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Three-Dimensional Displays: A Review and Applications Analysis

Nicolas S. Holliman, Neil A. Dodgson, Gregg E. Favalora, and Lachlan Pockett

***Abstract*—S. Benton published a definitive taxonomy of the first one hundred and seventy years of 3D displays covering the field up to the year 2000. In this article we review how display technologies have advanced in the last ten years and update Benton's taxonomy to include the latest additions. Our aim is to produce a display taxonomy suitable for content producers highlighting which displays have common requirements for image delivery. We also analyze key technical characteristics of 3D displays and use these characteristics to suggest the future applications for each category of display.**

***Index Terms*—Human factors, image resolution, stereo vision, three dimensional displays.**

I. INTRODUCTION

THE field of three-dimensional display has become one with a fascinating variation and depth of research since the original observations by Sir Charles Wheatstone were presented to the Royal Society in London in 1838 [1] following his construction of the first stereoscope in 1832. The subsequent 170 years of progress in the development of three-dimensional displays were reviewed in Benton's definitive book [2] both highlighting progress in the field and providing a taxonomy within which new developments can be categorized. Here we review recent technology developments in the field within Benton's framework and then analyze the application suitability of different display designs.

The taxonomy we adopt [2] is based on the degree of parallax that a display system is capable of reproducing at any perceptual instant in time. The simplest are *two-view* systems which at any instant reproduce just two views, one for the left eye and one for the right eye. An intermediate display system in this taxonomy is the *horizontal-parallax* displays which produce multiple horizontal parallax views of a scene; also known as a parallax panoramagram [3]. These displays allow a viewer to look around objects in the 3D image and see differing views at differing horizontal eye positions. The most complete display type in our taxonomy are those that are *full-parallax*. These reproduce variations in the images seen by the viewer with both horizontal and vertical head movements.

The importance of this taxonomy is that it captures how close a display technology is to reproducing the real world experience of parallax and the characteristics of a display that are most important to content generators. Specifically, it defines how much information a particular display technology needs to be supplied with to operate, this in turn determines camera systems, edit functions and the communication bandwidth required to produce and distribute content.

A term recently used to describe 3D displays is light field displays. This has been adopted from computer graphics and computational photography where it describes the rendering of light traveling in a set of directions from an object [4]. A similar term used is free viewpoint TV where a synthetic camera is used to render views not captured by a physical camera. All displays reproduce some form of light field and as the directionality of the display increases, i.e. the number of parallax views increases, the closer the light field produced becomes to that of the real scene.

II. TWO-VIEW 3D DISPLAYS

The category of displays that generate two separate viewing zones, one for each eye, is large and ranges from simple handheld Wheatstone stereo viewers through head-mounted electronic displays to autostereoscopic head tracked displays. These fall into different categories as shown in Fig. 1.

A. Wavelength Selective Displays

One of the earliest and simplest forms of two-view display is the color anaglyph in which a user views a color print or display encoding left and right views in two different color channels with a pair of colored filter glasses, often red for the left eye and cyan for the right eye. This has the advantage that almost any color display device can be used to present the stereo-pair image but the obvious disadvantage is that each eye is seeing a different color stimulus.

A recent adaptation of the anaglyph approach is the Infitec [5] system. This transmits two different full color images to each eye, by using different narrow waveband primary colors for each eye. While normally the red primary is a broad range of wavelengths centered at a wavelength of about 600 nm, in the Infitec approach only a small range of red wavelengths are transmitted to the left eye, centered on 600 nm and spanning about 50 nm, while a different range, centered on 650 nm and spanning 50 nm, are transmitted to the right eye. The user then wears glasses that are tuned so that the left eye filter only lets through narrowband wavelengths around 600 nm and the right eye only

Two-view			Horizontal parallax	Full parallax	
Eyeglasses	**Stereoscopes**	**Autostereoscopic**	**Autostereoscopic**	**Autostereoscopic**	
Wavelength selective Wavelength selective glasses [5] *Time sequential* ZScreen circular polarisation [13] ALPS linear polarisation [13] *Time parallel* Twin-LCD polarising with half-mirror [16]	*Two-view HMD* HMD using HOE [10] HMD using diffractive grating element [9] *Volumetric HMD* Multi-planar volumetric HMD [65]	*Time sequential* Prism film, switching backlight [14] *Time parallel* Polarisation activiated microlens [18] Bulk optics twin LCD [20,21] Tracked two view, one viewer [22,24] Tracked two views, many viewers [25]	*Multiview* Lenticular element multiview [33,35] Parallax barrier multiview [36,37,38] Multi-projector [39,40] Multiview using HOE [45,47] *Super multiview* Multi-projection [41]	*Integral imaging* HOE curved lens [51] Integral imaging with extended depth of field [52,53] Integral imaging with head tracking [26] *Holography* Head-tracked holography [27]	*Volumetric* High resolution [61] Slice stacking moving diffuser [63,64] Volumetric with occlusion [54, 66, 67] Volumetric free-air plasma [62] Volumetric solid state [57,68,69]

Fig. 1. The taxonomy we use categorizes displays based on the amount of simultaneous parallax the displays generate and then based on the technology choices made by the designers [2]. We highlight the parallax characteristic as this is the key requirement that application and content producers must consider when producing images for 3D displays.

lets through wavelengths around 650 nm. A similar difference is implemented for the green and blue primaries.

