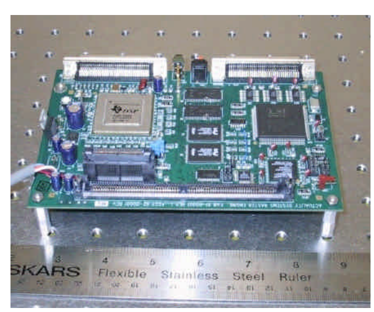

Fig. 4. Photograph of raster engine, which converts 3-D image data into a time-sequence of 2-D "image slices."

At the time of writing, the optical system is under construction. Fig. 5 is a photograph of the projection engine, projection optics (inside the housing), and the rotating screen assembly. A fixed, transparent, outer dome, as well as a stylized housing, will be mounted around these components. These are illustrated in Fig. 6.

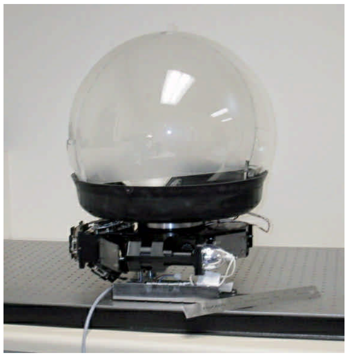

Fig. 5. Photograph of the projection system and screen inside rotating dome.

Fig. 6. Product rendering illustrating stylized base and stationary outer dome.

Data for the display can come from three sources:

1) *"Guaranteed compatibility."* In certain cases, Actuality Systems, Inc. will work with software vendors to ensure compatibility between popular application packages and the 3-D display. Many vendors of high-end visualization software support 3^{rd}-parties who create interoperability with their products.

2) *OpenGL®-based software.* The display system software includes a method capable of routing graphics library calls to the 3-D display while allowing simultaneous output on the traditional CRT. This is expected to make the display compatible with a variety of software packages based on this widely accepted graphics library. However, applications which hide data from the OpenGL® system (*e.g.* those which perform hidden-surface removal before GL) will not be able to properly display 100% of the intended image data. At the time of writing, the authors have demonstrated interoperability with molecular visualization and mechanical CAD software packages.

3) *API.* An application programming interface (API) based upon the open-source graphics library Mesa is under development. This is similar to OpenGL®, and is readily understood by those familiar with graphics programming.

A software-based simulation of the volumetric display was created as an element of the system design and debugging process. This *3-D display simulator* provides an interactive rendering of the 3-D display as it receives the intercepted graphics library calls from unaltered 3^{d}-party applications. Fig. 7 is a cropped screen shot of a popular MCAD package; Fig. 8 illustrates output of our display simulator, which receives OpenGL® calls over the office LAN from a computer running the application elsewhere.

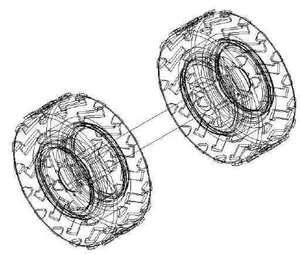

Fig. 7. Screenshot of commercial MCAD software in wireframe rendering mode.

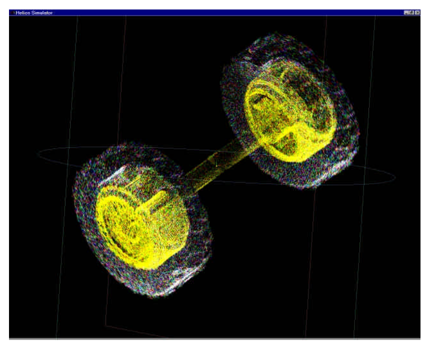

Fig. 8. Screenshot of the 3-D display simulator, which simulates the swept-screen architecture, rasterization, and simulated hidden-surface removal algorithms.

IV. Deployment

A. Applications

The 3-D display system described here can be made compatible with a range of existing 3-D visualization applications. These include air-traffic control, molecular visualization, medical imaging, entertainment, military tactical visualization, and virtual prototyping. The ability to view the imagery from any angle makes it suited for multiple simultaneous users.

B. Application to Telecommunications

One aspect of the display that may be of interest in the field of telecommunications is the ability to use the 3-D display as an I/O device for distributed applications. That is, design teams located in North America, Europe, and Asia may collaborate on designs interactively, eliminating the need to ship costly prototypes around the world. This has the potential to speed the product design process and reduce its cost. Furthermore, as the color gamut and resolution of the display increases, it may be used as a component of a virtual reality telecommunications system, in which conference participants may see each other in a realistic manner.

A second aspect relating to this field is the ability to send the 3-D data over existing networks. Notice that the highest bandwidth (100s of MB/s) connections are localized to the display, while the lower-bandwidth geometry data is streamed over Ethernet, SCSI, or IEEE 1394, for example. Since the display's rasterization system can essentially decompress mathematical descriptions of 3-D scenes into the appropriate 2-D projection patterns, networks such as the Internet can be used to transmit real-time 3-D imagery for the display. As described above, an office LAN has been demonstrated which allows one user to interact with a mechanical CAD application at one computer while another user can rotate and zoom that data in real-time on another computer.

C. Problems to be Resolved

The authors expect to improve the 3-D display architecture described here, most notably in resolution, number of colors, and the ability to hide surfaces that should not be visible from a given user's location.

V. Conclusions

The authors are completing the construction of a volumetric 3-D display that creates imagery which occupies a true volume and which may be inspected from nearly any angle. A specialized graphics architecture and fast projector system are used to create 3-D imagery that is composed of at least 90 million voxels in 3-bit color which is refreshed at 20 Hz. Applications include virtual collaborative prototyping, molecular imaging, medical visualization, and entertainment.

Acknowledgments / Copyright Notice

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