WHITE PAPER

On Exemplar 3D Display Techniques:

Summary Discussion

Dr Barry G Blundell

Auckland University of Technology

April 2012

www.barrygblundell.com
barry.blundell@physics.org

On Exemplar 3D Display Techniques:

Summary Discussion

Dr Barry G. Blundell FBCS
Auckland University of Technology
barry.blundell@physics.org

Abstract Three-dimensional (3D) display techniques offer to serve a broad spectrum of distinctly different functions and may be implemented in numerous ways. Furthermore, although today's 3D systems invariably capitalise on binocular vision (specifically stereopsis) this is not the only visual mechanism by which we are able to gain a strong sense of form and spatial positioning across three physical dimensions. Consequently, the formulation of a single, all embracing, and clear-cut description of the fundamental essence of the 3D display paradigm is not entirely straightforward. Perhaps the most obvious approach is to consider 3D displays as supporting image depiction techniques able to present synthetic spatial content in ways that are consistent with our natural perception of the 3D world in which we live. However, when considered in the context of scalable approaches able to operate satisfactorily across a broad range of applications, this seemingly simple objective is far from trivial. In this document, various useful terminology is briefly summarised, and this provides a framework for introductory discussion on a number of 3D paradigms and their application.

1. INTRODUCTION

The overarching purpose of all 3D display systems is to present content to the human visual system in a manner that facilitates the formulation and clarity of mental impressions concerning the geometric form of image entities, and of their distribution over 3D space. In this way a technology may, for example, serve to more fully immerse an observer within a synthetic world, facilitate the extraction of spatial information (in terms of cognitive effort, accuracy and rapidity – see, by way of an elementary example, Figure 1), and/or may enable the use of innovative techniques that advance spatial interaction.

Our visual impression of the natural world is underpinned by a broad range of cues to depth, and although it is convenient to discuss each cue individually, in practice they are seldom perceived in isolation (for related discussion see Reichelt *et al.* [2010], Blundell [2008, 2011a]). Indeed our perception of a 3D scene is based on information derived from the complex coalescence of cues to depth - the role played by individual cues varying according to the nature of the scene under observation, the viewing distance of components upon which we fixate, and the form of the information that we consciously or subconsciously wish to visualise. In addition, prior experience/expectation play a crucial role in the visualisation process and it is important to recognise that the subconscious analysis of a visual scene is a dynamic process in which sampling is driven by rapid saccadic movements of the eyes. Thus although discussion below focuses on the role played by individual cues, we recognise that this is a simplification that does not properly reflect the dynamic and generally adaptive nature of the visual sense.

With these thoughts in mind, it remains convenient to group cues to depth into three general categories. Firstly, the various monocular cues employed by artists when mapping 3D perspective space onto a 2D surface are usually referred to as pictorial cues. Their harmonious incorporation within artistic works was perfected during the Italian Renaissance period and enabled painting to achieve and even transcend photorealism (See Table 5 for a list of various pictorial cues.)

In viewing near-field objects within our natural surroundings, accommodation and convergence are physiologically coupled and so operate in synchronism such that the eyes are driven to focus on, and their visual axes converge on, the object of fixation. As these cues to depth are underpinned by physical changes of the eyes (and despite the inherent binocular nature of the convergence process), they are commonly referred to as oculomotor cues.

The physical separation of the eyes enables each to gain a slightly different view onto a 3D scene. Geometrical disparities in these two views provide the powerful impression of three-dimensionality referred to as binocular parallax (stereopsis). When coupled with motion parallax (see below) this cue plays a crucial role in our ability to accurately judge absolute and relative distances. By way of example, consider two needles (or similar markers) which are oriented vertically and located at different distances in front of an observer. Assuming that the nearest needle is at a distance of ~65cm, then under photopic lighting conditions the minimum detectable difference in depth is ~0.3mm. However, this level of stereo acuity rapidly diminishes with increasing fixation distance.

Figure 1.1: A stereogram depicting a bleak WWI landscape. This can readily be fused by slightly crossing the eyes (initially, it is helpful to fixate on the tank at the top of the photographs). The augmented information content provided by the 3D view is readily apparent. (Reproduced from Blundell [2011a].)

As discussed shortly, binocular parallax can also arise by inducing a temporal imbalance into the information streams generated by the two eyes. We refer to this special case as giving rise to binocular parallax based on temporal asymmetry.

Information concerning the spatial form of a dynamic image scene can be inferred from the relative motion of components under observation. In addition in viewing our surroundings, even small changes in vantage point can greatly assist in the determination of both relative and absolute distances. Following a previous work [Blundell 2011b], we refer to the former as motion Parallax derived from Image Dynamics (PID) and the latter as motion Parallax derived from Observer Dynamics (POD). We assume that PID embraces geometrical changes, the kinetic depth effect, and dynamic occlusion.

In relation to POD, when regarding the natural world we anticipate that changes in vantage point across all three spatial dimensions will frequently yield a change in view. In contrast, 3D paradigms may simply not support motion parallax, may limit support to one dimension (invariably horizontal changes in vantage point), may provide 2D support (horizontal and vertical changes in vantage point), or may mimic the natural world experience by fully supporting this important cue. To distinguish between these situations, it is convenient to prefix the form of motion parallax in an appropriate way. Thus, for example H,POD indicates a display supporting motion parallax for horizontal changes in vantage point, whereas H+V,POD indicates support both horizontally and vertically. 3-POD indicates support across all three dimensions – so accommodating observer movement towards, or away from, an image scene.

2. CLASSES OF DISPLAY Although the number of cues to depth supported by a 3D paradigm does not necessarily provide a meaningful performance metric for display comparison, it can form a useful starting point in identifying technologies that *may* be suited to particular type(s) of application – or conversely in the elimination of technologies that are unsuitable. In parallel, as summarised in Section 4, it is also necessary to consider other vital (and often inter-related) factors. From a technical perspective these include the nature of the intended application(s), viewing and presentation parameters, data capture, processing and throughput issues, and in some instances interaction opportunities that are offered by a particular display modality. Indeed, if the opportunities arising from the presentation of 3D content to the human visual system are to be exploited to maximum advantage, mapping a display paradigm to a particular application or range of applications is by no means trivial, and invariably involves a number of carefully balanced compromises. The technical issues are complex, and when considered from the perspectives of both visual and interaction requirements, it is most unlikely that in the short-term any single 3D display paradigm will be able to offer excellence in performance across a broad spectrum of applications.

In Table 1, six general classes of display are identified. Moving from left to right, there is a general increase in the number of supported depth cues – although, as indicated above, this does not necessarily imply a corresponding increase in merit. This simple scheme provides a useful framework for structuring discussion, and assists in emphasising fundamental visual issues. In this respect, it is crucial to ensure that the visual characteristics of a display are subordinate to the complex expectations of the human sense of sight. Thus the latter should not be required to adapt, in an unnatural manner, to the former (especially when a display is to be viewed for extensive periods of time). Whatever the extent of the hype directed towards the promotion of a particular 3D technology, if it does not properly satisfy the natural expectations/requirements of the human visual system - it will ultimately fail. Below we briefly summarise aspects of each class of display.

(a)MONOCULAR This class of display is assumed to be limited to the presentation of the pictorial depth cues together with 3-PID (for example traditional forms of television and computer display). However, as indicated below in certain circumstances, displays of this type can be used to support binocular parallax arising from temporal asymmetry.

A fundamental feature of monocular displays is that the eyes are presented with geometrically identical views onto an image scene – the geometrical disparities associated with natural binocular parallax are absent. Thus image components invariably appear to be located within the plane of the screen. However, this is not an inherent limitation and given the remarkable capabilities of the human visual system, it is possible to compensate for the absence of binocular parallax and depict content in which image components appear to span 3D space. In this respect, it has long been recognised that the effectiveness of the pictorial cues together with PID can be greatly enhanced when an observer's awareness of the image depiction surface is dispelled. This general notion was exploited in the Phantasmagoria which gained rapid popularity in the late eighteenth century [Blundell 2011a], and may have been employed by Filippo Brunelleschi in his demonstrations of geometrically accurate perspective painting in the early fifteenth century (Edgerton [1976] and Blundell [2011a]).

In brief, by minimising a viewer's subsidiary awareness of the display screen, and by eliminating the spatial stability effects occurring around the display border, 3D image scenes can be formed.

	Monocular	**Monocular (tracked)**	**Stereoscopic**	**Stereoscopic (tracked)**	**Autostereoscopic Class I**	**Autostereoscopic Class II**
Examples	Conventional flat-screen display		Chromatic/ Polarized Overlay. Temporal coding. Spatial coding.	Non-coded. Chromatic/ Polarized overlay. Temporal coding.	Multiview. Integral imaging (in fact this may also support Class II characteristics).	Volumetric. Varifocal. Electro-holography
Pictorial Cues	Yes	Yes	Yes	Yes	Yes	Yes
3-PID	Yes	Yes	Yes	Yes	Yes	Yes
Binocular Parallax (temporally asymmetric)	Yes (with glasses)	Yes (with glasses)	N/A	N/A	N/A	N/A
Binocular Parallax	No	No	Yes	Yes	Yes	Yes
H,POD	No	Yes (NSV)	No	Yes (NSV)	Yes	Yes
H+V,POD	No	Yes (NSV)	No	Yes (NSV)	Unlikely	Yes
3-POD	No	Yes (NSV)	No	Yes (NSV)	Unlikely	Yes
Natural A/C	N/A	N/A	No	No	No	Yes
Glasses-free	Yes or with Pulfrich glasses	Yes or with Pulfrich glasses	Possibly	No	Yes	Yes

Key: NSV: Normally Single Viewer, PID: Motion Parallax based on Image Dynamics, POD: Motion Parallax based on Observer Dynamics, H: Horizontal, V: Vertical, A/C: Accommodation/Convergence.

Table 1: A simple classification scheme in which display paradigms are grouped in accordance with their ability to support various forms of depth cue.

The Pulfrich effect provides a further example of a technique that can be used to enable monocular displays to depict dynamic scenes in an apparent 3D space. Reported by Carl Pulfrich in 1922, the effect is based on differences in the amount of light entering the two eyes, and this may be readily accomplished by placing a neutral density filter over one eye (e.g. by donning a pair of sunglasses with one eyepiece removed, or by tilting the glasses so that only one eye is covered). This impacts on the rapidity of data transfer to/within the visual cortex, and as a consequence the visual system acts on data streams between which there is a temporal offset. In this situation, disparities occurring over time form the basis for our perception of three-dimensionality. However, as with many facets of the human visual system, the mechanisms involved are by no means properly understood, and in the case of the Pulfrich effect, discussion on temporal offset must strive to take into account the dynamic nature of the processes which underpin the sampling of the visual scene. This gives rise to various possible explanations - one of which is based on a relationship between saccadic suppression periods and the level of illumination. Specifically, reducing the level of light entering one eye may cause the saccadic suppression periods of the two eyes to become asymmetrical.

