A Survey of 3DTV Displays: Techniques and Technologies

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***Abstract*—The display is the last component in a chain of activity from image acquisition, compression, coding transmission and reproduction of 3-D images through to the display itself. There are various schemes for 3-D display taxonomy; the basic categories adopted for this paper are: holography where the image is produced by wavefront reconstruction, volumetric where the image is produced within a volume of space and multiple image displays where two or more images are seen across the viewing field. In an ideal world a stereoscopic display would produce images in real time that exhibit all the characteristics of the original scene. This would require the wavefront to be reproduced accurately, but currently this can only be achieved using holographic techniques. Volumetric displays provide both vertical and horizontal parallax so that several viewers can see 3-D images that exhibit no accommodation/convergence rivalry. Multiple image displays fall within three fundamental types: *holoform* in which a large number of views give smooth motion parallax and hence a hologram-like appearance, *multiview* where a series of discrete views are presented across viewing field and *binocular* where only two views are presented in regions that may occupy fixed positions or follow viewers' eye positions by employing head tracking. Holography enables 3-D scenes to be encoded into an interference pattern, however, this places constraints on the display resolution necessary to reconstruct a scene. Although holography may ultimately offer the solution for 3DTV, the problem of capturing naturally lit scenes will first have to be solved and holography is unlikely to provide a short-term solution due to limitations in current enabling technologies. Liquid crystal, digital micromirror, optically addressed liquid crystal and acoustooptic spatial light modulators (SLMs) have been employed as suitable spatial light modulation devices in holography. Liquid crystal SLMs are generally favored owing to the commercial availability of high fill factor, high resolution addressable devices. Volumetric displays provide both vertical and horizontal parallax and several viewers are able to see a 3-D image that exhibits no accommodation/convergence rivalry. However, the principal disadvantages of these displays are: the images are generally transparent, the hardware tends to be complex and non-Lambertian intensity distribution cannot be displayed. Multiple image displays take many forms and it is likely that one or more of these will provide the solution(s) for the first generation of 3DTV displays.**

***Index Terms*—Holography, TV, 3-D displays.**

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I. Introduction

THE DISPLAY is the last, but not the least, significant aspect in the development of 3DTV and vision. As has been outlined in other papers in this issue, there is a long chain of activity from image acquisition, compression, coding transmission and reproduction of 3-D images before we get to the display itself.

The concept of a 3-D display has a long and varied history stretching back to the 3-D stereo photographs made in the late 19th century through 3-D movies in the 1950's, holography in the 1960's and 1970's and the 3-D computer graphics and virtual reality of today. The need for 3-D displays and vision grows in importance by the day, as does the number of applications such as scientific visualization and measurement, medical imaging, telepresence, gaming, as well as movies and television itself. Many different methods of 3-D displays have manifest themselves over the last few decades, but none has yet been able to capture the mass market. Much of development in 3-D imaging and displays of the latter end of the 20th century was spurred on by the invention of holography, and this was the catalyst which led to some of the significant advances in autostereoscopic and volumetric methods, whereas, advances in techniques of virtual reality have helped to drive the computer and optics industries to produce better head mounted displays and other 3-D displays.

Many approaches have been outlined from simple stereo with anaglyph glasses through to full parallax holography. What technology is applied in a given circumstance will largely depend on the application itself. For example, it maybe that a full parallax, full color, interactive holographic display would be used in air traffic control but that an autostereo-display is more appropriate for low level computer aided drawing (CAD) applications. What is clear is that no single approach is likely to dominate and it will be the application which will determine which technology is adopted. The form that such displays would take is one aspect which needs considerable thought and is a major factor in consumer acceptance. Will the consumer want to see "Star Wars" images in a central table or will a flat panel in the corner of a room suffice?

II. 3-D Displays and Associated Perception Factors

The technologies currently being pursued for 3-D display can be broadly divided into the following categories, although there are various other methods of classification used and the terminology is not always clear.

- Autostereoscopic displays (Sections III–V).
- Volumetric displays (Section VII).
- Holographic displays (Section VIII).

Strictly speaking, the term "autostereoscopic" could be applied to all of the first three categories above, since it describes those displays which create a stereoscopic image without the need for any form of special glasses or other user-mounted device. However, it is usual to restrict the term to cover displays such as binocular (single user), multiview (multiple discrete stereoscopic views) and holoform systems where only multiple 2-D images across the field of view are considered. Autostereosystems are limited by the number of viewers and eye or head tracking is usually needed. In holographic displays the image is formed by wave-front reconstruction, and includes both real and virtual image reconstruction. In holography the 3-D scene is encoded into an interference pattern, this requires a high resolution recording medium and replay medium which place severe constraints on the display technology employed. Nonetheless, holography can be deployed in reduced parallax (e.g., stereo-holography or lenticular) systems, which relax some of the constraints. Volumetric displays form the image by projection onto a volume, or use discrete locations of luminescence within a volume, without the use of light interference (e.g., rotating or vibrating light emitting diode matrix). These displays tend to have limited resolution. Head mounted displays such as those using, for example, liquid-crystal-on-silicon (LCOS) devices or retinal scanning devices (RSD) are disadvantaged by the requirement to wear devices and in certain synthetic vision applications suffer from binocular rivalry [1]. These display devices already have established well-defined niche markets and will not be the focus of this paper [2]. The more traditional stereo-technologies, all require the use of viewing aids and will not be covered in detail here.