The result is that a left image can be analyzed with one set of primary filters and seen only in the left eye, and similarly for the right eye. As the coding does not rely on polarization there is a benefit that any standard projection screen can be used to view the images and low crosstalk levels are reported. Because of the shift in wavelength the left and right eye images do individually appear to be different colors. However when combined the effect is less noticeable and color signal processing can be used to pre-adjust the color of the images for color critical applications.

B. Stereoscopes and Head-Mounted Displays

The standard approach to designing a stereoscopic head mounted display is to use a pair of micro displays and matched enlarging optics to generate a finite distance virtual image [6]. While there have been incremental steps in micro-display technology, and optical elements [7] the fundamental principle of many designs of HMD remains as described by Benton [2].

A new approach to HMD design is to replace the pair of bulky optical elements in front of the eyes with a waveguide [8], [9], looking very much like a conventional pair of glasses. The waveguide enables the bulk of the optical engine to be removed from in-front of the eyes placing it on the side of the glasses or between the eyes.

The high-precision waveguide transmits light via total internal reflection from a display source to the eyes, it is aided by two diffractive gratings that provide in-coupling and out-coupling. The in-coupling diffractive grating couples infinitely focused light from the optical engine into the waveguide, where it is internally reflected through the waveguide to the out-coupling grating where the order of light is changed enabling it to be refracted out of the waveguide and into the eye. The angle of reflection is preserved throughout in order to preserve the image's integrity. Waveguides can additionally serve as optical expanders, enlarging the size of the exit pupil, and thus allowing smaller sized display optics to be used to create a much larger freedom of eye position.

This resulting display allows the user to see full-color images overlaying their view of the real world. Further advantages of this technology over standard HMD technology are that it provides improved form factor, transparent devices when the display is switched off, reduced weight and components, and where the same image is monoscopically presented to both eyes it also removes all forms of misalignments between the eyes.

Waveguide technology has issues of maintaining color across the image as the strength of the internally reflected light diminishes across the width of the grating. Varying grating depth across the out-coupling varies the percentage of light extracted and thus compensates for loss in signal strength across the width of the waveguide. Differences in efficiency between red, green and blue cause color artifacts in the image, this can be improved by stacking waveguides, causing a different number of reflections for each color [10].

Recent analysis using diffraction theory and ray tracing have enabled specially designed slanted gratings to be etched into glass and plastic substrates, enabling control of the dominant direction of light propagation and increased in-coupling and out-coupling efficiency. Slanted gratings can be manufactured to create waveguides by use of holographic interference to create holographic films that are placed on the substrate [10]. Use of etching techniques enable a steeper slant on gratings causing improved efficiency, and the possibility of replicating the waveguides [9].

C. Time-Sequential Two-View Displays

The interleaving of images in time allows a single display device to be used to generate two or more alternating views. If the views switch quickly enough, greater than 58 Hz per eye for large bright stimuli [11], then the viewer should not perceive the switching nor any related flicker. A classic example of this approach is the electronic shutter glasses which use an LCD cell that switches on and off in time with the appropriate image being displayed on a CRT [12].

1) Time-Sequential Polarization: An alternative to placing a switching device at the eye is to attach the switching device to the display and, for example, use polarization as the mechanism to code left and right views. The viewer then wears a pair of passive polarizing glasses to filter the light so that each eye sees the appropriate view. A recent implementation of this method is the RealD technology [13] used in both cinema and professional markets. An important component in this approach is a DLP projection device which has the capability to exceed the minimum flicker fusion frequency for each eye when operated in stereoscopic mode.

The RealD approach is to fit a fixed polarizer followed by a liquid-crystal polarization switch. In the Zscreen the device uses two pi-cells which both provide a quarter wave retardation and in combination act as a half-wave switch giving the $\pi/2$ rotation angle required. This generates the required quasi-circular polarizations and is matched by circular analyzers in the viewer's glasses. A second design, ALPS, reported in detail in [13] uses a stack of passive retarders in combination with two LC pi-cells to implement an alternative linear polarizing solution, which needs to be matched by implementing linear analyzers in the viewer's passive glasses.

With all solutions the quality of the end-to-end system determines the viewer's experience of the 3D effect and for polarizing projection the screen choice is an important part of the whole. With a good polarization preserving screen both systems are able to provide good low crosstalk performance, although head and viewing angles are factors and long throw lenses are recommend. A tradeoff is that, like LC shutter glasses, a significant portion of the light that would be seen in a 2D operating mode is absorbed by the polarizers and further light is lost due to sequential operation.

2) Time-Sequential Backlight: An autostereoscopic solution for a time-sequential display is to use directional optics behind a spatial light modulator (SLM) display to direct light alternately through the display in two different directions. If, as above, the display device can switch quickly enough in time with the switching of the directional light then the user need not wear 3D glasses and yet will see a binocular image from the display.

