Progress in Volumetric Three-dimensional Displays and Their Applications

Gregg E. Favalora
Actuality Systems, Inc., 1337 Massachusetts Ave. #128, Arlington, MA 02476
favalora@post.harvard.edu

Abstract: Volumetric displays create volume-filling 3-D imagery, usually with full parallax and a wide viewing angle. Widespread commercial adoption has not yet occurred, but they may add value to fields such as medical imaging and petroleum exploration.

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1. Introduction to volumetric three-dimensional displays

The taxonomy of three-dimensional (3-D) displays continues to evolve, but the author's description from a recent publication seems appropriate several years later: "Although the field's vocabulary is not standardized, volumetric displays generate imagery from light-emitting, light-scattering, or light-relaying regions occupying a volume rather than a surface in space [1], as averaged over the display's refresh period [2]." We incorporate certain multiview displays – such as panoramagrams and light field displays - into our discussion because they are increasingly able to reconstruct light fields that can be examined at the localized voxel level. Therefore, the categorical line is blurring between certain volumetric, multiview, and electro-holographic displays.

We explore a snapshot of volumetric display development in 2009. Regarding introductory surveys, see Halle [3] on autostereoscopic 3-D displays, and for historic and contemporary volumetric displays see Blundell [1] and Favalora [4]. Canonical pre-1990 volumetric 3-D displays include: Hartwig's laser projection onto a spinning helix [5], Lewis et al's explorations of solid-state 3-D display [6], Traub's varifocal mirror display [7], and the swept-screen system of Hirsch [8]. Exhaustive collections of volumetric displays can be found in [1,9].

2. Multiplanar volumetric displays

Multiplanar volumetric displays reconstruct a 3-D scene in a "slice-wise" manner. The Perspecta Display (Actuality Systems, Inc., Arlington, MA) generates 10" (25 cm)-diameter volume-filling imagery by projecting a series of 2-D scene cross-sections onto a diffuser screen rotating at 900 rpm. It uses three Texas Instruments (Plano, TX) Digital Light Processing (DLP) engines at 6,000 frames per second and roughly XGA resolution to project images with approximately 100 million voxels at a visual refresh rate of 30 Hz [10]. The LightSpace Technologies DepthCube (Twinsburg, OH) also uses DLP technology, projecting a total of >15 million voxels onto a stack of 20 liquid crystal panels [11]. Perspecta and the DepthCube use graphics processing unit-based algorithms in order to achieve real-time rendering. Perspecta is no longer commercially available; Actuality began to wind down operations in 2009. Specialized lower-resolution volumetric displays are being used as research platforms to investigate the human visual system, for example Akeley et al [12].

It is also possible to generate multiplanar imagery through "solid state" processes such as two-step upconversion [6]. 3DIcon Corp. (Tulsa, OK) uses 30 W lasers at 1532 nm and 850 nm to activate green voxels within an Er-doped YLF 17 mm x 17 mm x 60 mm crystal in planar cross-sections, modulated by DLP [13]. Ohira et al employ a liquid display volume in which a custom MEMS-based scanner directs a 5 W 1064 nm Q-switched laser to convert regions of water to visible plasma discharge [14], elsewhere reporting alternative substrates [15].

3. Light field displays as volumetric displays

The author is unaware of any widely-accepted definition of "light field display." They could be considered systems that reconstruct 3-D imagery by piecewise approximation of a radiation field, for example, by projecting a collection of rays through the reconstructed scene. A single voxel, for example, would be reconstructed by passing at least two rays through the region occupied by the voxel. Whereas the display's physical components might not necessarily occupy the display space, it could be argued that the reconstructed scene is volumetric.

Examples of light field displays include: the multi-projector system of Holografika [16], a variety of systems that emit directed light from a rotating surface [2, 17, 18], or a system that creates 198-view imagery by performing view-multiplexing with two overlaid lenticular sheets undergoing rapid relative translational motion [19].

4. Point-scanning and other volumetric displays

Point-scanning volumetric displays are akin to vector-scanned displays in that they reconstruct an image by projecting one (or a number close to one) voxels at a time. The early helical vector-scanned display of Hartwig [5] is such a display. Recent progress in point-scanned displays includes the air plasma display of Saito et al [20].

Nayar and Anand illuminated regions of a physical point cloud within a material that had undergone precise laser-induced damage to generate volumetric images of approximately 200k voxels [21]. There are several examples of illuminating real-world moving objects to augment their appearance [22, 23]. Choi et al have combined integral imaging and volumetric displays [24].

5. Applications of volumetric displays

At the time of writing, volumetric displays have not achieved mainstream adoption. The author posits several reasons for this: the ideal application of volumetric 3-D has not yet been found, its return on investment not yet been suitably quantified, and it is possible that the price point of recent systems may be too high. Further, the author is not aware of any companies offering high-quality volumetric systems at this time.

The natural progression of display technology from 2-D to 3-D suggests that volumetric displays will one day reach commercial maturity. The utility of volumetric imaging in medical visualization has been studied in the field of external beam cancer treatment [25] using the Perspecta display. A recent advance in the light field display [17] is exploring 3-D videoconferencing by projecting imagery onto a rotating brushed-aluminum tent. Over the last 20 years, the author has anecdotal and direct evidence that many applications are being explored, such as: oil and gas exploration and production (such as real-time visualization of 3-D fluid flow), security applications such as luggage visualization, pharmaceutical molecular modeling, and interventional and diagnostic medical imaging. The field awaits the proper combination of display architecture and application for commercial adoption to escalate.

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