In order to make a highly believable 3-D display, there are a number of important physiological cues that must be presented to the eye-brain system. The main requirement is to create the illusion of depth or distance by using a series of cues such as binocular disparity, motion parallax, ocular convergence and accommodation [3], [4]. If an autostereoscopic based system is to be considered, conflicting cues can lead to discomfort and fatigue. There are also a number of psychological depth cues such as linear perspective, shading and shadowing, aerial perspective, interposition, retinal image size, texture gradient, and color. In the case of a mismatch between convergence and accommodation eyestrain in stereoscopic virtual displays may occur. The larger the depth of the stereoscopic virtual image, the larger the mismatch and the resulting visual strain.

Binocular asymmetries, the difference between the left and right images of a stereo pair, cause viewing discomfort and limit the widespread use of stereo image based displays. The factors that determine viewing comfort most strongly are vertical disparity and crosstalk between the left and right images. Even small amounts of each can cause noticeable discomfort [5].

There are many solutions offered to reduce the impact of human factors on the acceptance of 3-D images, such as eye-tracking, adaptive optical systems [6], or physically moving the source-location in scanned beam displays, and controlling the amount disparity and keeping it within a "comfortably viewable" range [7], [8]. For the presentation of a completely realistic image, the angles subtended by objects in the image should be the same as in real life so that the image is orthoscopic, but this is difficult to achieve for small displays [9]. For optimum viewing of TV, the viewing distance should be about three times the picture height [10]. Another related phenomenon is the "puppet theatre" effect, which manifests itself by objects in the image occupying a smaller region on the retina than they would in a natural scene [11]. This is intrinsically no more disturbing than viewing the miniaturized 2-D images that we currently seem to find acceptable. It can be reduced by "toeing-in" the cameras so that their axes cross at the subject distance [12] and results in zero disparity. The brain, however, can adapt to and correct for a wide range of ocular distortions and the question arises as to whether these effects are as important as is commonly thought. We will quite happily watch a distorted 2-D image, without this really bothering us [13]. The improvement afforded by 3-D over monoscopic images has been widely reported. Pastoor, for example, states that the overall psychological impact of a 3-D screen is equal to flat images twice their size [14].

In addition to human factors, many features of the display itself influence 3-D perception. If a pair of stereo images is of differing quality, the subjective quality of the fused pair is determined by the better image [15]. If the high-frequency spatial components in a stereo pair are in rivalry, and the low-frequency components are not, the image-pair can be fused readily. These effects have important implications for stereo image coding. Progressive scanning in a TV camera, as opposed to interlaced, improves perceived image quality. At a field rate of 50 Hz an interlaced scan only appears to have a resolution of 1.2 times that of a progressive scan with half the number of lines [16]. Crosstalk is arguably the most important factor concerning the design of autostereoscopic 3DTV. Reduction in disparity can reduce crosstalk, as can color selection [17]. A useful means of reducing the effects of crosstalk is afforded by the "kinder, gentler approach" that aims at "just enough reality" [18]. Image flicker influences the method of image multiplexing, and hence the display-type. The critical flicker frequency (CFF)—the frequency at which flicker becomes just visible—increases with luminance [19] (from 13 Hz at a luminance of 3.4×10^{-3} nits (lm/m^{2}sr) to 51 Hz at 343 nits). However, other factors also influence CFF, such as age, foveal or peripheral vision and the luminance of screen surround [20]. Thin-film translator liquid crystal displays (TFT-LCDs) will exhibit flicker at half the field frequency. Driving the display in such a way that the phase of the flicker is inverted on alternate rows can eliminate this [21].

Depth plane quantization is the separation of the image into discrete planes, due to the effect of the horizontal pitch of the display pixels producing disparity quantization. The threshold for this to become apparent is 0.8 min of arc [22]. Disparity quantization is doubled in simple lenticular 3-D displays where left and right images are displayed on alternate pixel columns.

III. Multi-Image Displays

Multiple image displays, where two or more images are seen across the width of the viewing field, can take three basic forms. In the first category, a large number of views are produced in order to give the appearance of smooth motion parallax. As these give a hologram-like appearance, they are referred to here as "holoform." Displays where a smaller number of discrete views are presented across the viewing field are termed multiview. The simplest multiple image displays are binocular where only a single stereo pair is displayed. Head tracked displays come under the category of multiple-image.

A. Holoform

Holoform displays aim to provide smooth motion parallax as the viewer traverses the viewing field laterally. This is achieved by producing a large number of closely spaced discrete views that give an image with a hologram-like appearance. One early approach [23], "the Stereoptiplexer," used picture information from rapidly moving cine film to produce a moving "aerial exit pupil" from scanning mirrors. The exit pupil is effectively a vertical narrow aperture that traverses the region between the viewer and the virtual 3-D scene. A variation on this is to replace the "aerial exit pupil" with a physical slit. The earliest work on this appears to be the "Parallactiscope" [24], which utilizes a slit moved rapidly in front of a CRT screen. This method requires an extremely fast frame rates to achieve display of video. A version of this display using a 400-element ferroelectric array with no moving parts was later developed [25].

Integral imaging can be considered as a variation of holoform displays. McCormick *et al.* [26] adapted the concept to produce an autostereoscopic display with full motion parallax. Integral imaging uses an array of small lenses that are either spherical or cylindrical to produce the familiar stereoscopic photographs where a lenticular sheet of vertically aligned cylindrical lenses provide pictures with a horizontal parallax only 3-D image. A variation of this locates a lens array behind a transmission-type display and inserts a polymer-dispersed liquid crystal between the lens array and the collimated backlight [27]. This feature enables 3-D/2-D conversion.