Jacobs and Karpf [2012] describe active Pulfrich glasses in which light attenuation is controlled by the dynamics of the displayed image scene thereby, in principle, allowing the 3D experience to be continuously optimised.[1]

(b) MONOCULAR TRACKED As with (a) above, we assume that displays in this category do not support the standard form of binocular parallax. However, by incorporating a tracking system able to monitor the vantage point of an observer, it is readily possible to extend the basic monocular system to provide support for 3-POD. Further, by tracking the eyes individually it is also possible to accommodate viewpoint shifts caused by tilting the head. Although this technique is normally limited to accommodating changes in the vantage point of a single viewer, a form of temporal coding (see below) may be used to accommodate several viewers (typically up to three) – although viewing glasses are then required.[2]

(c) STEREOSCOPIC Displays within this category are fundamentally underpinned by the techniques pioneered by Charles Wheatstone and David Brewster in the first half of the nineteenth century. They are characterised by their ability to support the cues associated with monocular displays, together with the standard form of binocular parallax. In the context of content creation, this latter cue provides a powerful, mathematically rigorous framework for controlling the apparent depth of image components, and as noted previously is based on our subconscious interpretation of small geometrical disparities in the images presented to the two eyes. However, if indeed such disparities constitute the overriding mechanism for our perception of three-dimensionality, then pseudoscopic stereopairs (in which the left and right images are swapped – see, for example, Figure 2) should always exhibit a reversal in perceived depth. In practice, this is often not the case - suggesting that in many situations other cues play a dominant role (or alternatively that stereopsis may go beyond computations of retinal disparity).

In Figure 3, two further stereopairs are presented. In the upper illustration, an additional source of retinal disparity has been introduced through the relative scaling of the two images, and in the lower stereopair the images also differ significantly in brightness and contrast. Despite these manipulations, the stereograms can be readily fused and three-dimensionality is preserved.

The perceived 3D nature of images depicted using stereoscopic techniques is entirely illusionary, and as such has no physical basis. Consequently, it is convenient to associate an 'apparent' form of image space with this display modality (see Table 4 for a summary of other types of image space). This may reside in front of, behind, or may span the stereo plane.

---

1 For an interesting exemplar video clip demonstrating the three-dimensional nature of the Pulfrich effect see, http://www.youtube.com/watch?v=1mnWI_u_zBg&feature=related (Last accessed January 2012.)

2 In this case, each viewer's individual perspective onto a scene is output sequentially. The glasses ensure that the appropriate set of frames is visible only to the intended viewer. Unlike the temporal coding used in the context of stereoscopic displays, the eyepieces of each user's viewing glasses are switched in phase between transparent and opaque states.

The earliest stereoscopic images were drawn by hand (see, for example, Figure 4) – but stereo-photography soon gained widespread popularity. By way of example, the London Stereoscopic Company was established in 1854 and within four years had sold over half a million stereoscopes. Stereograms sold by the million, and throughout the second half of the nineteenth century, 3D was all the rage.

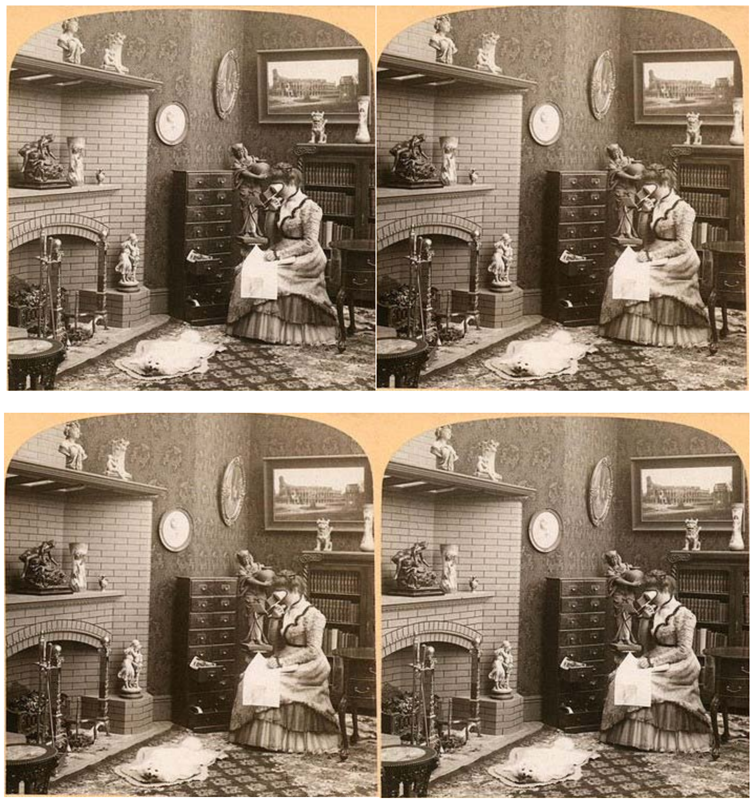

Figure 2: If retinal disparity is the only factor determining the 3D *relief* that we perceive in a stereoscopic image, then the pseudoscopic image should contain fully inverted *relief*. However this is often not the case. The upper stereogram is depicted normally and below this is the pseudoscopic version in which the left and right-hand views have been transposed. Note that this does not have an *overall* impact on the 3D scene which largely retains its spatial integrity. The most apparent effect relates to the ornament located to the left of the lady, which now appears to float in front of her. (Reproduced from Blundell [2011a].)

Today's most widely used 3D display technologies are based on the principle of the stereoscope, and differ most significantly in the methods adopted to ensure that the left and right stereo views are each directed to the appropriate eye. Various approaches are summarised in Table 2.

In the case of the traditional stereoscope, the left and right stereo views are depicted side by side such that the left view is visible only to the left eye, and the right view only to the right eye. Consequently this stereo presentation technique does not employ any form of image coding/decoding. A key advance pioneered by Otto Schmitt in the 1940's was the replacement of left and right stereo photographs with small CRT-based display screens.[3] This enabled the formation of an immersive (wholly electronic) 3D environment although, at that time, it was necessary to perform perspective calculations using analogue computational techniques. This display technique underpins the operation of today's immersive virtual reality headsets.

Figure 3: The upper stereopair may be readily fused despite the difference in size between the left and right views and hence the additional disparity which this introduces in the retinal images. (Hint: when fusing the images, initially fixate on the circular picture on the right-hand side of the photographs.). In the case of the lower stereopair, the images differ not only in size but also in contrast and brightness. However, the visual system is still able to fuse and interpret the three-dimensionality of the scene. (Reproduced from Blundell [2011a].)

In the case of temporal coding, the left and right stereo views are depicted sequentially as alternate frames. Two exemplar scenarios are indicated in Table 2. The first involves the use of active viewing glasses containing eyepieces that may be individually switched between transparent and opaque states in synchronism with the output of image frames. When the left stereo view is depicted, the left eyepiece is switched to a transparent state while the other

[3] There were certainly a number of earlier electromechanical approaches (see for example the flawed, but highly innovative, technology proposed by Joseph Bayer in 1930 – US Patent 1,876,272). However, the system described by Otto Schmitt appears to be the first fully electronic display.

eyepiece is in an opaque state. As the right stereo view is displayed, the optical states of the two eyepieces are reversed. Thus the appropriate set of images is directed to each eye. Traditionally, CRT-based displays were widely used - although the different decay times of the phosphors often resulted in undesirable cross-talk in which the individual stereo views are, for brief periods of time, simultaneously visible to both eyes. However, the use of DLP projector-based displays eliminates this problem.

Coding Technique	Display Method	Viewing Method	Overhead
Non-coded	Two small display screens (plus optics) are used to present the L and R views	Each eye views the content depicted on the corresponding display screen	Requirement for two display screens
Temporal	L+R views displayed as alternate frames	Active glasses with opaque/transparent filters	Doubling of the frame rate
Temporal	L+R views displayed as alternate frames. A switchable polarizing filter is located in front of the display screen	Passive glasses with polarizing filters	Doubling of the frame rate
Chromatic Overlay	L+R views are overlaid in different complementary colours	Filter glasses	Negative impact on image colour content
Polarized Overlay	Dual DLP projectors each equipped with polarizing filters – output overlaid on a single screen	Passive glasses with polarizing filters	Need for two DLP systems with accurate alignment
Spatial	Two display screens located at right-angles and a half-silvered mirror which directs output into viewing zones	Glasses-free	Need for two display screens with accurate alignment
Spatial (lenticular)	L+R views interleaved – viewing zone created using a lenticular lens sheet	Glasses-free	Pixel capacity of the display is shared between L+R views
Spatial (static barrier)	L+R views interleaved – viewing zone created using a barrier comprising alternating sets of transparent and opaque strips.(located in front of display screen)	Glasses-free	Pixel capacity of the display is shared between L+R views. Reduced light output
Spatial (active barrier)	As above. Also barrier may be switched between 2D and 3D modes	Glasses-free	As above.
Spatial (dynamic barrier)	As above. Also barrier characteristics are continuously variable	Glasses-free	As above.
Spatial (static rear barrier)	L+R views interleaved – viewing zone created using a barrier comprising alternating sets of transparent and opaque strips (located *behind* the display screen)	Glasses-free	Pixel capacity of the display is shared between L+R views.

Table 2: Summary of exemplar methods that can be used in mapping the left (L) and right (R) stereo views to the two eyes such that the correct view, and only the correct view, is visible to the intended eye.

A second exemplar system employing temporal coding uses a switchable polarizing filter faceplate which is attached to the display screen. This is able to orthogonally polarize the left and right stereo frames. Passive viewing glasses equipped with two orthogonally polarized filter eyepieces are then used to map the left and right views to the designated eye.
These temporal coding techniques result in each eye being presented with 50% of the displayed frames. Consequently, in order to avoid image flicker issues (visible or subliminal), it is necessary to at least double the frame refresh frequency.

In the case of the chromatic coding technique referred to in Table 2, the left and right stereo views are overlaid – each view being coded in a separate colour, or range of colours. Filter glasses are used to ensure that each view is visible only to the intended eye. This method is fundamentally based on the pioneering work of Wilhelm Rollmann and Joseph D'Almeida in the 1850's, although some thirty years were to pass before Ducos Du Hauron coined the term 'anaglyph' (derived from the Greek *anagluphein* – 'to carve in relief'). The chromatic coding technique provides a simple means of implementing 3D display systems, but usually at the cost of restricting colour content.

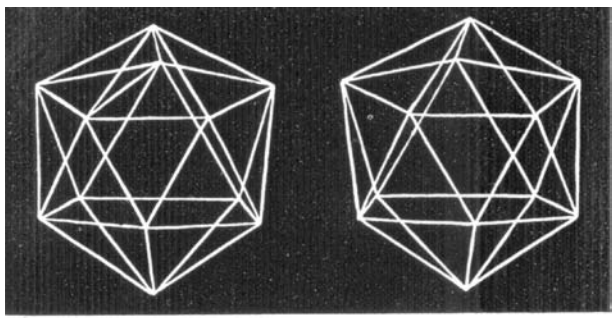

Figure 4: A nineteenth century hand-drawn stereogram attributed to Sir David Brewster. The image can be easily fused by slightly crossing the eyes to merge the left and right views.

In the case of large format, glasses-based 3D, the left and right stereo views are commonly generated by two separate DLP projectors. Both projectors are equipped with filters such that the stereo views are orthogonally polarized and overlaid. Passive viewing glasses comprising orthogonal polarizing filters are then used to ensure that each eye is presented with the correct content. Naturally, this approach requires a high degree of alignment between the two projector systems.