Nelson and Brot [14] describe one such device using a backlight with a double sided lenticular-plus-prism film in combination with a Fresnel lens element. The backlight is designed to have a light source on each side of the display with a wave-guide surface between them. The optical design of the backlight plus the prism film is such that when the right-hand light source is switched on light is directed so that the display can be seen only by the viewer's left eye and vice-versa. The Fresnel lens, between the prism film and the SLM, serves to extend the size of display that can be used at short viewing distances. At a typical desktop viewing distance of 330 mm the combined effect allows up to a 500 mm diagonal display to be used.

One significant benefit of this display design is that unlike many autostereoscopic 3D displays there is no pseudoscopic viewing position, the viewer either sees the correct orthoscopic 3D image or sees the same 2D image in each eye. A further benefit is that it can be driven from the same video signal as the widely available electronic shutter glasses. However the potential for crosstalk from stray light reflections in the backlight optics and from slow switching of the SLM is always there. Nelson and Brot explicitly suggest this is only suitable for SLM displays with a switching speed of over 90 Hz, to achieve at least 45 Hz in each eye. Depending on the brightness and size of the display [11] this should be fast enough to avoid flicker in many embodiments of the design.

D. Time-Parallel Two-View Displays

In contrast to time-sequential displays, time-parallel displays present the two views simultaneously to both eyes. These displays do not normally suffer from temporal artifacts, such as flicker, as both views are driven synchronously. However they have the disadvantage that the varied optical designs require many different image interlacing schemes and as these are not standardized they require a wide range of drivers to be available in graphics systems. This lack of standards can result in variations in perceived depth reproduction between different displays types [15].

1) Stereoscopic Time-Parallel Displays: Displays which use glasses and generate two simultaneous images include the widely available dual projection systems which combine two projectors and polarizing filters matched with appropriate glasses. These are easy to construct and are currently widely available from many suppliers. The quality of the polarizers and the polarization preserving nature of the projection screens are important in controlling crosstalk and maintaining even brightness across the screen.

In addition there are display designs [16] that use dual LCD panels and a half mirror so that one image is seen in transmission and one in reflection, this rotates the natural polarization of the reflected display so that linear polarizing glasses can be used for viewing. These are simple, but effective, re-embodiments of Land's original 1937 design [17] which used prints, polarizing sheets and a half mirror.

2) Autostereoscopic Time-Parallel Displays: The majority of two-view auto-stereoscopic displays use either a parallax (slit) barrier or a lenticular lens array as the directional optical element in combination with an SLM device such as an LCD panel. The slits or lenses are aligned vertically so that half of the display is visible from the left eye and half from the right eye. The result is a display with a central viewing sweet-spot at a designed viewing distance from the display. There are normally a number of repeat viewing positions to each side of the central viewpoint that also provide a stereoscopic view.

Harrold *et al.* [18] describe an autostereoscopic two-view 3D display that uses micro-lenses as the directional optical element. The design consists of a stack of three elements, the first two a TFT-LCD and a micro-lens array form a conventional design for an autostereoscopic display. The third layer is a liquid crystal switch which in combination with the specially designed polarization activated micro-lens allows the 3D effect to be electronically switched on and off. The micro-lens is activated when the LC switch is in one polarization state and deactivated when it is in the other.

The resulting display retains comparable brightness in both 2D and 3D display modes, which is a benefit compared to slit barriers that inherently block light and reduce brightness. The design also has low cross-talk between the two viewing channels at less than one percent in the central viewing position. Repeated experience shows low crosstalk is very important in delivering a high quality 3D experience for high contrast images with significant depth [19]. As with all time parallel devices that use a single LCD panel the resolution in each eye is half the full panel resolution.

An alternative design is to use two LCD panels in combination with bulk or micro optics to steer the light through one panel to the left eye and through the other panel to the right eye. Cobb [20] describes one such design using bulk optics, and McKay [21] describes another. Both of these designs generate a stereoscopic viewing position at a sweet spot in-front of the display, there are no repeated viewing positions so these are single user displays. The benefit of this approach is it delivers a full resolution image in each eye and zero crosstalk as the two viewing channels are optically isolated from each other; the result is a high quality perceived 3D image.

E. Head-Tracked 3D Displays

Head tracking systems can either follow the viewer's head position or, more accurately, track the eye positions. For 3D displays simply being able to track the center line of the face is often enough to drive a view steering mechanism that allows the left view to follow the left eye and the right view to follow the right eye.

Displays like the Sharp micro-optic twin-LCD design [22] tested various head tracking methods implementing both IR detectors and video tracking systems. In this auto-stereoscopic display the steering mechanism was constructed from micro-optics, lenses and slit arrays that were moved mechanically to make the left and right views follow the observer. Key to performance is minimizing the latency between the viewer's head movement and the system responding by moving the views. The higher the latency the lower the maximum head speed supported. Several head tracked single LCD panel designs were developed by Sharp [22] and a similar design, the Free2C, was created by the Fraunhofer HHI group.