Quasi-holographic 3-D display systems such as holographic stereograms, are an alternative approach to display. With holographic stereograms, multiple views across the viewing field are produced using diffractive optics. St Hilaire [28] considers the effect of the image appearing to "jump" between adjacent views. This phenomenon is similar to aliasing when a waveform is under-sampled. An optimum of 20 views per interocular distance to achieve the appearance of smooth motion parallax was determined [29].

The Hungarian company Holografika has a 3-D display that they call quasi-holographic [30]. QinetiQ, advertise an "Autostereo 3-D Display Wall" on their website [31]. The display consists of an array of 40 projectors that project images on to a screen that diffuses light in the vertical direction only. The effective width of the array is increased by employing two side mirrors that produce virtual extensions to the actual array. The image is produced both in front and behind the screen.

B. Multiview Displays

In multiview displays, a series of discrete views are presented across the viewing field. One eye will lie in a region where one perspective is seen, and the other eye in a position where the adjacent perspective is seen. The number of views is too small for continuous motion parallax but strategies such as merging one image into the adjacent image and limiting the disparity in order to keep the apparent image content close to the plane of the screen can minimize the apparent "jumping" between views. Multi-view displays fall within four broad categories. These are: lenses, either in the form of Fresnel lenses or sheets of cylindrical lenses, parallax with "point" light sources: holographic viewing zone formation and "Cambridge" type displays with fast light shutters giving spatiotemporal formation of zones [32].

A method, simple in principle but cumbersome to implement [33], uses an arrangement of projection lenses, a Fresnel field lens and vertical diffuser to produce a series of viewing zones (4, 7, 13, or 21) depending on configuration across the viewing field. This provides a trade-off between the number of views and resolution.

Vertical lenticular screens can be used to direct light from columns of pixels on an LCD into viewing zones across the viewing field. A liquid crystal layer lies in the focal plane of the lenses, and the lens pitch is slightly less than the horizontal pitch of the pixels in order to place viewing zones at the chosen optimum distance from the screen. In this case, three columns of pixels contribute to three viewing zones. Early multiview displays with four zones are described in [34] and NHK developed a system in 1990 [35]. Simple multiview displays with this construction suffer vertical banding on the image known as the "picket fence" effect. Secondly, when a viewer's eye traverses the region between two viewing zones, the image appears to "flip" between views. These problems were originally addressed by the simple expedient of slanting the lenticular sheet in relation to the LCD [36]. The latest embodiment of the Philips display presents nine images across the viewing field [37]. The slanted lenticular screen has a pitch that is 1.5 times the pixel pitch of the LCD and is slanted at an angle of $\arctan(1/6)$. The resolution is reduced by a factor of three in both the horizontal and vertical directions. This display is switchable between 3-D and higher resolution 3-D. This is achieved with the use of an active system where a liquid crystal material is in contact with the lenses.

Although multiview displays are limited in the quality of the stereo effect, the size of the usable viewing region and the restricted depth of image field, the actual appearance of these displays is remarkably good, bearing in mind their simplicity. Other similar displays are marketed by Stereographics [38] and Sanyo [39]. The Sanyo display is four-view device that utilizes a parallax barrier (a pin hole array) and a 40-in LCD with 1280×768 pixels. "Point" light sources behind an LCD are used by a Korean group to direct images to the viewing zones

[40]. A simple 32×32 pixel display is described, where the light sources are obtained from a collimated blue laser beam passing through a microlens array. Each light source lies behind a 6×6 array of pixels, therefore providing both horizontal and vertical parallax. The paper acknowledges that the display suffers from the loss of resolution—this is particularly severe as both parallaxes are available.

Holographic optical elements (HOE) are another method used to form viewing zones [41].

Moore *et al.* [42] opted for temporal multiplexing where a series of images is presented in sequence. Although a sufficiently fast device was not available to perform this function, the operation of the display can be best understood by considering a transmission LCD rather than CRT system. Instead of a view being displayed on an LCD, it is projected on to the Fresnel lens by a lens located where the illumination sources were. A ferroelectric liquid crystal shutter replaces the illumination sources. This shutter is in the Fourier transform plane of the projection lens, and its real image forms the exit pupil. However, this is not seen on the image perceived by the viewer. Various versions of the display provide up to 16 views, and color. Color is obtained by using a Tektronix sequential liquid crystal shutter. Another version [43] uses a 50-in concave spherical mirror to overcome the scattering of ambient light from which Fresnel lenses suffer. Images are derived from three primary-color CRTs whose outputs are combined by dichroic mirrors for maximum efficiency. A further development provides two sets of viewing zones that are derived from two sets of CRT subsystems. This version is particularly suitable for two-player arcade. Recently, the method was revised to incorporate a fast ferroelectric display, with an array of LEDs as the light source [44].

IV. Multiple Image: Binocular, Fixed Viewing Zones

The simplest type of display is binocular or two-image, where a single pair of viewing zones is produced. These can be of five basic types; the viewing zones can be formed by lenticular screens, with twin projectors, by parallax methods, by holographic optical elements (HOEs) or prismatic screens. Twin projector methods produce exit pupils that are real images of the projector lenses, with the image formed on a double lenticular screen or a special reflecting screen. Parallax displays use an opaque mask, an array of orthogonally polarized image multiplexing elements or a series of line illumination sources behind an LCD.