Figure 5 depicts an exemplar embodiment in which two separate display screens are used to provide a glasses-free stereoscopic display. The screens are positioned orthogonally and their output is combined by means of a half-silvered mirror.

In the case of all other approaches summarised in Table 2, the left and right stereo views are segmented into a set of narrow vertical strips which are interleaved and simultaneously displayed. An optical element is then used to ensure that when an observer is located within a defined 'viewing zone', the image strips constituting the left view are visible only to the left eye, and similarly that the right view image strips are visible only to the right eye. A key advantage to this general approach is that viewing glasses are unnecessary.

These spatially coded displays differ in the way in which the viewing zones are formed. The two most widely used methods employ a faceplate comprising an alternating set of transparent slits fabricated in an otherwise opaque surface (the parallax barrier approach), or a set of cylindrical lenslets (the lenticular approach). In Figure 6, the basic operation of a parallax barrier is summarised, and in Figure 7 the lenticular approach is illustrated. As is evident, the two approaches differ significantly in terms of their efficiency in conveying light from the display screen to the user. In the case of the barrier method, the opaque portions of the barrier occlude the passage of light – thereby reducing image brightness. The lenticular approach does not suffer from this problem – but nor does it yield a display that is well suited to both 2D and 3D applications. In an alternative scenario, the barrier is located behind the display panel (see Figure 8).

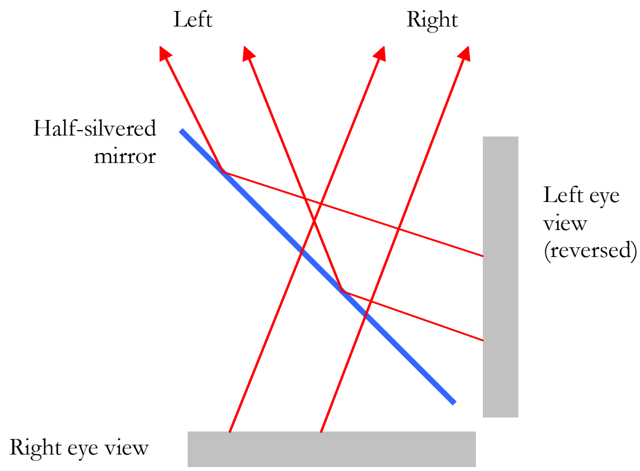

Figure 5: The use of a half-silvered mirror to provide spatially coded stereo views. The left and right views are directed into two separate viewing zones - one for each eye. Although a half-silvered mirror may be used, other partially transmissive, partially reflective arrangements can be employed, such as Swan's Cube. (Reproduced from Blundell [2011a].)

The use of active and dynamic barriers (implemented by means of mechanical components or an appropriate liquid crystal panel faceplate) significantly advance the capabilities of displays employing spatial coding techniques. The former may be electrically switched to support 2D and 3D image depiction (this includes the opportunity to simultaneously support 2D and 3D over different of regions of the display screen – although if not used judiciously this can have a negative impact on the visual system). Thus a 3D glasses-free display employing this type of barrier can also seamlessly accommodate 2D applications. In addition, the dynamic form of barrier allows the barrier pitch to be continually adjusted to accommodate changes in viewing location – however this assumes that the user's vantage point is tracked.

In the case of these spatial coding techniques, the pixel capacity of the display screen is split between the left and right stereo views. When these approaches are extended to create n sets of unique viewing windows, the pixel count (P_e) of image content presented to each eye is given by:

$$P_e = \frac{P_d}{2n}, \tag{1}$$

where P_d denotes the pixel capacity of the display. In practice, lenticular lenses are tilted relative to the vertical and so the burden of increases in n are shared between the display's vertical and horizontal pixel capacities.

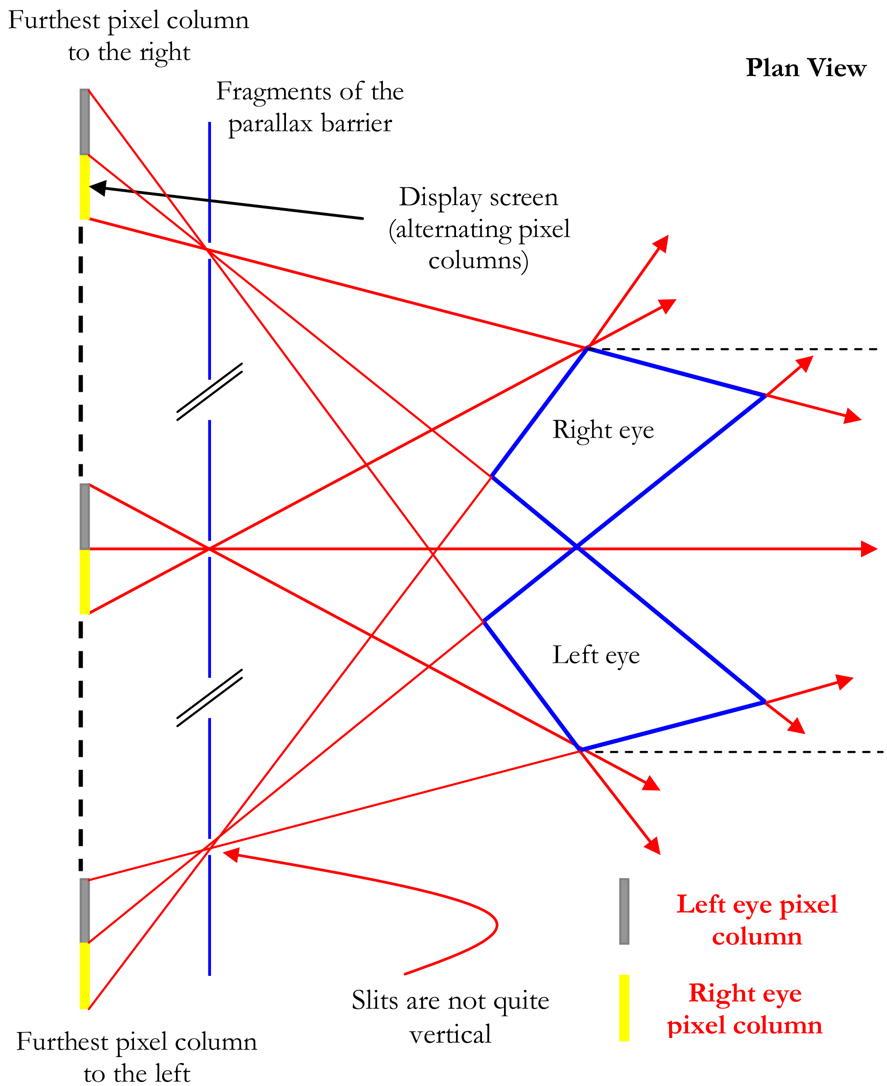

Figure 6: The general principle of operation of the parallax barrier technique for providing spatially-coded stereoscopic views. The two views comprising the stereopair are interleaved in alternating columns of pixels on a flat screen display, and the barrier ensures that from the correct viewing zones each eye sees only the corresponding (designated) view. The two quadrilaterals indicated by the thicker blue lines denote the viewing window ('sweet-spot' regions) within which stereoscopic vision is fully supported. For example, in the case of the upper region, all right-eye pixel columns are simultaneously visible to the right eye. Note that the viewing windows repeat themselves on either side of the central viewing position. Consequently, if the viewer moves to the right or left (away from the central viewing position (upwards or downwards in the diagram)), the pseudoscopic image *may* be seen. (Adapted from Blundell [2011a].)

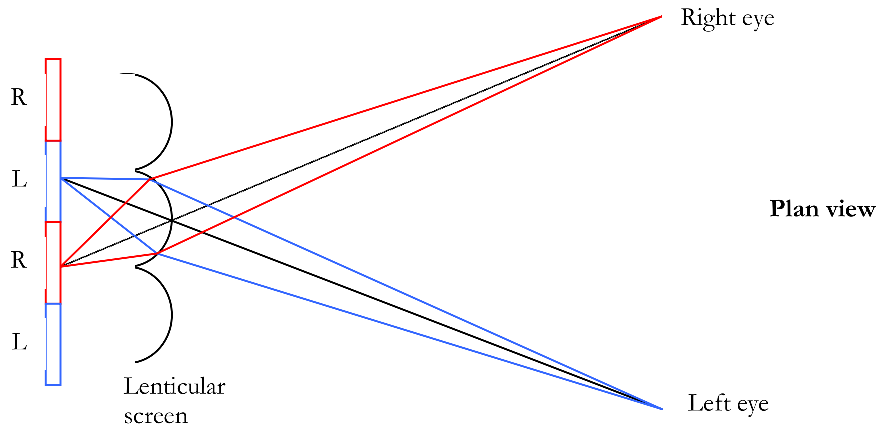

Figure 7: The general principle of operation of a 'lenticular' based display. A lenticular faceplate comprising a set of cylindrical lenslets is fitted to the outer surface of a conventional display. A stereopair is then interleaved in such a way that the lenslets are able to direct the appropriate image to each eye. (Reproduced from Blundell [2011a].)

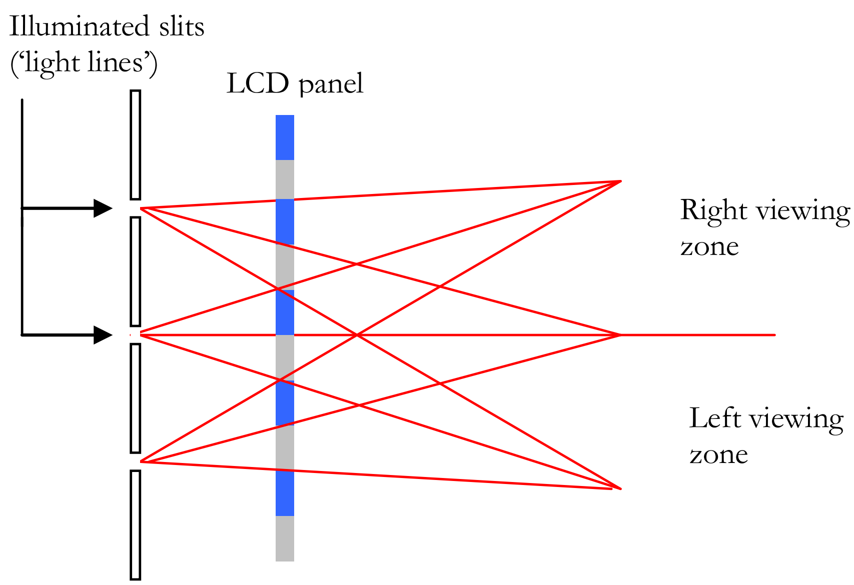

Figure 8: Plan view of an alternative barrier configuration. A pixel is visible when - and only when - it is interposed between the eye and an illuminating slit. (Reproduced from Blundell [2011a].)