Head tracking systems have a number of benefits, first they can extend the viewing range of the display laterally and, in some designs, also perpendicularly to the display. In addition if the head position data is accurate enough it can be fed to a computer graphics system and the images on the display updated as the viewer moves. This results in realistic look-around effects where the viewer can see around, above and below the object on the screen. It also removes the unnatural shearing that results from not updating the view correctly in response to head movements [23].

A design for a single LCD head tracked display was presented by Perlin [24], this proposed the use of an electronically programmable slit barrier in front of the LCD to steer the views. The design aim being to allow the slits to vary with the viewer's eye position and allow lateral and perpendicular movement to be tracked, in addition the design could respond to head rotation. Theoretically this could respond to all possible head movements of the viewer and maintain a correct stereoscopic view. In practice the challenge of building an electronically programmable slit barrier are significant.

Multi-viewer displays with head tracking of each viewer have been reported, such as the HELIUM3D display [25]. This design uses lasers and a fast light valve in combination with individual pupil trackers to deliver binocular images to several simultaneous viewers. This approach requires a very high frame rate in order to deliver flicker free images to viewers.

The benefits of eye tracking system for 3D optical and content producers are that the bandwidth of the display system can be reduced to support only that information required for the viewer from their current viewing position. This has been exploited in stereoscopic displays designs, as above, and also in integral imaging [26] and pseudo-holographic displays [27]. In the later case the eye tracking used is critical in reducing the computational and optical bandwidth required so that an image can be generated in real time as the viewer moves.

III. Horizontal Parallax Multiview 3D Displays

These displays provide stereoscopy without eyeglasses and often without head tracking [28]. Such a display produces multiple different images, each of which is visible only in a particular viewing zone. These zones are usually 20–30 mm wide at the optimal viewing distance and abut one another. Each of the viewer's eyes is in a different zone, so each eye sees a different image on the screen, and therefore we achieve stereoscopy. The multiple images are generated from multiple cameras, either real or virtual, arranged in a horizontal row.

This type of display has traditionally been called autostereoscopic: because it automatically produces stereoscopy without any artificial aids. For disambiguation, this is often qualified as multi-view autostereoscopic. More recently, the term automultiscopic was coined, by Konrad and Agniel, as a shorter description of this type of display [29].

Many technologies have been developed to produce the multiview effect. All have an optimal viewing distance and all have regions where stereoscopy works and regions where it does not. Analysis of the viewing zones, and of exactly what is visible on the screen from any given location, can be found in Dodgson's papers [30], [31]. Empirical analysis of the number of viewing zones required and benefits for task performance are reported by Hassaine [23].

A. Lenticular Displays

The most common type of multi-view display uses lenticular lenslets: vertical slices of cylinders abutting one another in front of a flat-panel display. These ensure that each column of pixels is visible only in a particular zone in space, thus dividing the resolution of the underlying display into a number of distinct views: one visible in each zone. The traditional vertical alignment of the lenticulars had two problems. It meant that there are dark regions between the viewing zones in space, where the inter-pixel gaps are projected rather than the pixels themselves. And it also means that traditional lenticular displays are, for practical purposes, limited to 4 views, because the horizontal resolution of the underlying display is being shared between the views. The vertical resolution, by contrast, is not shared between the views and each view thus has the same vertical resolution as the underlying flat panel. For example, a monoscopic 1920 × 1080 display becomes a four-view 480 × 1080 display.

In 1996, van Berkel, at Philips, succeeded in producing a seven-view lenticular display, by slanting the lenticulars relative to the underlying pixels [32], a technique also proposed by Winnek in 1968 [33], [34]. This solves the dark zone problem and divides both vertical and horizontal resolution rather than just the horizontal resolution. He thus succeeded in producing a multiview display with more than four views and with a usable resolution in both directions. Many commercially available lenticular displays have used the slanted-lenticular idea, for example displays have been available that produce between seven and nine views. Recent research by Hassaine *et al.* [23] into the optimal number of views required for task performance has shown that a low number of views (less than one viewing zone per cm) is the maximum required to achieve good stereoscopic results. While Speranza *et al.* [35] suggest higher number of views give improved perception of smoothness. There are experimental displays with rather more views, such as the 60 view experimental display produced by LG Display [36], but their individual view resolution is too low to be of practical use (the LG display has only 260 × 480 pixels in each view).

B. Parallax Barrier Displays

Another type of multi-view display design uses a parallax barrier (or raster barrier) element, in which an array of vertical or slanted translucent and opaque regions enables an observer on one side of the barrier to see only a subset of the illumination on the other side of the barrier This creates a set of viewing zones in each of which only some of the pixels are visible. As with lenticular displays, using vertical slits will limit a practical display to about four views. And again, as with lenticular displays, slanting the barriers allows for more views [37]. Parallax barriers have, traditionally, been less successful than lenticulars because they are considerably less bright, as by design the barrier blocks most of the light.