A simple lenticular screen display may consist of an LCD with a screen in front of it. The screen consists of a series of vertically aligned cylindrical lenses with a pitch slightly less than double the horizontal LCD pitch. This allows for the viewer being at a finite distance from the screen. As the majority of LCDs have the RGB subpixels in the vertical stripe configuration, the LCD has to be operated in the portrait mode in order to avoid coloration and distortion of the colors in the image. Left and right images are displayed on alternate columns (parallel to the lenticular lenses) [45]. An LCD can be operated in the normal landscape mode in a display utilizing a chequered mask and orthogonally aligned lenticular screens [46]. The left and right images are multiplexed on alternate pixel rows. The display consists of five layers, in order from the back; backlight panel, chequered pattern mask, vertically aligned lenticular sheet, horizontally aligned lenticular sheet and the LCD. The horizontal pitch of the mask and the pitch of the vertically aligned lenticular sheet are about double the LCD horizontal pitch. These perform the same function, but in a different manner, to the lenticular screen in the previous method. Rows of the chequered pattern are directed to the appropriate rows of pixels by the horizontally aligned lenticular sheet. A more recent lenticular display, is capable of 2-D/3-D switching [46]. Microlenses activated on incident of polarized light can be used to either divert the images to the appropriate eyes in the 3-D mode, or enable light to pass through without deviation to allow the display to be used in the normal 2-D mode [47].

In projection displays, only a single pair of viewing regions is formed, thereby restricting the viewing region even more. A larger viewing region is provided by using HOEs [48]. Instead of producing diamond-shaped regions, the right image is directed to the right side of the viewing field, and the left image to the left. The distance from the screen over which 3-D can be seen is considerably increased. Also, when both eyes are in the right side of the field, a right image is seen by both of them, and a left image by both eyes when they are in the left side of the field.

A. Parallax Barrier

The first of the parallax methods uses thin vertical illumination lines behind the LCD in order to direct the light to the appropriate viewing regions [49]. The lines are produced on a diffusing screen by a lenticular sheet that is mounted behind it. The primary light sources are a series of vertical lamps that are located behind slit apertures and are focused by the lenticular sheet. An earlier display used masks to produce a simple and effective means of supplying 3-D to a single viewer [50]. In later versions parallax barriers, both behind and in front of an LCD, are used to present images with virtually no Moiré fringing. These barriers consist of masks that have vertical apertures in them.

Polarization can be used to provide what is effectively a vertical slit mask. In one system, an image-multiplexing screen consists of an array of vertical strips of dichroic polarizing material of alternating orientation; a Fresnel lens produces exit pupils from a pair of illumination sources that have polarizers in front of them to select the odd and even columns of pixels [51]. Difficulties were encountered with the manufacture of the multiplexing screen. The optics are very basic as the pupils are produced with a Fresnel lens. Also, the multiplexing barrier would probably have been more simply obtained by using an off-the-shelf micropolarizer array [52].

Sharp Corporation and Sharp Laboratories Europe, Ltd. (SLE) jointly developed a TFT 3-D LCD, which can switch between 2-D and 3-D display modes [53]. The LL-151-3-D monitor is capable of displaying dynamic 3-D images. Using a parallax barrier, light from the LCD is split so that different patterns reach the viewer's left and right eyes. With the DTI (Dimension Technologies Inc.) display [54], viewing zone formation is accomplished with a special illumination pattern and optics behind the LCD screen which make alternate columns of pixels visible to the left and right eyes of a viewer sitting directly in front of the display and in certain regions to either side. This displays left and right images of stereo pairs on alternate columns of pixels on the LCD. The left image appears on the odd numbered columns and the right image appears on the even numbered columns. For example, for an LCD with 1024 columns and 768 rows, each complete stereoscopic image consists of 512 columns and 768 rows. Both halves of a stereo pair are displayed simultaneously and directed to corresponding eyes. This is accomplished with a special illumination plate located behind the LCD. Using light from compact, intense light sources, the illumination plate optically generates a lattice of very thin, very bright, uniformly spaced vertical light lines, in this case 512. The lines are precisely spaced with respect to the pixel columns of the LCD. Because of the parallax inherent in our binocular vision, the left eye sees all of these lines through the odd columns of the LCD, while the right eye sees them through the even columns. The left eye sees only the left eye portion of the stereo pair, while the right eye sees only the right eye portion. This enables the observer to perceive the image in 3-D.

V. Multiviewer Head Tracked Displays

Surman *et al.* [54] developed a display with multiviewer capability with head tracking. A high-resolution direct-view LCD, presenting a stereo image pair simultaneously, can form the basis of a 3-D display. Regions are formed in the viewing field where a left, or a right image only, are seen across the complete area of the screen. The positions of these exit pupils follow the positions of the viewers' eyes under the control of a head tracker and enable a high degree of freedom of movement. The exit pupils are produced by novel optics, located behind the LCD that replace the conventional backlight. The display operates in a similar manner to anaglyph (red/blue glasses) or polarized glasses, but without the need for glasses. The core technology is based on a spatial multiplexing screen and an illumination system with steering optics. The steering optics incorporates a large number of white LEDs whose outputs are determined by viewers' head positions. Motion parallax cannot be displayed, but the presentation on two images only can be a positive advantage in a television system as it enables the simplest capture and transmission, and places the smallest demands on the display in terms of the amount of information that has to be displayed.