Displays that are fundamentally based on the principles of the traditional stereoscope (embracing image depiction on a single static screen or pair of screens) do not provide natural support for the oculomotor cues of accommodation and convergence. Recall from Section 1 that when we view near-field objects, the eyes focus on and their visual axes converge on, the feature of fixation. In contrast, in the case of stereoscopic display techniques the eyes focus on the display surface(s) but converge on the feature of fixation within the apparent image space. Thus the further an object appears from the stereo plane, the greater is the decoupling of the oculomotor cues. This is commonly referred to as accommodation/convergence (A/C) breakdown. In the case of 3D cinema, the consequences of this breakdown can be greatly ameliorated by judicious use of the third dimension (particularly in relation to the use of 'negative' space (lying between the stereo plane and audience)) and by controlling the rate at which cue decoupling takes place. Furthermore in cinema the screen is at a significant distance from the audience, and as this distance increases there is a gradual weakening of accommodation/convergence cohesion and in the ability of these cues to provide depth information. In contrast, in the case of 3D TV the audience is much closer to the display screen, and consequently the ramifications of A/C breakdown are likely to be somewhat greater – especially as TV tends to be used for extensive periods of time and it is therefore most important that visual stress should be minimised. Of course display screens on hand-held devices are usually in even closer proximity to the eyes, but unlike television these devices are seldom used for extensive and sustained periods of time. For related discussion see Hoffman *et al.* [2008].

Visual characteristics vary widely between individuals and relatively little is known about the long-term consequences of extensive exposure to 3D systems in which the accommodation and convergence cues are *significantly* decoupled. Younger viewers whose visual systems are still under development may be particularly at risk, and much work remains to be done in the area. For the present, visual strain is reduced by limiting the extent to which 3D content penetrates the space between the stereo plane and observer, restricting the overall scene depth, and restricting the rate at which accommodation and convergence are decoupled.

(d) STEREOSCOPIC TRACKED Displays in this category are assumed to require the use of viewing headgear/glasses, but as with monocular systems that incorporate tracking (see (b), above), they are able to provide support for POD. Exemplar systems include displays based on the use of immersive virtual reality (IVR) headsets, and displays equipped with a vantage point tracking system and which employ chromatic or temporal coding techniques. This approach is also used in the implementation of the CAVE, and its derivatives such as the RAVE (see, for example, Defanti *et al.* [1992], Burdea and Coiffet [2003] and Blundell [2008, 2011a]. Developed at the Electronic Visualization Laboratory (University of Illinois), the CAVE is an IVR environment which takes the form of a cube with walls measuring ~3m onto which temporally coded stereoscopic images are projected using external DLP projectors. Although a number of people may simultaneously enter the CAVE, the vantage point of only one person is tracked and the stereo images are updated accordingly. Others within the CAVE therefore receive an inferior (although still impressive) view of the 3D scene which completely occupies each person's field of view. Naturally, the adoption of temporal coding makes it necessary to don viewing glasses.

An important difference between the CAVE-based delivery of IVR and the dual screen headset technique concerns the occupancy of virtual space. In the case of the latter, virtual space is naturally void - any visible content (including views of the hands/fingers, etc) must be digitally processed and depicted via the two display screens. In contrast, in the case of the CAVE, the body, physical interaction tools, and the like, remain directly visible and so too do other people located within the environment. In the context of interactive applications, the ability to directly view hands and fingers increases dexterity and for complex design and visualisation tasks this is often a significant advantage. On the other hand, the physical extent of the CAVE restricts movement – which contrasts with the approach adopted in the implementation of the Cybersphere (see Fernandes *et al.* [2003] and Blundell [2011a]).

(e) AUTOSTEREOSCOPIC CLASS I In common with the Stereoscopic approaches outlined above, Autostereoscopic displays provide support for POD but are distinguished by their ability to be used without recourse to viewing glasses. Here, we briefly follow discussion in two previous works (Blundell [2011a,b]) and identify two broad forms of Autostereoscopic display.

It is assumed that in the case of Class I systems, accommodation and convergence are not supported in a manner that is consistent with our natural world experience, and so in the near field these cues are decoupled. In contrast, in the case of Class II displays A/C breakdown is avoided, and so the focusing of the eyes and the convergence of their visual axes takes place in an harmonious manner. This has the further important advantage that accommodation is, in principle, able to contribute to the depth cue portfolio.

The most widely used form of Class I Autostereoscopic display employs a parallax barrier - with a plurality of stereo views onto a 3D scene being segmented into sets of narrow vertical strips which are interleaved for simultaneous display. The barrier ensures that from a particular viewing position the appropriate stereoscopic view onto the image scene is visible (i.e. the appropriate set of left and right image strips).

As summarised in Table 3, this approach may be used to create multiple different views onto an image scene, and if the number of views are sufficient, H,POD can be supported in an effective manner. Eq. 1 applies and as the number of views is increased, there is a gradual diminution of the pixel count available for each view. However, as the performance of display and barrier technologies continues to rapidly advance, ever larger multiview displays become practical. Attempts to extend this technique to provide support for H+V,POD further reduce the number of pixels per view, and cause additional complications in the design of the optical arrangement which is responsible for controlling the directions in which light propagates from the display screen. As a consequence, practically all multiview systems are limited to H,POD.

Usually the number of views generated by a display system is defined at the time of manufacture. However, in an alternative scenario efficiency may be increased by adopting technology capable of dynamically adjusting the number of views according to ever changing viewer requirements. In short, presentation efficiency is reduced when overheads are incurred by delivering content into regions in which there are no viewers. One solution is to employ dynamic barrier technology in conjunction with a camera-based system which is used to track the vantage point(s) of user(s), and on this basis optimise display output. Traditionally, such tracking systems required users to don passive or active devices whose positions could be monitored in 2D or 3D space. Subsequently, camera-based systems able to detect and track the eyes were introduced, but in the early days significant latencies were experienced and this resulted in perceptible delay between user movement and display update. However, current camera-based tracking technologies are much more robust, and tracking latency has been greatly reduced. Eye position may be tracked using either a pair of conventional cameras or a single conventional camera augmented with a time of flight

(volumetric) camera thereby, in principle, enabling 3-POD (assuming, of course, that this is supported by the display). By way of example, SeeReal Technologies GmbH - who supply dual camera based eye-tracking systems - indicate a total tracking cycle latency of less than 63ms (Stolle *et al.* [2008]).
Dependent on the capabilities of the display technology, independently tracking the location of each eye can be advantageous as it allows support for motion parallax to include tilting movements of the head – thus more closely matching our natural world experience.

Class of Display	Viewing Scenario	Binocular Parallax	POD	Details
Monocular	Multiple viewers	Temporally asymmetric	No	Pulfrich glasses required
Monocular Tracked	Normally single viewer	Temporal asymmetric	Yes – capable of 3-POD	Usually only a single viewer is tracked. However, temporal coding may be used to support multiple viewers. This requires specialised viewing glasses that support decoding and possibly the Pulfrich effect.
Stereoscopic (glasses-based)	Multiple viewers	Yes	No	For example, 3D cinema projection
Stereoscopic (glasses-free)	Single viewer	Yes	No	Appropriate for hand-held devices and other forms of personal display.
Stereoscopic (glasses-free)	Multiple simultaneous viewers with synchronous content	Yes	No	Each viewer is presented with the same view onto a scene – although these may vary in quality.
Stereoscopic Tracked	Multiple simultaneous viewers with synchronous content	Yes	Yes - but with single viewer tracking	For example, the CAVE.
Autostereoscopic Class I	Multiple simultaneous viewers with asynchronous content	Yes	Yes – but usually limited to H,POD.	For example, multiview displays
Autostereoscopic Class II	Single viewer	Yes	Yes	Unusual scenario
Autostereoscopic Class II	Multiple simultaneous viewers with asynchronous content	Yes	Yes – up to 3-POD	Each user is presented with a potentially unique view onto a scene. This view changes in accordance with individual shifts in vantage point.

Table 3: Summarising a number of exemplar viewing scenarios. This list is by no means exhaustive.

(e) AUTOSTEREOSCOPIC CLASS II As indicated above, we distinguish between the two classes of Autostereoscopic systems according to their ability or otherwise to support the oculomotor cues in a natural (and hence synergistic) manner. In principle, this enables both accommodation and convergence to contribute to the depth cue portfolio. Thus in terms of the categories of display identified in Table 1, Class II Autostereoscopic displays are, in principle, able to satisfy the largest range of cues to depth and as with Class I systems offer glasses-free display solutions. In Table 1, three forms of Class II display are identified – volumetric, varifocal and electro-holographic approaches. Below, we briefly summarise aspects of these display modalities.

(1) The Volumetric Approach: Research into volumetric systems spans 100 years - the earliest description that I have been able to locate concerning a volumetric embodiment is provided in a patent filed in 1912 by Emile Luzy and Charles Dupuis (French Patent 461,600). Despite the originality of the technique described by these inventors, their technique is unfortunately flawed. Following extensive research, it appears that John Logie Baird (pioneer of television) was the first to detail a practical volumetric display (British Patent 373,196 - filed in 1931). Since that time many diverse forms of volumetric system have been researched and these are extensively reviewed in Blundell [2007]. Following Blundell [2011b], the volumetric paradigm can be defined as follows:

> *'A volumetric display device permits the generation, absorption or scattering of visible radiation from a set of localised and specified regions within a three-dimensional space. In certain cases a volumetric system may allow the controlled anisotropic propagation of radiation from each of these regions. The display paradigm is assumed to be able to support a visual image continuum across all three spatial dimensions.'*

And,

> '*In the most general terms, the volumetric display paradigm offers to support the creation of a light engine whereby it is possible to control the spatial, temporal, and directional output of visible radiation from an image space.*' [Blundell 2011a]

Fundamental to the volumetric approach is a transparent physical volume (image space) in which static and animated image components may be placed. Since images depicted in this way are able to span three dimensions, their inherent three-dimensionality closely mimics that of physical real-world objects. This minimises the likelihood of the type of conflict that can occur when the visual system is presented with cues to form, spatial occupancy and motion which do not harmoniously match everyday experience.

Volumetric images may be viewed directly without recourse to glasses, and in theory implementations should impose very little restriction on viewing position, with multiple users able to view an image scene from practically any position around the display volume. However, as outlined shortly, in practice implementation characteristics often cause image quality to vary with viewing direction. As indicated in Table 4, we usually associate a 'physical' form of image space with this display modality – although a small number of implementations give rise to Types I or II Ethereal image space.

With few exceptions volumetric images are constructed from voxels (the 3D equivalent of pixels), which may be positioned within the physical 3D space. In general terms, differences in volumetric architectures concern the techniques adopted in the implementation of the three key subsystems comprising the display. These relate to the methods used in the formation of the transparent image space, the physical process(es) that

underpin the production of visible voxels, and the technique(s) employed in order to stimulate light output from each voxel. We refer to these as the image space formation, voxel generation, and voxel activation subsystems respectively.
The two most widely used approaches to image space formation give rise to 'static' and 'swept' volume displays. In the case of the former the image space is created without recourse to mechanical motion, and comprises a volume of homogeneous material or arrangement of discrete materials. Such an image space may be solid, liquid or gaseous. In contrast, in the case of the swept-volume approach, the image space is formed by the rapid cyclic motion of a surface (screen) or 3D structure. This use of mechanical motion is often considered to be a cause for concern. This is discussed in Blundell [2007] – an extract from which reads as follows:

> '*…because of the pivotal reliance that is placed on rapid, cyclic mechanical motion, swept-volume systems are often regarded with a degree of skepticism. This is perhaps surprising when we consider the prevalence, diversity and reliability of a wide range of technologies that impact on every aspect of our daily lives and whose operation is underpinned by rapidly moving mechanical components. The reciprocating motion of pistons in a conventional car engine (and from which rotational movement is derived), and the remarkable rotational speed achieved by components within a jet engine, provide obvious examples of engineering feats which become all the more impressive when we consider the harsh conditions under which these systems operate, and their life-span.*[4]
>
> *Mechanical motion underpins the operation of many forms of modern storage media (both digital and non-digital) and, for example, the precise and rapid movements of the read/write heads within a hard disk are generally taken for granted (along with disk reliability). In fact a vast number of appliances and systems that impact on our lives rely on reliable cyclic mechanical movement.*[5]
>
> *When we examine the design and implementation of the mechanical mechanisms needed for the implementation of swept-volume systems and consider these in the light of other mechanical feats (such as those mentioned above), their implementation would seem almost trivial, and reliability appears to be assured. However, it is important to remember that many of the mechanically based appliances and systems that are now mass-produced and operate with such astounding reliability have, for years, been continually refined and gradually brought to a state of cost-effective perfection.*'

Certainly the development of volumetric systems which do not place reliance on mechanical motion for image space formation is an ultimate goal – but the present, swept-volume systems are able to offer pragmatic engineering opportunities.