Over the last decade, there have been three interesting extensions to parallax barriers, each of which makes them more attractive. In one, 4D-Vision produced a “wavelength-selective filter array”, which provides a different parallax barrier for each of red, green, and blue and which, they claim, provides a better looking result [37]. In a second extension, the parallax barrier is made dynamic, changing rapidly so that every pixel on the screen is visible to the eye at some point within the eye’s integration time (i.e., within a thirtieth of a second) [38]. In a third extension, the display is constructed from two fully addressable panels, and a system of equations is solved in order to create the optimal color for pixels on both panels [39]. While the front panel can still be considered to be a parallax barrier, in some sense, this extension of the idea goes well beyond the traditional concept of a barrier and this third extension takes us outside the realm of horizontal parallax displays.

C. Multi-Projector Displays

Both of the methods above work by dividing the resolution of an underlying display panel into multiple views of lower resolution. The multi-projector displays, by contrast, use a single projector to generate each view. The projectors are mounted in a horizontal row some distance behind a special screen. The screen is normally a vertically diffusing double-lenticular lens or holographic optical element, which use a single projector to create each narrow zone in front of the screen. The result is a display that, visually, appears much the same as parallax barrier and lenticular displays and which works, visually, in the same way, as described by Dodgson [30], [31]. The advantage of multi-projector displays is that the screen can be much larger, as it is not limited by the size of an underlying flat-panel. The disadvantages are that it requires one projector per view and that these projectors must be precisely aligned. Despite this, several research laboratories have vigorously investigated such displays, including a sixteen-view experimental display from Mitsubishi [40] and a 128-view experimental display from the Tokyo University of Agriculture and Technology [41].

As the number of views increases, the terminology reaches for more superlatives, and we have super-multi-view displays [42]. These are displays where the pitch between viewing zones is so small that a single slice is no wider than the pupil of the eye. Once this density of viewing zones has been reached Speranza [35] concludes increasing the density further will not be able to improve smoothness. However, recent research suggests that there are benefits in building displays that can reproduce multiple views across the width of the pupil. It should then be possible to support physical accommodation cues and Hoffman *et al.* [43] conclude that these are important in accurate depth reproduction at shorter viewing distances.

An alternative approach has been to time-multiplex the projectors, so that a single projector can produce more than one view. The original prototypes used a single projector, producing between four and sixteen views. Such displays have been pushed as high as 28 views, with four projectors producing seven views each [44]. The optical path length required by such displays makes them commercially unappealing in an age of flat-panel displays.

D. Displays Using Holographic Components

Two companies, Holografika and Qinetiq, have attempted to address the problem of view density by tackling it in a different way: essentially by replacing distinct viewing zones with something closer to a continuum. Both companies use holographic elements in their displays, but do so in different ways.

Holografika produce a display that uses a sheet of holographic optical elements (HOE) as its principal screen [45], [46]. These direct the light coming from different directions behind the screen into different sectors in front of the screen. The screen is illuminated by a series of laser projectors, each of which is modulated so that each “pixel” on the screen is illuminated by several projectors from different angles. The HOE sheet ensures that these beams are emitted in carefully controlled angular sections, so that each pixel is visible from all directions, but that the pixel’s color can be different for different directions. The effect is similar to a horizontal parallax multi-view display, because Holografika only allow differences in the horizontal direction; there is no modulation vertically. However, it is different to a multi-view display because it does not have individual views, in the way described by Dodgson [30], [31]. Instead, each pixel has its own set of angular sectors, determined by its location relative to the laser projectors. This means that the viewed imagery seems more continuous, without the jumping between views visible in other types of display. It also means that creating imagery for the Holografika displays is not simply a matter of rendering multiple views of a scene taken from multiple cameras, but also requires a sophisticated view interleaving scheme. Holografika's displays have pixel counts of between 10^7 and 10^8 pixels. This pixel-count is similar to that enjoyed by the super-multi-view displays, described about, where there are around 10^2 views with around 10^6 pixels each.

Qinetiq use optically-addressed spatial light modulators (OASLM) which are able to affect the phase of laser light [47]. The resulting interference patterns create a holographic effect. Spatial quantization is required to make it possible to calculate the necessary phase array and the result is therefore similar to a horizontal parallax multi-view display. Vertical parallax can be achieved at the same time, with some loss of acuity compared with horizontal-only. Using three lasers, of different colors, and time-multiplexing the different color channels, they have been able to demonstrate full-color hologram-like imagery. Their experimental system used 10^8 pixels to produce an image 140 mm wide with an update rate of 30 Hz. To make truly holographic displays, Qinetiq estimate that they would need 10^{11} pixels [48]. This is clearly not possible with today's technology but it is possible that future developments will make such a display possible.

IV. Full Parallax Multiview 3D Displays

Full parallax 3D displays allow viewers to see a scene in 3D from any viewing angle. This requires both vertical and horizontal parallax to be available so that full look-around can be supported. In addition a viewer tilting their head should still be able to see a valid stereoscopic image on the display at any angle. These displays can be simulated using a head-mounted display in combination with a six-degrees of freedom head-tracking. However, in this section we concentrate on displays that are not attached to the viewer and are required to generate views simultaneously in many viewing directions.