VI. Head Tracking Systems

Real-time position and orientation tracking of viewers is an important component for many 3-D displays [55], [56]. For some displays or applications, only orientation or position can be tracked. This imposes many limitations but also simplifies the task significantly. There already exist small, cheap and accurate inertial sensors which can be attached to HMDs. The accuracies of static position and orientation and dynamic movement measurements are important. Also features like sample rate, number of targets tracked, range of tracking, latency, update rate, registration, and space requirements may be important. It is highly important that the viewer is tracked and the scene gets updated very fast. Many head tracking methods are available including electromechanical, electromagnetic, acoustic tracking, inertial tracking and optical tracking. No single tracking method is universally applicable. There are dozens of methods for position and orientation tracking for various purposes and they are well documented e.g., in virtual reality textbooks. Hybrids of all the methods can naturally be used. They improve the accuracy but usually require more calculation. State-of-the-art head trackers deploy passive (optical) markers and active (optical, acoustic, magnetic) emitters and receivers as well as inertial system components such as gyros, gravimeters and accelerometers. Some advanced systems even combine different components, e.g., optical and inertial subsystems, in order to make the tracker more robust against changes in the environment or in the case of occlusions. Generally, these systems are intrusive since they require the user(s) to be tethered to the measurement equipment, or at least to wear some parts of the equipment.

The earliest head tracking displays used infrared light reflected from the viewer's head. In a Fresnel lens single viewer display [57], the head detector moves with the lens. Illumination of each side of the viewer's head by two wavelength bands of infrared light has also been applied [58]. A further display uses a large format convex lens to illuminate the left side of the viewer's head with IR in the 830–870-nm range, and the right side of the head in the 930–970-nm band. The outputs of a pair of cameras with matching filters are used to control the illumination from a monochrome 2-D display directly without the use of any additional processing. This method is used in other displays by the same researchers [59], [60]. Retinal reflection is used in some head trackers, for instance using "Red-eye" reflection [61]. Identifying the time during which the viewer blinks and measuring the size of the pupil has been considered [62]. A pair of cameras and a feature-based stereo algorithm can be used to extract interest points in the images [63]. Those points representing the eyes are determined by means such as stereo correlation, template matching and detection of synchronously moving pairs. Near to real-time (120 Hz) frame rates were achieved by a high-precision single-person 3-D video head tracker [64], [65].

VII. Volumetric Displays

Volumetric displays reproduce the surface of the image within a defined volume of space. As volumetric displays create an image in which each point of light has a real point of origin in space, the images may be observed from a wide range of viewpoints and angles. Additionally, the eye can focus at a real point within the image giving a sense of ocular accommodation. Such displays are usually more suited for computer graphics than video applications due to the difficulty in obtaining suitable natural image capture. However, their most important drawback with regard to TV displays is that they invariably suffer from image transparency where parts of an image that are normally occluded are seen through the foreground object. Another difficulty is the inability to display surfaces with a nonLambertian intensity distribution. A large variety of volumetric display techniques have been proposed but few successful large scale devices are available, although a number of smaller scale displays have been developed. Volumetric displays can be of two basic types: virtual image where the voxels are formed by a moving or deformable lens or mirror, and real image where the voxels are on a moving screen or are produced on static regions.

A. Virtual Image Methods

One of the earliest virtual image methods [66], [67], uses a mirror of varying focal length to produce a series of images at different apparent distances. The variable curvature of the mirror allows smaller movement than would be required from a moving flat surface giving the same effect. The mirror consists of a thin silvered Mylar film that is attached to the front of a loudspeaker which is driven at between twenty and several hundred Hertz. A variation on this uses a stretchable membrane mirror [68], [69] of 1.2 m diameter that can be varied over a large range of F-numbers. The image can be produced both in front of, and behind the plane of the mirror. Lenses can also be used to produce a similar effect. In the "xyzscope" [70] a rotating lens is used to effectively vary the distance between the object and the lens centre. A combination of variable focus lenses and integral photography has been proposed by Yanagasiwa *et al.* [71]. However, the lens array described would be difficult to make due to the varying radius of curvature needed by the lenslets. Schowengerdt and Seibel [72] developed a "True 3-D Display" that matched the accommodative and vergence requirements of the human visual system for viewing objects in depth. The accommodative cue is generated in hardware using wavefront shaping deformable membrane mirrors. In addition, software cues, such as blurring, relative size, and occlusion, are tested for their ability to trigger appropriate accommodative responses in 3-D displays.

B. Real Image Methods—Moving Displays

A solid image can be produced in a volume of space by displaying "slices" of the image on a moving screen (swept volume). If, for example, a sphere has to be displayed, this can be achieved by displaying a series of circles of varying size on to a moving surface. Most attempts to create volumetric 3-D images are based on swept volume techniques, because they can be implemented in the near term with today's hardware and software.

Favalora *et al.* [73] have developed a system with a 100 million voxel resolution sufficient for video display. This is obtained by presenting 200 radially-disposed slices consisting of 768×768 pixel images. These are provided from a modified projector that can supply hundreds of colors. Images are projected on to a disc that rotates at 900 rpm and frames are updated at 30 Hz. This is being developed by Actuality Systems under the trade name Perspecta™ [74]. It creates an image within a desktop 20-inch dome. It has limited immersion, no entry into volume, and is only suitable for small objects. However, it be made interactive by external cameras, which track the user's hands on the dome.