Techniques used in the implementation of both static and swept-volume volumetric displays are discussed extensively in other works (for example, Favalora *et al.* [2001a,b, 2002, 2009], Sullivan [2003, 2004], Blundell [2011b], Blundell [2007], and Blundell and Schwarz [2000]), and so below we briefly focus on general attributes of this display modality.

---

[4] '*For example, during the typical life of a modern car engine, each piston will be expected to complete some hundreds of millions of cycles of motion within an extremely harsh operating environment. This is achieved with little, if any, maintenance other than the occasional and generally begrudged oil change… Average operation of such an engine requires rotational rates on the order of two thousand crankshaft revolutions per minute (~33Hz), which approximates to the rate at which we seek to sweep out an image space.*'

[5] '*The heart must represent one of the most remarkable 'mechanical systems'. If we assume an average pulse of 65min*$^{-1}$ *then for a person who reaches the age of 80 it will have performed some 2,730 million beats (servicing generally being unnecessary).*'

Three of the key issues that have hampered the development of high quality volumetric systems relate to aspects of the image formation technique, characteristics of the image space, and data flow.

Display Modality	Form of Image Space	Notes
Monocular (traditional)	Planar	**Planar Image Space:** Comprises a static surface on which images are depicted.
Displays fundamentally based on the principle of the stereoscope	Apparent	**Apparent Image Space:** Although the image scene appears to reside in a 3D space, this is entirely illusionary and has no physical basis.
Volumetric	Physical or Ethereal Types I and II	**Physical Image Space:** A transparent physical volume. The techniques used for image space formation coupled with the presence of a physical enclosure prevent the insertion of physical objects into the volume. **Ethereal Image Space:** Associated with the formation of so called 'free space' images. **Type I** employs an optical projection arrangement. **Type II** supports image formation within some form of particle cloud.
Varifocal	Virtual or Ethereal Type I	**Virtual Image Space:** This appears to exist behind some form of optical arrangement. On the basis of interaction opportunities two general types may be identified (see Blundell [2011a,b] for discussion.
Holographic	Ethereal Type I or Virtual	See above.

Table 4: Summary of forms of image space coupled with exemplar display modalities For more detailed discussion see Blundell [2011a,b].

In the context of image formation, a display should enable voxels to be positioned at uniform locations across the three spatial dimensions of the image space. Thus the display should, for example, offer a regular lattice of possible voxel positions such that when an image component is subjected to a translation operation, the number and spatial distribution of voxels from which it is formed remains unaltered. In addition, voxel attributes such as size, form and light output, should not vary with voxel position.

However, even supposing that a display exhibits excellent image formation attributes, this does not guarantee that the visible image will be of a satisfactory quality. In this respect, it is necessary to consider characteristics of the image space which impact on the propagation of light. Components or structures within the image space may obstruct light as it travels in certain directions or may give rise to refraction. In either case, image quality is likely to vary with viewing direction – such that a superior image will be seen when it is positioned within a particular region of image space and viewed from a certain direction. To overcome this deficiency, it is essential to ensure that the image space exhibits satisfactory isotropic optical characteristics. A further important consideration relates to image distortion arising as a result of refraction as light emerges from the image space (boundary refraction).

In the context of data flow, consider a cubic image space with sides of length 40cm which offers to support voxel formation at positions defined by a rectangular lattice with a nearest neighbour voxel spacing of 0.5mm. Thus the maximum number of possible voxel locations (termed the voxel location capacity (N_l)) is 512×10^6. Assuming an image refresh frequency of 40Hz, the voxel throughput is $\sim 2 \times 10^{10} s^{-1}$.

However, in practice a volumetric display is most suited to applications which allow the majority of the image space to remain void. In such circumstances, complex spatial relationships and component dynamics are most easily discerned. Thus it is appropriate to define a voxel activation capacity (N_a) corresponding to the maximum number of voxels that can be activated during each image refresh period.[6] A fill factor parameter (ψ) can be defined such that:

$$\psi(\%) = \frac{N_a}{N_l}.100.$$

For many applications it is appropriate for the fill factor to be considerably less than 1% - although it is most important that during each image refresh period the number and spatial distribution of the set of voxels which may be selected for activation, is limited only by the bound imposed by the voxel activation capacity. In the case of swept-volume systems employing image slices (see the previous footnote) we apply this criteria to each individual slice. This approach does not necessarily compromise display performance, facilitates support for full image animation, and to some extent decouples voxel descriptor throughput requirements from the physical dimensions of the image space. However, in the case of swept-volume displays the approach is unlikely to reduce the peak voxel throughput (see Blundell [2000, 2011b] for further discussion including the desirability of ensuring that the voxel generation and activation processes are able to support parallelism in the formation of visible voxels).

In the literature it is frequently suggested that volumetric systems are intrinsically unable to support image opacity. In fact, this is not an inherent limitation of the volumetric approach and one solution is to bring together volumetric and multiview techniques in such a way as to support the formation of opaque images. Unfortunately, this method imposes viewing position restrictions, and unless the viewing locations of observers are tracked, it limits support for motion parallax to H,POD (see Cossairt *et al.* [2007] and also Blundell [2011b] for summary discussion – which includes reference to the use of photochromic materials).

Volumetric display technologies usually support image formation within a 'physical' image space (recall Table 4). This is assumed to take the form of a transparent volume, and the methods used in its formation coupled with the presence of some type of enclosure preclude the insertion of physical objects. Thus for example, haptic interaction tools are not able to make 'contact' with image components. Two general approaches may be employed to overcome this limitation. Firstly, an optical arrangement is used to project the contents of the physical image space into so-called 'free space', or secondly the volumetric image may be created in some form of particle cloud (the particles scattering incident light). Following previous nomenclature [Blundell 2011a,b], we respectively refer to these as giving rise to Type I and Type II Ethereal forms of image space. For details of exemplar embodiments,

[6] In the case of swept-volume displays, the image space is usually sub-divided into a number of slices into which voxels are mapped. Thus, for example when the image space is created using the rapid translational motion of a planar surface, the image space is usually divided into a set of slices which lie at right-angles to the direction of motion. In contrast, when the image space is formed by means of rotational motion, radial slices (sectors) are usually employed. In such situations, the fill factor represents the greatest percentage of voxels that may be activated *within each slice* [Blundell 2011b].

see US Patent 6,997,558 B2, Barnum [2010], Kameyama *et al.* [1993a,b] and Blundell [2008, 2011a,b].

(2) The Varifocal Approach: From the 1960's through until the mid-1980's Autostereoscopic displays employing a mirrored surface with a continuously variable curvature and hence focal length attracted considerable interest – particularly within the medical imaging community. Despite the significant opportunities offered by this form of display, two key commercialisation ventures failed (see, for example, the SpaceGraph technology) – most probably because, at that time, visualisation requirements were not sufficiently complex to warrant investment in this display modality. In addition, commercial development was hampered by complex patenting issues.

In the literature, the varifocal approach is frequently dismissed on the basis of the acoustic noise generated by the rapidly vibrating mirror. However, this issue is readily addressed and systems employing either a varifocal mirror or varifocal lenses offer simple, low cost, glasses-free display solutions.

The basic concept of this display modality is illustrated in Figure 9. In this simple configuration, a flexible reflective surface is mounted on a loudspeaker which is driven by a sinusoidal signal at frequency of ~30 Hz. The ensuing pressure variation creates a curved mirror that has a continually changing focal length. Image sequences depicted on a flat-screen display may then be projected onto the mirror in synchronisation with its motion. An advantage of the varifocal mirror approach is its great simplicity and the fact that a small amplitude of vibration provides a much larger depth of image space. Assuming that the diameter of a varifocal mirror is denoted d, the distance between the mirror and flat panel display u, and the maximum displacement of the mirror x_{max}, then:

$$v(t) \sim \frac{d^2 u}{16u|x_{max}|\sin\omega t - d^2},$$

where $v(t)$ denotes the image location and $\omega=2\pi f$ (see, for example, Blundell [2007, 2011b] and McAllister [1993]). By way of a simple numerical example, consider a varifocal mirror with a diameter of 40cm whose peak-to-peak displacement is 0.4cm, and let us assume that a flat panel display is located 80cm from the pole. Between the two extremes of mirror motion, the image will shift in position by ~26cm.

Unfortunately, the magnification of the mirror is also a function of its curvature and so, as loosely indicated in Figure 9, the image space takes the form of a frustum of a rectangular pyramid (although this effect can be ameliorated by continually adjusting the size of the displayed image slices in accordance with mirror curvature).

For related discussion in connection with the implementation of a multi-lens display which enables the formation of a plurality of depth planes see, for example, Love *et al.* [2009].

(3) The Holographic Approach: In many respects, electro-holography (also known as computed holography and holographic video) represents the ultimate form of Autostereoscopic display. However, the challenges associated with implementing practical holographic systems able to depict complete digital holograms in real time (thereby fully supporting animation and interaction) are daunting.

Current commercial systems that purport to provide 3D holographic solutions should often be examined with caution, as frequently their principles of operation are not in fact based on holographic techniques where, both the amplitude and phase of light emanating from a real or virtual object is recorded as an interference pattern (hologram).

In a remarkable single page article, Denis Gabor introduced the principles of holography in 1948 [Gabor 1948] – but it was not until lasers became accessible in the early 1960's that optical holography became a truly practical proposition. Subsequently, researchers at IBM developed the Kinoform technology (see, for example, Lesem *et al.* [1969], Okoshi [1976]) in which phase information of light emanating from a virtual object was calculated – computational overheads being reduced by neglecting amplitude variations. During the intervening years, major advances have taken place in the development of holographic systems – however the requirements of high-performance electro-holographic displays remain challenging.