A. Integral Imaging Displays

Integral imaging is an approach to auto-stereoscopic 3D display that adds vertical as well as horizontal parallax, moving a step closer to reproducing the visual experience that viewers have in the real world. It was first described as a photographic technique by Lippmann in 1908 [49] and has recently received attention from many researchers [50].

An integral display uses spherical, or more accurately hemi-spherical, micro-lenses instead of the cylindrical lenses used by lenticular displays. These micro-lenses are typically arranged in a regular 2D array, or fly's eye arrangement, over a 2D surface presenting the image information. Each hemi-spherical micro-lens directs light from the pixels it covers in different horizontal and vertical directions. This generates the vertical and horizontal parallax required. A similar micro-lens arrangement can be used to capture the images and a digital processing chain makes this most practical.

Integral imaging displays are less common than lenticular displays as, given the same pixel count, they sacrifice significant spatial resolution to be used as vertical directional resolution [3]. Among the additional challenges of these displays are a limited viewing angle, very limited depth of field in reconstructed images and the manufacture of micro-lens arrays of sufficient imaging quality.

One way to address the viewing angle concern is to use a curved lens array and curved image surface. This is practically complicated using real lenses but a recent advance proposed by Takahashi *et al.* [51] is to use a flat holographic optical element that works as a virtual curved lens. A prototype HOE demonstration implementing a 17x13 curved micro-lens array showed an improvement from fourteen to seventy degrees horizontal field of view.

The depth of field can be improved using image relay devices that create a floating image with extended longitudinal magnification [52], or using devices that create multiple imaging planes by such as moving the image plane mechanically or electrically [53].

For many viewing situations there is the practical question about whether the vertical parallax integral imaging displays can reproduce is worth the additional imaging cost. There is at this time limited evidence that vertical parallax has a substantial benefit in depth perception.

B. Volumetric 3D Displays

Volumetric displays generate imagery from light-emitting, light-scattering, or light-relaying regions capable of occupying a volume rather than a surface in space, as averaged over the display's refresh period [54], [55]. Typically, the image volume is composed of volume pixels, or voxels.

Over the 10 year scope of this article, advances in volumetric display development continue to be reported [56], though perhaps at a slower rate of progress than previously. These generally build on the themes of "canonical" types, such as: Hartwig's laser projection onto a spinning helix [57], Lewis *et al.*'s explorations of solid-state 3-D display [58], Traub's varifocal mirror display [59], and the swept-screen system of Hirsch [60]. There are also re-imaging displays that project a real 3-D image some distance from an object or image source [61]. Most electronic displays using this approach re-image a 2D display in free space but cannot be counted as 3D as the display does not produce a stereoscopic image.

New directions for volumetric displays are: image resolution with100 million voxels in one commercially-available system [62], the demonstration of nontrivial light field reproduction that supports viewer-position-dependent effects such as occlusion [54], and open-air volumetric display via plasma [63]. An open question remains at what point super-multiview displays, such as [42], would become functionally equivalent to volumetric displays providing voxels that both reproduce positional luminance and accommodation cues.

C. Multiplanar Volumetric 3D Displays

One subset of volumetric displays includes multiplanar, or "slice-stacking displays" in Benton's taxonomy [2]. They reconstruct a 3-D image by relying on persistence of vision to integrate multiple 2-D pattern-carrying surfaces into a 3-D volume. Some slice-stacking displays employ a rotating or reciprocating diffuser onto which 2-D patterns are projected, while others have an emissive surface.

Within the past 10 years there were two primary examples of slice-stacking displays having passive projection: the Perspecta Display [64] and the DepthCube [65]. The Perspecta Display (formerly made by Actuality Systems, Inc., Arlington, MA) generated volume-filling imagery of approximately 100 million voxels within a transparent 25 cm diameter dome. Perspecta accepted graphics commands over gigabit Ethernet from a standard Microsoft Windows XP workstation, which were interpreted and converted into R, G, and B voxel-illumination data by an NVIDIA GPU and stored in a custom dual volume buffer. Each volume was composed of 198 radially-disposed slices of 768 $\times$ 768 resolution and a 30 Hz volume refresh rate. Therefore, three Texas Instruments (Plano, TX) Digital Light Processing (DLP) engines projected $198 \times 30 = 5,940$ slices/second onto a diffuser screen rotating at 900 rpm.

The LightSpace Technologies DepthCube [65] also uses DLP technology, projecting a total of $>$15 million voxels onto a stack of 20 liquid crystal panels from a DLP projector. It resembles a large CRT, with a viewing zone of 90 degrees in both directions.

Love [66] reports a volumetric multiplanar display using a fast display and a novel fast switchable lens such that it repeatedly creates images at four different focal planes. The aim is to produce a display that can correctly support consistent binocular disparity, vergence and accommodation (focus) cues to depth. These features are found in many volumetric display designs and may prove to become a key benefit.