Another rotating screen system, by Holoverse [75], [107], [108], with 8 bit color depth is based on Texas Instruments' DMD (Digital Micromirror) Technology. They claim to eliminate the wobble and sway of competing systems, while increasing the resolution, color depth, and update rate. Their "HoloDeck Volumetric Imager" has an effective cross-sectional resolution of $1024 \times 768 \times 360$ in evenly distributed rotational planes. Further examples of rotating screen devices are the FELIX 3-D-display, which utilizes a helical screen and RGB lasers [76]. The 3-D image appears to be inside the cylinder, where an outer wheel with vertical slits revolves clockwise at a fast rate, while an inner wheel moving counterclockwise at a slower speed lined vertically with LEDs projects thin slices of a face. The system also requires a 360° digital camera surrounding the object, and the data to be sent to the cylindrical tube. The rapid succession of image slices seen through the slits produces the illusion that the viewer can see the person's entire face at once, in 3-D.

C. Real Image Methods—Static Displays

Static displays are those where voxels are produced on stationary regions in the image space. Some of these methods have the potential to overcome the problem of image transparency such as that where UV light is piped, via fiber optic guides, to individual voxels in a medium composed of a fluorescent dye [77]. The fluorescing region is not completely transparent as in virtual image or moving screen methods. The device described consists of a stack of transparent spacers, with layers of fluorescent dye between. The device was small at $11 \times 11 \times 5$ voxels, but is capable of being scaled up to $103 \times 103 \times 103$. The "solid FELIX" volumetric display is based on fluorescence excitation in a crystal. The images appear in a transparent crystal cube. The crystal, which describes the complete volume of the display, is doped with ions of rare earth elements. These ions are excited in two steps by two intersecting infrared laser beams and so start to shine. This process is called two-step up-conversion and is based on the absorption of two IR-photons by a rare earth-ion which then emits a visible photon. The medium in which the picture appears has to be solid, transparent and capable of being doped. These demands are fulfilled by crystals, glasses and, in future, even by plastic.

Dolgoff [78] describes a simple two-plane method which uses a partially reflecting mirror to combine the real foreground image behind it with the reflected background image. The foreground image is brighter in order for it to appear opaque. This type of display is not suitable for video, but does provide a simple and inexpensive display that can be very effective in applications such as advertising. An attempt to overcome the transparency problem was made by Son *et al.* [79]. They proposed the use of an SLM in front of a translucent volumetric image in order to block light in directions that would normally be occluded. However, it seems that the speed and spatial resolution of the SLM will be insufficient for this method to be effective.

FogScreen have patented a 2-D projection screen which utilizes a bank of "fog-like" particles [80]. The projected image appears to float in space and encourages the audience to interact with it. It is possible to project different images on both sides without interfering each other because screen transmits light more than it reflects. It can also be made interactive by integrating 2-D tracking. Although only 2-D it is a volumetric display in the sense that the floating image is formed within a volume of free space. It is difficult to add more projection layers to create depth, as the projection between the layers would need some space and the screens shine through to the next layer. However, it can be extended into a pseudo-3-D screen by using dual-sided rendering, head-tracking rendering and stereoscopic imaging [81].

VIII. Holographic Displays

While holography is well established amongst the scientific community, its impact has not yet impressed itself upon the general public. Many have seen the 3-D holographic images found on credit cards but are unfamiliar with the high quality images that holography can produce; even fewer people have witnessed dynamic holograms or holographic movies. Color holography produces 3-D images of startling reality, with depth cues and parallax that are difficult to achieve by other techniques. The main advantages of a holographic system are the recording of the true 3-D wavefront of a scene and the retention of motion parallax. However, this is offset against the need for a very high bandwidth and the difficulty of obtaining natural shading. The display of captured and transmitted 3DTV video signals by holographic means is highly desirable [82]. However, a full parallax, large area, interactive, moving, color holographic display, which is thought by many to be the ultimate goal of 3DTV, requires incremental and parallel development in many essential areas of technology before it can be brought to fruition. For example, a large display of say 100 mm diagonal will need dramatic improvements in very large scale integration (VLSI) techniques to enable a spatial light modulator (SLM) to be manufactured with sufficient pixel resolution. If the oft-quoted "Moore's Law" continues to apply then it could be ten years before a display with less than a micron pixel size is achieved [83]. An array of SLMs requires advances in interconnection technology and software required to drive them. Color displays require development of compact, safe lasers or LEDs with sufficient coherence and power. Synthesis of high-resolution computer generated holograms (CGH) with high-spatial frequency content for 3-D object presentation is most crucial for creation of true 3-D perception of real-world scenes with randomly distributed diffuse objects. The task of CGH synthesis is particularly challenging in the case of dynamic displays which require fast approaches for simulation of the underlying physical phenomena to enable refresh rates of the consecutive display frames suitable for real-time representation [84]. Compression within holography has been considered in various publications [85]. Given the present state of modern computer power and capacity, such an approach will rely on approximation techniques and correspondingly fast algorithms for its implementation.

Historically, holographic movies and television have been limited by their reliance on high-resolution emulsions for recording and reconstruction. More recently, developments in electronic sensor technologies and SLMs have moved the technology into the digital domain where transmission of holographic data is possible. The main drawback is the resolution of the existing dynamic SLMs such as LCD or DMD is not enough for reconstruction of the 3-D images with high quality. Only acoustooptic modulator (AOM) SLMs can provide such a resolution in the Bragg diffraction mode but they are 1-D structures which entails omitting vertical parallax. Prior to the development of high resolution charge coupled devices (CCDs) or CMOS optical sensors, holographic recording media have included: silver halide emulsions, photochromic, bacteriorhodopsin, and thermoplastics. In general, a recording medium is required that can resolve high spatial frequency interference patterns in the order of 1000 linepair/mm (for large angle off axis recording). Much of the work of reflection holography may be applied to the dynamic case of holographic television [86]–[89]. A number of challenges need to be overcome before holographic television is ready for the mass market. However, the prospect of full wavefront dynamic reconstruction of 3-D images is tantalizingly close and must be aspired to.