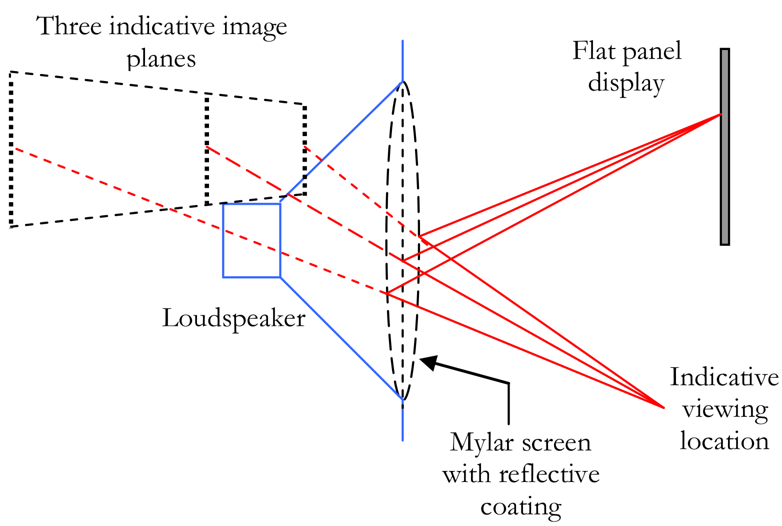

Figure 9: The general principle of operation of the varifocal mirror display. A sinusoidal signal is applied to the loudspeaker thereby driving the reflective Mylar mirror between concave and convex states. Images slices are projected onto the mirror from a planar screen – the slices being depicted in synchronism with a portion of the mirror's motion. Three indicative image planes are shown. In an alternative configuration, a beam-splitter is interposed between the planar screen and varifocal mirror – see, for example, King and Berry [1970]. (Reproduced from Blundell [2011a].)

The techniques used in recording and displaying holograms are explored in depth in numerous other works (see, for example, Benton and Bove [2008], and Saxby [1988]). Consequently we focus here on key features of holographic image depiction, and summarise some the issues that have prevented the widespread exploitation of electro-holographic display techniques.

Consider the formation of a holographic recording of light emanating from a static virtual object. In brief, this is achieved by considering wavefronts emanating from each 'point' on the surface of the object. We define the location of a virtual holographic plane, and as the wavefronts impinge on this, we compute and record the results of their interference with a virtual reference source. As for image reconstruction, the 2D holographic recording (fringe pattern) is depicted by means of a suitable planar display illuminated with an appropriate source. Assuming that the fringe pattern is depicted at a resolution on the order of the wavelength of light (~400-700nm), then light passing through the display panel will be diffracted in such a way as to reconstruct the wavefronts which emanated from the original virtual object.

This requirement roughly indicates that the display panel should be able support a resolution of ~2,000pixels/mm. More precisely, the number of digital samples *N* that need to be recorded in order to form a square hologram of height *h* and width *w* able to support 3-POD, is given by:

$$N = \frac{4wh\sin^2\theta}{\lambda^2},$$

where θ denotes the viewing angle (which is assumed to be the same in both the vertical and horizontal directions), and λ the wavelength (see, for example, St. Hilaire *et al.* [1992]). By way of a numerical example, consider that a 633nm laser illuminates a square hologram with sides of length 10cm, and that we require a viewing angle of 30° (vertically and horizontally). On the basis of the above equation, the hologram should comprise ~2.5×10^{10} digital samples of the recorded fringes. If we assume that each sample is represented by 8 bits, and that we require a 30Hz image update frequency, then the data flow to the display panel will be ~0.75TBs^{-1}. Furthermore, we would need to identify a display technology able to support at least 1600pixels.mm^{-1}.

These are indeed demanding performance requirements - although several approaches may be used to increase the viability of such a display. For example, we may eliminate support for V,POD, in which case the hologram would be formed from a vertical stack of 1-D holographic strips ('hololines'). We may also reduce the magnitude of the viewing angle – although this may compromise viewing freedom and hence the ability of the display to support H,POD. For example, in the case that the viewing angle is reduced to 15°, then at a viewing distance of 50cm the horizontal extent of the viewing window is ~27cm.

The high density of digital samples needed for the formation of a satisfactory holographic image is primarily driven by the diffraction process which underpins its reconstruction. Thus any reduction in *N*, or increase in the size of the holographic display screen – which is not matched by a corresponding increase in *N* (so as to maintain a constant sample density) will result in a decrease in viewing angle. In short, the formation of a large holographic image supporting significant freedom in viewing location, necessitates the use of a large holographic display panel comprising a high density of digital samples - reductions in either will impact on image size and/or viewing angle. In Section 3, we briefly consider an alternative strategy in which only the immediately visible portion of the image is computed and displayed.

For related discussion see, for example, Ritter *et al.* [1997, 1998], Lucente [1994, 1996], Halle [1996], and Yaras *et al.* [2011].

3. APPLICATION

In the above discussion we emphasised aspects of the visual interface – specifically the range of depth cues supported by various classes of display. However, as previously noted, this in itself does not usually provide a meaningful performance metric for display comparison.

Although the visual interface is of crucial importance, it is important to bear in mind that as we view and subconsciously interpret our natural surroundings, the role and importance of individual cues continually change. By way of example, consider binocular parallax. In many real-world situations this cue does not yield information relevant to the visualisation task at hand, and so at such times less reliance is placed upon it. In fact only a portion of the visual field contains binocular information (Figure 10) – however, as we view our surroundings we are usually quite unaware of the composite monocular/binocular nature of the field of vision.

Similarly, in the case of 3D display technologies, there are many situations in which support for binocular parallax is quite unnecessary, and may in fact place needless strain on the visual system. Conversely, when support for this cue is properly linked to the requirements of the visual system, it can be used to greater advantage – although it is necessary to appreciate variability in stereoscopic perception. In this latter respect a significant number of people have poor stereoacuity, but in viewing the natural world are generally able to compensate by placing greater reliance on both PID and POD. However, as we have discussed many approaches to 3D image depiction do not support (or provide limited support for) POD, and so this reduces the opportunity to compensate for reduced stereoscopic perception.

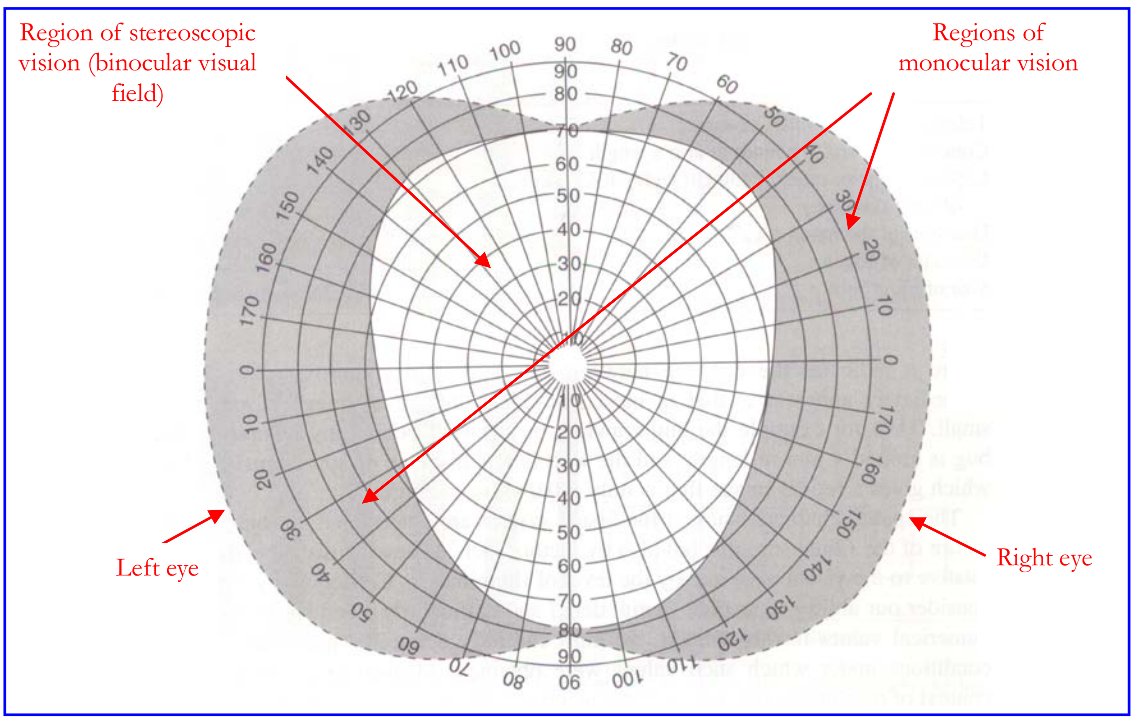

Figure 10: Illustrating the visual field. The region of overlap (not shaded) in the visual fields of our two eyes is the area of binocular vision. The two grey regions indicate areas that are restricted to monocular vision. (After Gibson [1950].)

In addition to considering the range of cues supported by a display, it is crucial to take into account differences that exist between their synthetic and natural renditions. A/C breakdown which, as discussed, is associated with displays based on the principles of the stereoscope, provides one obvious example of such a difference. By way of a further example, consider volumetric display technologies. As we have seen, images depicted using this general approach are able to occupy three physical dimensions, and so from a spatial perspective their three-dimensionality closely mimics our visual perception of the natural world. However, the activation of voxels comprising an image scene often occurs over time, and furthermore light output from activated voxels is invariably transient. Consequently, within the temporal domain significant differences exist between volumetric and natural world images.

In short, understanding and managing the visual interface is fraught with difficulty – and in parallel many other issues need to be considered in matching display technology and application. With this in mind, Table 5 summarises various facets of 3D within a loosely structured framework. Even at a cursory glance it is evident that in applying 3D systems, numerous matters should be taken into account. For example, in the case of 'Viewing Parameters', key issues include variability in viewing distances/positions, number of simultaneous viewers, viewing freedom and control/variability of ambient lighting conditions. Similarly in the context of 'Presentation Parameters', we are faced with issues such as glasses-based/glasses-free scenarios, the level of immersion (relating to occupancy of the visual field), and the required scene depth.

When we attempt to identify the technology most appropriate to a particular set of requirements, we are often faced with a somewhat bewildering range of possibilities. In this respect, although the structure employed in the Table 1 is useful, it is also overly simplistic. This is because it fails to show the diversity of approaches that can be adopted in the implementation of the various classes of display. Back in the 1940's during discussion on the seminal paper by Parker and Wallis [1948] at the IEE, R.A. Smith, commented:

> '*This paper gave me the impression that we are suffering from an embarras de richesse; anyone coming into this field finds so many possible displays that he may be in doubt about which line to investigate...*' [Parker and Wallis 1949]

This remark was simply directed towards volumetric display technologies – but can also be applied to other display paradigms, and with the passage of the years the number of possible techniques has grown ever larger. By way of example, consider the Class I Autostereoscopic multiview approach. We assume that our objectives are to support binocular parallax for multiple simultaneous viewers together with H,POD (the asynchronous content delivery scenario). In general terms, the display technology outputs a set of windows (views) onto the 3D scene – these being distributed in the horizontal direction. Each window gives a monocular view onto the image scene, and within a window POD is not supported. However, if the windows are sufficiently small, then the content of two different windows will be mapped to the eyes, and disparities contained in the views will provide support for binocular parallax. Further, this scheme provides support for H,POD and enables a number of people to simultaneous view window pairs.

We have previously referred to the use of lenticular and parallax barrier techniques which are in principle able to support this form of display. However, a number of other traditional methods may be adopted, including the use of multiple projectors, the time-varying collimated technique, and the moving slit approach. In brief, in the case of the former, a set of (*n*) 2D image projectors are positioned side by side and each depicts a unique view onto a 3D scene. A double lenticular screen arrangement (comprising a set of vertical cylindrical lenses) can be used to map their output to ensure that from a particular location, the two eyes are presented with the output from two (and only two) projectors. Thus the number of stereo views onto a scene is given by $n/2$.