Within the last 10 years, several researchers have created volumetric displays capable of depicting occlusion and other viewer-position-dependent effects to reproduce non-trivial directional light fields. This capability is often erroneously deemed impossible [2]. Two swept-screen occlusion-capable displays include Cossairt *et al.*'s Perspecta whose diffuse screen was replaced with mylar [54], and the display of Jones *et al.* [55] that employed a brushed-metal tented screen and more advanced rendering software. Yendo *et al.*'s "Seelinder" display [67] uses several vertically-oriented linear arrays of LEDs that rotate in one direction while a parallax barrier rotates in the opposite direction. The LEDs are activated with synchronization sufficient to create 3-D imagery. To-date, these systems are horizontal parallax only. There is no consensus on whether these are volumetric displays, "volumetric multi-view displays," or a different name entirely.

D. *Solid State Volumetric 3D Displays*

It is also possible to generate multiplanar imagery through "solid state" processes such as two-step upconversion [58], in which a first laser beam excites the electrons of a doped substrate (such as erbium in ZBLAN), to a metastable state, a second laser beam excites the region to a radiative state, and visible light is emitted [68]. The intersection point of the two lasers can be steered using mirror scanners, for example.

Voxel-selection can occur using more complicated means, as well. A recent advance is reported by 3DIcon Corp. (Tulsa, OK), which uses 30 W lasers at 1532 nm and 850 nm to activate green voxels within an Er-doped YLF 17 mm $\times$ 17 mm $\times$ 60 mm crystal in planar cross-sections, modulated by DLP [69].

There is a variety of candidate substrates for these solid-state displays, as surveyed in 2008 by Chekhovskiy and Toshiyoshi [70]. One recent example is tap water. Ohira *et al.* describe a system in which a 5 W 1064 nm laser converts regions of water to visible plasma discharge [71]. It is also possible to ionize air, as demonstrated by Saito *et al.* [72].

TABLE I
CHARACTERIZATION OF THE PERCEIVED DEPTH CAPABILITIES OF FOUR 3D TV DISPLAY DESIGNS, ASSUMING ALL ARE BASED ON A $52''$ FULL-HD DISPLAY. VOXEL DEPTH IS CALCULATED AS THE PERCEIVED DEPTH THAT IS REPRESENTED BY A ONE PIXEL DISPARITY AT THE DISPLAY PLANE. THE STEREO RESOLUTION IS THEN CALCULATED AS THE NUMBER OF VOXELS THE DISPLAY CAN REPRODUCE IN A DEPTH RANGE OF $+/-100$ MM AROUND THE DISPLAY PLANE. THE COMPARISON WITH HUMAN VISION ASSUMES A CONSERVATIVE VALUE FOR STEREO ACUITY OF 1/60TH OF A DEGREE. MATHEMATICAL DETAILS ARE GIVEN IN [73]

Display type	Pixel size (mm)	Voxel depth (mm)	Stereo resolution (vxls in +/-100 mm)
Full resolution	0.6x0.6	36.9	11
Row-interleaved	0.6x1.2	36.9	11
Column-interleaved	1.2x0.6	73.8	5
Nine-view	1.8x1.8	110.7	4
Human vision		17.8	22

V. APPLICATIONS ANALYSIS

A. *Characterizing Three-Dimensional Displays*

From a content production and delivery viewpoint the huge range of 3D display designs available provides a significant challenge, each type of display has different optical and electronic characteristics and the impact of these differences on depth perception can be significant, as reported by Froner *et al.* [15].

The single most important reason for using a 3D display is to experience depth perception, however 3D display performance in terms of perceived depth is rarely, if ever, reported. There are many parameters of interest but we first follow the analysis in [73] in considering the geometry of the 3D viewing experience to characterize the perceived depth characteristics of several different 3D display designs. Each of the display configurations compared in Table I are assumed to be built around an HD (1080p) screen with a $52''$ diagonal viewed at a distance of 2 m (within the viewing range recommended by THX of 1.5-2.3 m for this size display). We take the pixel pitch of an unmodified 2D display of this size to be 0.6 mm horizontally and vertically and for comparison with human vision use a conservative estimate of the stereo acuity of the eye to be 1/60th of a degree.

It is clear from Table I that at the viewing distance of 2 m the best displays can only reproduce perceived depth intervals at the display plane to within a factor of two of the acuity of the eye. However those display designs that reduce horizontal resolution can at best reproduce depth intervals several times larger than that the eye can perceive. As a direct consequence the stereo resolution of these display also drops. The best display analyzed here can reproduce 11 voxels in $+/-100$ mm at the display plane, this drops to 4 for the lowest resolution design and should be compared to 22 voxels that the eye can distinguish at this range.

We identify a number of additional display characteristics that we believe are important for content producers and delivery systems. These determine the amount of information that needs to be captured, edited and delivered to the display system and also directly determine the quality of the viewer's experience of the display. Finding a single set of characteristics that apply to all the displays we review is challenging because not all displays use the same approach to reproducing perceived depth. Those we feel are key are:

- Number of discrete viewing zones (eye positions).
- Resolution (pixels or voxels) per viewing zone.
- Total number of voxels reproduced by a display.
- Number of simultaneous viewers.
- Constraints on head position.
- Maximum and minimum physical display size supported.
- Working, comfortable, perceived depth range.
- Color reproduction capability.
- Crosstalk level between views.