An alternative to conventional holographic recording and replay is optical scanning holography (OSH) whereby 3-D information is recorded in a single 2-D scan. OSH uses heterodyning techniques, accomplished by the use of an AOM [90], [91]. A novel approach is to directly acquire horizontal parallax holograms from a scene using OSH and later reconstruct on these on a SLM [92]. Reduced parallax holographic systems are another alternative, i.e., systems which sacrifice one plane of parallax in order to reduce information content or increase brightness [93]. It has often been said that someone viewing a hologram for the first time only notices the presence of vertical parallax when "jumping up and down with excitement"! It is true that in the case of 3DTV or movies, the viewer will normally be seated and unaware of vertical parallax. However, in an operating theatre the argument for loss of parallax is not so valid. The combination of a lenticular sheet display and LCD represents a good cross-over of technologies with the autostereoscopic geometry. The 3-D content reduction for real-time visualization of 3-D moving objects could be realized by hybrid holograms with synthesized mosaic structures. The hybrid hologram represents a combined structure of high spatial frequency analogue (passive) hologram and a controllable low spatial frequency digital (computer synthesized) hologram. Natural shading may also pose a problem to a holographic display when the original scene is illuminated by lasers. The natural shading from the sun or room lighting would be lost in reconstruction.

A. *Underlying Technologies and Techniques*

As suggested above, the development of a full scale interactive holographic display requires the parallel development of many underlying technologies. While the spatial resolution of current SLMs is not yet high enough, spatial resolution has been constantly improving. SLMs modulate a coherent light source based on input control parameters. The two main types of SLM are optically and electrically addressable. With an optically addressable SLM a light source is used to write the prescribed spatial pattern onto the SLM. Electrically addressed SLMs can convert electrical signals into an interference pattern. Here, each pixel may be individually addressed. The main qualities required from a SLM in digital holography are that they are fast, have high transmittance and a good optical efficiency [94].

Existing SLM technologies include LCDs, AO displays and digital micromirror devices. Liquid crystal SLMs are electrically addressed devices with a driving mechanism similar to that used in commercially available LCTVs. *LC* displays can be used to write a dynamic interference pattern. Displays such as metal–insulator–metal (MIM) and twisted-nematic (TN) have been used in electronic holography displays [95]. Liquid-crystal-on-silicon (LCOS) devices use a combination of a liquid crystal and a mirror to perform optical modulation. The main advantage of LCOS technology is the high fill factor of up to 93%. An optically addressed liquid crystal device (OALCD) converts an intensity pattern into a phase or amplitude modulation. The backside (writing side) of the display is illuminated by the intensity pattern which creates a corresponding 2-D-modulation of the refractive index in the liquid crystal film on the other side of the display (reading side). The incoherent light is converted into a voltage applied to the liquid crystal layer. Therefore, the magnitude of refractive index change is dependent on the incident intensity.

Digital mirror devices [96] form another group of systems for spatial light modulation. DMDs consist of an array of tiltable micro-mirrors mounted on hinges over a CMOS static RAM chip. Pixel counts of more than 1280×1024 can be obtained with pixel pitches less than 16 μm. The mirrors are addressable via binary data sent to the SRAM, which produces an electrostatic charge distribution, causing the individual mirrors to tilt either ON or OFF. DMDs have been utilized in an array to enable holographic video display [97]. One advantage of DMDs over LCDs is that the incident light is reflected with high efficiency, while the liquid crystal systems always suffer from a certain amount of light absorption, even if they are changing the phase only. Additionally, because of the lower absorption, mirror based devices can be used with higher light intensities without running into thermal problems. DMDs are used in a wide-range of applications such as optical switching, spectroscopy, scanners, confocal microscopes, hologram memory devices, telecommunication applications, biomedical imaging, interferometry and bar-code readers.

Polymer dispersed liquid crystals (PDLC) and their holographically formed counterpart (HPDLC) are composite materials with *LC* nano-scale droplets dispersed in photopolymer film. They can provide low cost, high resolution, high contrast, with good switch-on/switch-off times, but this is at the cost of relatively high control voltage and limited viewing angles [98]–[100]. AO SLMs have been used for some time in 3-D holographic video [101], [102]. AO SLMs utilize the interaction of travelling acoustic waves and a coherent light source within a medium, to modulate the properties of the transmitted optical wavefront. The AO medium may consist of a piezo-electric transducer bonded to a suitable crystal such as fused silica. On application of a radio frequency (RF) signal to the medium, the acoustic wave acts like a "phase grating" travelling through the crystal at the acoustic velocity of the material and with an acoustic wave-length dependant on the frequency of the RF signal. The incident laser beam is then diffracted by this grating. Acoustooptic SLMs generate a 1-D modulation and require a scan mechanism. The scanning optics in AOM system requires synchronization to the fringe data stream and optical processing to for the reconstruction.