Facets	General Factors	Breakdown	Further Details
Visual Interface	Pictorial cues	Occlusion	
		Height in the visual field	
		Shadows and shading	
		Linear perspective	
		Aerial perspective	
		Familiar size	
		Texture	
	Oculomotor cues	Accommodation	A/C synchronism
		Convergence	A/C breakdown
	Binocular cues	Binocular parallax	Without temporal offset
			With temporal offset (Pulfrich)
		PID	
		POD	H,POD
			H+V,POD
			3-POD
	Image refresh/update	Display exhibits SSLO	Refresh to support animation
		Display exhibits TLO	Refresh to eliminate flicker + support animation
	Colour capabilities		
Presentation Parameters	Glasses-based	Chromatic coding	Passive glasses
		Temporal coding	Passive or active glasses
	Glasses-free	Spatial coding	
		Non-coded	
	Image size	Extent in the visual field	Restricted
			Occupies entire FOV
	Scene depth	Essentially unlimited	
		Limited by display	
	Window onto the 3D scene	Single	
		Curved	Continuous surface
			Tiled
		Outside – looking in	
Viewing Parameters	Viewing distance	Well defined	
		Highly variable	
	Number of viewers	Single viewer	
		Multiple simultaneous viewers	Synchronous delivery
			Asynchronous delivery
	Viewing freedom	Highly constrained	
		Little constraint	Single vantage point
			Continuous change in vantage point
	Tracking of viewing position(s)	Conventional camera technology	Possibly accompanied by time-of-flight camera technology
	Ambient lighting conditions	Controlled	
Data Transfer Rate	Monocular	With or without SV tracking	Traditional throughput $N.P_H.P_V$.

		With tracking asynchronous POD delivery for *M* viewers	$\sim M.N.P_H.P_V$.
	Stereoscopic	Without tracking SV	Up to $2N.P_H.P_V$.
	Autostereoscopic Class I	H,POD	Up to $2M.N.P_H.P_V$.
	Autostereoscopic Class II		Significant variations between forms of display
Interaction Parameters	Image space	Planar	
		Apparent	
		Virtual	Type I
			Type II
Facets	**General Factors**	**Breakdown**	**Further Details**
		Ethereal	Type I
			Type II
		Physical	
	Extent of image space		
	Camera based (tracking)		
	Haptic based interaction?		

Key: TLO: Transient Light Output, SSLO: Steady State Light Output. N denotes the frame rate, M the number of multiple simultaneous viewers. P_H and P_V respectively represent the horizontal and vertical pixel counts.

Table 5: Loosely summarising various facets of 3D for consideration when matching display technology and application.

The time-sequential collimated view technique allows the set of windows (views onto the 3D scene) to be generated sequentially, such that all display pixels are able to contribute to each view (an exemplar approach is summarised in Figure 11). In order to succeed, the frame rate of the display must be increased in accordance with the total number of views generated at different angular positions. See, for example, Kollin [1988], Travis [1990], Lang *et al.* [1992], Travis *et al.* [1995], Dodgson *et al.* [1999], and for summary discussion Blundell [2011a].

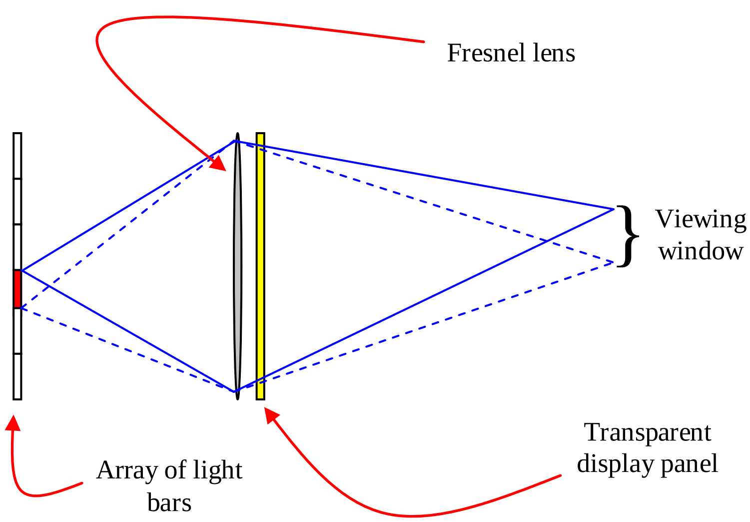

Figure 11: An example of the time-sequential collimated view technique. Only one light bar is active at any time and illuminates the display panel in its entirety. The lens ensures

that the image of the display panel is only visible from a particular region. Thus each light bar maps an image of the display panel to a different viewing window. This approach places demands on the temporal performance of the display.

In addition to the above examples and as previously mentioned, tracking the vantage positions of viewers enables display output to be directed into those regions in which users are present – thereby increasing presentation efficiency. Furthermore spatial and temporal coding techniques may be combined to enable the left and right sets of spatially coded views to be output sequentially. By way of example, see Stolle [2008] where discussion is provided regarding the use of electro-wetting prism arrays for sequentially switching display output to direct the left and right stereo views into the corresponding eyes (also see Liquavista [2009] for summary details of electro-wetting technology).

Turning now to electro-holography, the previous remarks in respect of this approach indicated somewhat daunting performance requirements, thereby suggesting that practical electro-holographic display technologies remain an elusive and distant vision. Certainly, if the goal is to reconstruct a complete holographic image over a wide viewing zone, then difficulties abound. On the other hand a more pragmatic approach adopted by SeeReal Technologies GmbH, is to limit the reconstruction of the wave field to content that is to be delivered to a region which is in close spatial proximity to the viewer's eyes, and to neglect content which goes unobserved.

Each point or pixel within a conventional hologram does not store information on a single corresponding object point, but rather contributes to the information stored about all points that comprise the object (thus when a hologram is broken, each individual fragment can be used to reconstruct the object – but at a smaller size and lower resolution). However, in the case of the SeeReal approach, the position of a viewer's eyes is tracked and a small viewing window is defined about each. Consider an arbitrary point on the object. A projection is made from the edges of the viewing window through the point onto the holographic display panel - thereby defining the extent of a 'sub-hologram' associated with the point. This defines the extent of the region on the hologram which stores information on the point. The sub-holograms for all image points are formed in a similar way and superimposed, thereby creating the overall holographic recording of the object for a particular viewing location. Naturally, this approach greatly reduces the computational overheads and allows support for POD (providing that the eye-tracking system is able to operate with sufficient accuracy and rapidity).

As for binocular parallax, the SeeReal approach uses temporal coding to output the left and right views. This assumes that the positions of both eyes are known, and that the display is able to sequentially direct the two views to the intended eyes. In general terms, this provides a further example of the benefits that may be derived by robustly tracking the positions of viewers and using this as basis for increasing the presentation efficiency. For further discussion, see Häussler *et al.* [2008, 2009], Reichelt *et al.* [2008, 2010], Lunazzi *et al.* [2009], Zschau *et al.* [2010], and Schwerdtner *et al.* [2007]. Also see Balogh [2006].

The volumetric approach also has the potential for significant advancement. Key beneficial characteristics associated with this general technique include natural support for a broad range of depth cues (including 3-POD), support for multiple simultaneous viewers (the upper limit being imposed by physical practicalities as compared to the technical limitations associated with multiview displays/systems that track viewer location), freedom in viewing position, and interaction opportunities that may be derived by mapping volumetric images into Ethereal space. On the other hand, consider a display that enables images to be depicted in a glass sphere such that all viewing positions about a hemisphere are supported (described in Blundell [2011b] as the 360°,2π(sr) configuration). This all-round viewing freedom makes it impossible to increase the perceived depth of the image space through the artificial manipulation of vanishing points. Indeed, the vanishing points associated with any view onto an image scene occur naturally and automatically relocate in response to changes in vantage position. In contrast, when viewing freedom is more restricted (e.g. limited to a single window onto the physical image space), vanishing point(s) can be manipulated at will.

As previously indicated, a further issue associated with the majority of volumetric systems constructed to date concerns image translucency. For some applications, this can be advantageous (e.g. medical diagnostics where it is often desirable to be able to view external and internal forms of content simultaneously). However, in other cases opacity is desirable. We have already alluded to a hybrid volumetric-multiview technique which supports the formation of optically opaque images – but this imposes viewing location restrictions and, in order to support V,POD it is necessary to include eye-tracking technology. Other possible solutions include the formation of voxels which are made visible on the basis of their ability to scatter ambient light – see Blundell [2007] for summary discussion.

In the worst case scenario, and unless image resolution is reduced, the depiction of a stereopair doubles the amount of data that must be transmitted to the display system. However, in the case of 3D TV, it is necessary to employ methodologies that enable 3D transmission to take place over existing networks. One approach is to halve the data content of the left and right stereo views (e.g. Sky 3D). Alternatively, it is possible to capitalise on the coherence that exists between the left and right stereo views such that many aspects of the two views will be the same or can be inferred (for basic relevant discussion see, for example, Adelson and Hodges [1993]). This general approach supports a reduction in data transmission requirements as it simply entails the transmission of a single view plus metadata that enables the computation of the stereopair. However, the deployment of glasses-free 3D TV able to support POD places far greater demands on the data transmission pipeline. In this context, the electro-holographic approach is the most demanding, and it is unclear as to whether techniques such as the sub-hologram method summarised above can significantly reduce data transmission requirements without incurring unacceptable latency between observer movement/interaction and display update.

4. DISCUSSION

The opportunities that may ultimately be derived from the formation of volumetric images in Ethereal space, coupled with the development of controllable opacity voxels is likely to further align this imaging modality with traditional forms of sculpture. Indeed the direct comparison of holographic and volumetric approaches with display paradigms that are fundamentally based on the principles of the stereoscope is often misleading. Thus, for example, in terms of information content, the pixel and voxel are not equivalent and give rise to images that in many respects offer to fulfil quite different needs.

As for the formation of so-called 'free-space' (Ethereal) images, it is important to appreciate that basic laws of nature cannot be circumvented. This is succinctly explained by Halle [1997] in the following way:

> '*A display medium or element must always lie along a line of sight between the viewer and all parts of a spatial image.*'

He goes on to add:

> '*Photons must originate in, or be redirected by, some material. The material can be behind, in front of or within the space of the image, but it must be present. All claims to the contrary violate what we understand of the world... Technologies lavished with claims of mid-air projection should always be scrutinised with regard to the fundamental laws of physics.*'

In short, light travels in a rectilinear manner unless influenced to do otherwise by the presence of optical components or some form of material on which it impinges. By way of example, curved mirrors[7] or lenses may be used to project an image so that it appears to 'float' in mid-air, or light may impinge on particles via which it is scattered. In this latter case the particles may not be readily visible but if they were removed, image formation would no longer take place.

In the above discussion, we have briefly referred to a number of exemplar technologies and have summarised various issues that should be taken into account in developing and applying innovative 3D systems. Without doubt many challenges must still be overcome before we are able to develop display systems that are truly able to work harmoniously with, and capitalise on, the strengths of the human visual system. From a technical perspective opportunities abound - although a great deal of fundamental research remains to be done.