A quality concern for some, but not all displays, relates to the inherent accommodation-vergence conflict for stereoscopic images viewed at close range. This is where the eye's focus system and vergence system are provided conflicting cues by a stereoscopic display such that the eye must maintain focus on the display plane while the vergence system is driven to follow the stereoscopic image cue and verge away from the display plane.

Only a few studies investigate this in detail [74] and the evidence now suggests that certainly for close viewing distances, less than 2 m, there is an effect on perception and comfort. Hoffman *et al.* [43] investigate how mismatched accommodation affects comfort in stereoscopic image perception and Liversedge *et al.* [75] investigate how eye vergence movements differ in 2D, stereo 3D and real world 3D. However, at TV and cinema viewing distances (greater than 2 m) the eye has a large depth of field and it seems unlikely this particular concern is such an important issue. Contemporary reports of problems with comfort in these situations seem at least as likely to be due to poor quality content production than to accommodation-vergence conflicts.

B. Application Recommendations

Given the broad range of capabilities of the different technologies we have reviewed and the needs of different applications it does not seem that a single technology will form the basis for a universal 3D display, rather certain technologies will become better suited to certain applications. We identify five application areas with distinctive display requirements and the characteristics of the displays that could in future work well for them.

1) 3D Cinema: Here the solution of a pair of 3D glasses per viewer and matching polarized or wavelength filtered projection seems suited to the viewing environment and cost constraints involved. Time-parallel solutions could help reduce temporal artifacts.

2) 3D Information Presentation and Advertising: In group presentation situations the glasses free multiview and volumetric displays could see long term success; providing viewing freedom and removing the need to wear glasses.

3) 3D TV Display: Glasses based solutions are available at the time of writing but in the long term 2D/3D switchable multiview displays may be an improvement. These allow automatic switching to and from 3D mode and remove the need for viewers to know where the glasses are, recent solutions have low crosstalk values which is a key quality criteria.

4) 3D Desktop Display: Here displays using glasses can work well, while autostereoscopic solutions that retain resolution are potentially attractive for a wide range of desktop tasks. Super-multiview could help resolve accommodation-vergence conflict resulting from the short viewing distance.

5) 3D Portable Display: For portable devices, cell phones and games systems, it seems likely that display users will wish to avoid the use of glasses and the ability to implement a {2D/3D} switching autostereoscopic display on a volume market cell phone has already been demonstrated.

Fundamental challenges lie in developing content production and delivery tools that can cost effectively target the broad range of 3D displays that are becoming commercially successful [76].

VI. Conclusion

We have reviewed the most important approaches to 3D display that have emerged over the past decade and have emphasized the application of the displays. We have grouped them with respect to their ability to reproduce parallax, because this affects the range of possible head positions, the smoothness with which users can look-around objects, and the ease of task performance.

For applications and content generators the parallax requirements of a 3D display are critical because each new parallax view requires the content generator to provide that view. Resolution and size changes for 2D displays are relatively easy to support, but adding a new parallax view to a 3D display requires a new image to be captured or rendered from a new camera position. Intermediate view synthesis techniques are emerging but these have difficulty interpolating missing image data from occlusions and disocclusions accurately.

Stereoscopic and autostereoscopic technologies are now developed to a point where they are being used in everyday applications. Volumetric displays are still a niche product, but could see a new lease of life as interest in displaying the results of computational photography and light fields increases. For the future, computational holography is still experimental but may, one day, find its way into commercial products.

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Nicolas S. Holliman is a Senior Lecturer in the School of Engineering and Computing Sciences at Durham University, U.K., where he heads the Innovative Computing Group. In 1994 he established the Durham Visualization Laboratory to research all aspects of the application, use and human factors of 3D displays. Prior to joining Durham he was Principal Researcher at Sharp Laboratories of Europe, Oxford, UK, leading a team researching graphics and imaging algorithms for 3D display systems (http://www.durham.ac.uk/n.s.holliman).

Neil A. Dodgson is Professor of Graphics and Imaging at the University of Cambridge Computer Laboratory in England, where he is part of the Graphics and Interaction Research Group (Rainbow). He has undertaken research in stereoscopic displays (since 1992), subdivision surfaces (since 2000) and aesthetic imaging (since 2002), with forays into other 3D modeling, imaging, and animation applications. In 2007, he was awarded a higher doctorate (Doctor of Science) by the University of Cambridge in recognition of his research achievements.

Gregg E. Favalora received the BS from Yale University, New Haven, CT, and the SM degree from Harvard University, Cambridge, MA.

He founded Actuality Systems, Inc. in 1997, which developed and sold the Perspecta Spatial 3-D System. While at Actuality, Mr. Favalora directed the creation of a 198-view scanned-lenticular display, several light field displays, a single-SLM 20 Mpixel projector, and the 100 Mvoxel Perspecta. He is currently Principal at Optics for Hire. In 1999 he was listed as one of the top innovators under 35 by *Technology Review* magazine.

Lachlan Pockett received the double degree of mechatronic engineering and mathematics and computer science from Adelaide University, Australia. He is currently working on a related Ph.D. at Durham University. He is a Stereoscopic Imaging Specialist at Nokia Research Center.