The major disadvantage of SLMs compared to conventional emulsion-holograms is the lower space-bandwidth product (SBP) of these devices. SBP is defined as the product of the device dimension and the pixel frequency. With a resolution of 3000 line-pair/mm and a size of 20 cm^2 a conventional hologram has a SBP in the region of 1000, whereas current SLMs approach 100. This low SBP has a strong influence on the resolution limit. The smaller the pixel pitch and the larger the wavelength, the smaller is the achievable distance between the object and SLM during the reconstruction for the same object. The reduction of pixel size in combination with an increasing number of pixels leads to a decreasing speckle size in the reconstructed image. Another advantage of a shorter distance between SLM and object is the reduced intensity loss and thus better reconstruction of the object. SLM technologies are constantly evolving with reduced pixel pitch and increased pixel count.

The development of lasers to meet the specific requirements of holographic display systems requires some thought. A color holographic display using an LCOS SLM, would require the selection of three wavelengths, to provide chrominance and wavelength matching of the characteristics of the SLM and human eye. Typical wavelengths for this would be blue 476 nm, green 532 and red 648 nm [103]. The spatial coherence of lasers used, must be considered to provide even illumination of the SLM (Hologram) and temporal coherence must be considered with regards to speckle. The power output of such lasers and their compactness for a television system must also be calculated, to provide adequate illumination. High power lasers would be required ($>$300 mW, visible), along with careful thought on the ocular hazards (for example, suitable beam expansion, fail safe mechanisms etc.). The two main methods for color holography are color mixing [104] and time-division multiplexing illumination [105]. In color mixing, three lasers are combined using beam splitters to form a color hologram. In time-division multiplexing, the lasers are rapidly alternated using an aperturing arrangement or pulsed lasers. Recently, a color electroholography system using three colored reference sources that required no additional optics (e.g., shutters, etc.) was demonstrated [106]. Color displays require development of compact, safe lasers or LED's with sufficient coherence and power.

IX. Future of 3-D Displays

Clearly no display method is without its problems or limitations. The development paths which have to be followed before a full 3-D display can be realized are very complex. Given the current state-of-the-art, nonholographic displays, such as volumetric or autostereo, are in a more advanced state of development and it is felt that they are more likely to reach the market place in a shorter time frame. Many approaches have been outlined, from simple stereo through to full parallax holography. It is not clear which particular technology will dominate future 3-D displays. However, it is thought that it will be the application that drives the technology development. Those stereo technologies, which require glasses or other viewing aids, are unlikely to be accepted by the general consumer.

Volumetric displays attempt to achieve a very ambitious goal: an autostereoscopic walk-around true 3-D display. In general, there are numerous bright ideas, but the field is still in its infancy. Economics dictates that there must be enough market demand to provide and develop products for the future. This is not the case for most volumetric displays. Many volumetric displays already have some special applications which may have a profitable market. However, it is difficult to see any of them replacing current CRT or LCD displays in homes within ten years.

Although there is much activity surrounding head-tracked 3-D displays, there are few methods that have the potential to be developed into a multiple viewer display suitable for television. Any display that uses a Fresnel lens has a limited area over which exit pupils can be formed and are unlikely to form the basis of a multiuser display. Method utilizing a lenticular screen will suffer likewise. The geometry of the parallax methods does not allow any of them to serve more than one viewer. A number of successful HMDs have been developed for simulator and gaming applications. There is a huge amount of interest from military, industrial, and consumer markets in having realistic 3-D displays and rendering tools. However, the lack of accommodation depth cues in stereo display leads to binocular rivalry. Some projection methods have the potential for multiple viewer operation, but these would require extremely large housings.

A holographic display will inevitably rely on digital holography and spatial light modulation techniques. The quality of reconstruction with digital holography is dependant on the availability of high resolution SLMs and CCDs. The capture of holographic images using CCDs will provide the high resolution data required to drive the SLM. Alternatively, computer generated holograms may be used to drive the holographic reconstruction. Research is required into finding suitable SLMs for reconstruction and techniques to improve on the limited resolution provided by these sensors.

Liquid crystal displays are well suited to dynamic digital holography since they are electronically addressable. HPDLC displays offer high resolution compared to the conventional LCOS displays. LCOS displays are commercially available, but their limited spatial resolution and pixel count produces a small imaging area. LCDs have formed the basis of most implementations of holographic TV. The knowledge gained from optimizing LCOS displays for holographic reconstruction, will be invaluable in the progress of the technology and creating larger displays. Learning how to maximize the limited resolution will produce techniques that optimize the efficiency of later displays and help to reduce bandwidth. Further, research is required into methods of producing realistic color images from multiplex SLMs. MEMs devices can be used as spatial modulators for the holographic display, with commercial devices available such as the DMD. DMDs provide pixel counts and pixel pitches of a similar order to current LCOS technology, however, each pixel acts in a binary intensity mode that reduces the quality of reconstruction. The main advantage of DMDs is that light is reflected with a high efficiency compared to LCOS technologies. It is thought that until and unless other technologies are developed holography will be reliant on LCOS technology for the display. Further it is expected that the SBP of these displays will increase, thus improving the imaging area and quality of reconstructions.

Although advances in holographic displays are gathering momentum, it is felt that the advances currently being made in autostereo displays suggest that a multiviewer, high resolution, bright display could be achieved earlier than a holographic one.

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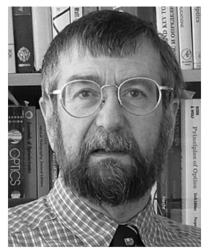

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