5. AUTHOR'S NOTE

6. REFERENCES

Adelson, S.J., and Hodges, L.F., 'Stereoscopic Ray-Tracing', *The Visual Computer,* **10** (3), pp. 127-144 (1993).

Balogh, T., 'The Holo Vizio System', *Proc. SPIE,* **6055**, pp.279-290 (2006).

Barnum, P.C., Narasimhan, S.G., and Kanade, T., 'A Multi-Layered Display with Water Drops', *ACM SIGGRAPH 2010 (Emerging Technologies section)* (2010).

Benton, S. B. and Bove Jr, V. M., *Holographic Imaging*, John Wiley & Sons Inc (2008).

Blundell, B.G., and Schwarz, A.J., *Volumetric Three-Dimensional Display Systems*, John Wiley & Sons Inc (2000).

Blundell, B.G., *Enhanced Visualization: Making Space for 3-D Images*, John Wiley & Sons Inc (2007).

Blundell, B.G., *An Introduction to Computer Graphics and Creative 3-D Environments*, Springer-Verlag (London) (2008).

Blundell, B.G., *3D Displays and Spatial Interaction: Exploring the Science, Art, Evolution and Use of 3D Technologies, Volume I, From Perception to Technology*, Walker & Wood Limited (2011a). Available from www.walker-and-wood.com (not available via Amazon.)

Blundell, B.G., *About 3D Volumetric Displays*, Walker & Wood Limited (2011b). Available from www.walker-and-wood.com (not available via Amazon.)

Burdea, G.C., and Coiffet, P., *Virtual Reality Technology*, (2nd edn.), John Wiley & Sons Inc (2003).

[7] For an exemplar embodiment see the Microsoft 'Vermeer' display: www.tweaktown.com/news/22167/microsoft_tease_3d_360_degree_holographic_interactive_displays/index.html (Last accessed January 2012.) For discussion on this technique, see Blundell [2007].

Cossairt, O.S., Napoli, J., Hill, S.L., Dorval, R.K., and Favalora, G.E., 'Occlusion-Capable Multiview Volumetric Three-Dimensional Display', *Applied Optics,* **46** (8), pp. 1244-1250 (2007).

DeFanti, T., Cruz-Neira, C., Sandin, D., Kenyon, R., and Hart, J., 'The CAVE: Audio Visual Experience Automatic Virtual Environment', *Communications of the ACM,* **35** (6), pp. 64-72 (1992).

Dodgson, N.A., Moore, J.R., and Lang, S.R., 'Multi-View Autostereoscopic 3D Display', *Proc. International Broadcasting Convention (September 10-14, Amsterdam),* pp. 497-502 (1999).

Edgerton, S.Y., *The Renaissance Rediscovery Of Linear Perspective*, Harper and Row (1976)

Favalora, G.E., 'Progress in Volumetric Three-Dimensional Displays and Their Applications', in *Frontiers in Optics*, OSA Technical Digest (CD), paper FTuT2 (Optical Society of America) (2009).

Favalora, G.E., Dorval, R.K., Hall, D.M., Giovinco, M., and Napoli, J., 'Volumetric three-dimensional display system with rasterization hardware', *Proc. SPIE,* **4297***,* p. 227 (2001).

Favalora, G., Hall, D.M., Giovinco, M., Napoli, J., and Dorval, R.K., 'A Multi-Megavoxel Volumetric 3-D Display System for Distributed Collaboration', *Application of Virtual Reality Technologies for Future Telecommunication System Workshop, IEEE Globecom 2000 Conference* (2001).

Favalora, G.E., Napoli, J., Hall, D.M., Dorval, R.K., Giovinco, M.G., Richmond, M.J., and Chun, W.S., '100 Million Voxels Volumetric Display', *Proc. SPIE,* **4712***,* pp. 300-312 (2002).

Feenstra, J., and Hayes, R., "Electrowetting Displays", Liquavista White Paper, http://www.liquavista.com/files/LQV060828XYR-15.pdf (Last accessed January 2012.)

Fernandes, K.J., Raja, V., and Eyre, J., 'Cybersphere: The Fully Immersive Spherical Projection System', *Communications of the ACM,* **46** (9), pp. 141-146 (2003).

Gabor D, "A New Microscopic Principle", *Nature*, **161**, pp.777-778 (1948).

Gibson, J.J., *The Perception of the Visual World*, Houghton Mifflin (1950).

Halle, M., 'Multiple Viewpoint Rendering', *Proc. SIGGRAPH '96* (1996).

Halle, M., 'Autostereoscopic Displays and Computer Graphics', *Computer Graphics (ACM SIGGRAPH)*, **31** (2), pp. 58-62 (1997).

Häussler, R., Schwerdtner, A., and Leister, N., 'A New Approach to Electro-Holography for TV and Projection Displays', *Proc.SID*, **32**, pp.1224-1227 (2007).

Häussler, R., Schwerdtner, A., and Leister, N., 'Large Holographic Displays as an Alternative to Stereoscopic Displays', *Proc. SPIE,* **6803**, 68030M (2008).

Häussler, R., Reichelt, S., Leister, N., Zschau, E., and Missbach, R., 'Large Real-time Holographic Displays: From Prototypes to a Consumer Product', *IS&T/SPIE Proc. Electronic Imaging 2009* (2009).

Hoffman, D.M., Girshick, A.R., Akeley, K., and Banks, M.S., 'Vergence-accommodation Conflicts Hinder Visual Performance and Cause Visual Fatigue', *Journal of Vision* **8**(3):33, pp.1-30 (2008).

Jacobs, K., and Karpf, R., 'Continuously Adjustable Pulfrich Spectacles for Mobile Devices', *IS&T/SPIE Multimedia on Mobile Devices Conference 2012, January 24-25* (2012).

Kameyama, K., and Ohtomi, K., 'A Shape Modelling System with a Volume Scanning Display and Multisensory Input Device', *Presence*, **2** (2), pp. 104-111 (1993a).

Kameyama, K., Ohtomi, K., and Fukui, Y., 'Interactive Volume Scanning 3-D Display with an Optical Relay System and Multidimensional Input Devices', *Proc. SPIE,* **1915***,* pp. 12-20 (1993b).

King, M.C., and Berry, D.H., 'Varifocal Mirror Technique for Video Transmission of Three-Dimensional Images', *Applied Optics* **9** (9), pp.2035-2039 (1970).

Kollin, J.S., 'Collimated View Multiplexing: A New Approach to 3-D', *Proc. SPIE,* **902** *(Three Dimensional Imaging and Remote Sensing Imaging)*, pp. 24-30 (1988).

Lang, S.R., Travis, A.R.L., Castle, O.M., and Moore, J.R., 'A 2nd Generation Autostereoscopic 3-D Display', in *P.F. Lister (ed.), Proc. 7th Eurographics Workshop on Graphics Hardware (Cambridge, UK, 5-6 September 1992),* pp. 53-63 (1992).

Lesem, L.B., Hirsch, P.M., and Jordan Jr, J.A., 'The Kinoform: A New Wavefront Reconstruction Device', *IBM J.Res.Develop.*, 13, pp.150-155 (1969).

Love, G.D., Hoffman, D.M., Hands, P.J.W., Gao, J., Kirby, A.K., and Banks, M.S., 'High-Speed Switchable Lens enables the Development of a Volumetric Stereoscopic Display', *Optics Express,* **17** (18), pp. 15716-15725 (2009).

Lucente, M., *Diffraction-Specific Fringe Computation for Electro-Holography*, Ph.D. Thesis, Massachussetts Institute of Technology (1994).

Lucente, M., 'Holographic Bandwidth Compression using Spatial Subsampling', *Optical Engineering,* 35 (6), pp.1529-1537 (1996).

Lunazzi, J.J., Magalhães, D.S.F., Rivera, I.R., and Serra, R.L., 'Holo-television System with a Single Plane', *Optics Letters*, 34(4), pp.533-535 (2009).

McAllister, D.F. (ed.), *Stereo Computer Graphics and Other True 3D Technologies*, Princeton University Press (1993).

Okoshi, T., *Three-Dimensional Imaging Techniques*, Academic Press (1976).

Parker, M.J., and Wallis, P.A., 'Three-Dimensional Cathode-Ray Tube Displays', *J.IEE*, **95**, pp. 371-390 (1948).

Parker, M.J., and Wallis, P.A., 'Discussion on "Three-Dimensional Cathode-Ray Tube Displays"', *J.IEE*, **96**(III) (42), pp. 291-294 (1949).

Reichelt, S., Sahm, H., Leister, N., and Schwerdtner, A., 'Capabilities of Diffractive Optical Elements for Real-time Holographic Displays', *Proc. SPIE*, 6912 (2008).

Stephan Reichelt, Ralf Haussler, Norbert Leister, Gerald Futterer, Hagen Stolle and Armin Schwerdtner, 'Holographic 3-D Displays - Electro-holography within the Grasp of Commercialization', in *Advances in Lasers and Electro Optics*, Nelson Costa and Adolfo Cartaxo (eds.), InTech (2010).

Reichelt, S., Häussler, R., Fütterer, G., and Leister, N., 'Depth Cues in Human Visual Perception and their Realization in 3D Displays', *Proc. SPIE,* 7690,76900B (2010).

Ritter, A.O., Wagener, H., and Strothotte, T., "Holographic Imaging of Lines: a Texture Based Approach", *Proc. International Conference on Information Visualization IV'97,* London, August, pp.272-278 (1997).

Ritter, A.O., Bottger, J., Deussen, O., and Strothotte, T., *Fast Texture-Based Interference for Synthetic Holography*, Technical Report 3/98, Fakultät für Informatik, Otto-von-Guericke-Universität Magdeburg, Germany (1998).

Saxby, G., *Practical Holography*, Prentice-Hall (1988).

St. Hilaire, P., Benton, S., and Lucente, M., 'Synthetic Aperture Holography: a Novel Approach to Three-Dimensional Displays', *J.Opt.Soc.Am.A.,* **9** (11), pp.1969-1977 (1992).

Stolle, H., Olaya, J.C., Buschbeck, S., Sahm, H., Schwerdtner, A., 'Technical Solutions for a full-resolution Auto-stereoscopic 2D/3D Display Technology', *Proc. SPIE*, **6803**, 68030Q, (2008).

Sullivan, A., '58.3: A Solid-State Multiplanar Volumetric Display', *Proc. SID '03 Digest* (2003).

Sullivan, A., 'DepthCube Solid-State 3D Volumetric Display', *Proc. SPIE,* **5291**, pp. 279-284 (2004).

Travis, A.R.L., 'Autostereoscopic 3-D Display', *Appl.Opt.*, **29** (29), pp. 4341-4342 (1990).

Travis, A.R.L., Lang, S.R., Moore, J.R., and Dodgson, N.A., 'Time-Multiplexed Three-Dimensional Video Display', *Journal of the SID*, **3/4**, pp. 203-205 (1995).

Yaraş, F., Kang, H., and Onural, L., "Circular Holographic Video Display System", *Optics Express*, **19**(10), pp.9147-9156 (2011).

Zschau, E., Missbach, R., Schwerdtner, A., and Stolle, H., 'Generation, Encoding and Presentation of Content on Holographic Displays in Real Time', *Proc. SPIE,* **7690**, 76900E (2010).

