3D Display Systems

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1 Introduction

Today’s 3D display systems provide new advantages to end-users; they are able to support an auto-stereoscopic, no-glasses, 3D experience with significantly enhanced image quality over previous generation technology. There have been particularly rapid advances in personal auto-stereoscopic 3D display for desktop users brought about because of the opportunity to combine micro-optics and LCD displays coinciding with the availability of low cost desktop image processing and 3D computer graphics systems.

In this chapter we concentrate our detailed technical discussion on personal 3D displays designed for desktop use as these are particularly benefiting from new micro-optic elements. We emphasize the systems aspect of 3D display design believing it is important to combine good optical design and engineering with the correct digital imaging technologies to obtain a high quality 3D effect for end users. The general principles discussed will be applicable to the design of all types of stereoscopic 3D display.
2 Human Depth Perception

Defining the requirements for 3D display hardware and the images shown on them is an important first step towards building a high quality 3D display system. We need a clear understanding of how a digital stereoscopic image is perceived by an end user in order to undertake valid optimisation during the design process.

Binocular vision provides humans with the advantage of depth perception derived from the small differences in the location of homologous, or corresponding, points in the two images incident on the retina of the eyes. This is known as stereopsis (literally solid seeing) and can provide precise information on the depth relationships of objects in a scene.

The human visual system also makes use of other depth cues to help interpret the two images incident on the retina and from these build a mental model of the 3D world. These include monocular depth cues (also known as pictorial [18] or empirical [40] cues), whose significance is learnt over time, oculomotor cues in addition to the stereoscopic cue [40]. We consider these in turn and introduce in detail binocular vision both in the natural world and when looking at an electronic 3D display.

2.1 Monocular and oculomotor depth cues

Redundancy is built into the visual system and even people with monocular vision are able to perform well when judging depth in the real world. Therefore in the design of 3D displays it is important to be aware of the major contribution of monocular 2D depth cues in depth perception and aim to provide displays with at least as good basic imaging performance as 2D displays. Ezra [12] suggests this should include levels of brightness, contrast, resolution and viewing range that match a standard 2D display with the addition of the stereoscopic cue provided by generating a separate image for each eye.

The monocular depth cues are experiential and over time observers learn the physical significance of different retinal images and their relation to objects in the real world. These include:

- Interposition: objects occluding each other suggest their depth ordering.
- Linear perspective: the same size object at different distances projects a different size image onto the retina.
- Light and Shade: the way light reflects from objects provides cues to their depth relationships, shadows are particularly important in this respect.
- Relative Size, an object with smaller retinal image is judged further away than the same object with a larger retinal image.
- Texture Gradient: a texture of constant size objects, such as pebbles or grass, will vary in size on the retina with distance.

- Aerial Perspective: the atmosphere affects light travelling through it, for example due to fog, dust or rain. As light travels long distances it is scattered, colours lose saturation, sharp edges are diffused and colour hue is shifted towards blue.

![Diagram showing depth cues](image)

Figure 1: Picture illustrating the depth cues available in a 2D image, (photographer David Burder).

Many of these cues are illustrated in figure 1 and can be considered to be 2D depth cues since they are found in purely monoscopic images.

Two other non-binocular depth cues are available: motion parallax and oculomotor cues.

Motion parallax provides the brain with a powerful cue to 3D spatial relationships without the use of stereopsis [40, 18] and this is the case when either an object in the scene or the observer’s head moves. Motion parallax does not, however, make stereopsis redundant, as comprehending images of complex scenes can be difficult without binocular vision. Yeh [68] and others have shown that both stereopsis and motion parallax combined result in better depth perception than either cue alone.

Oculomotor depth cues are due to feedback from the muscles used to control the vergence and accommodation of the eye. They are generally regarded as
having limited potential to help depth judgement [40, 42, 16] and we will move on to consider how human binocular vision works when used to view the natural world.

2.2 Binocular depth perception in the natural world

Extracting three-dimensional information about the world from the images received by the two eyes is a fundamental problem for the visual system. In many animals perhaps the best way of doing this comes from the binocular disparity that results from two forward facing eyes having a slightly different viewpoint of the world [5]. The binocular disparity is processed by the brain giving the sensation of depth known as stereopsis.

![The horopter is all points perceived at the same depth as the point of fixation, F.](image)

All objects within Panum’s fusion are seen as single fused images.

Figure 2: The geometry of the binocular vision when viewing the natural world.

Stereo depth perception in the natural world is illustrated in figure 2. The two eyes verge the visual axes so as to fixate the point $F$ and adjust their accommodation state so that points in space at and around $F$ come into focus.

The vergence point, $F$, projects to the same position on each retina and therefore has zero retinal disparity, i.e. there is no difference between its location in the left and right retinal images. Points in front or behind the fixation point project to different positions on the left and right retina and the resulting binocular disparity between the point in the left and right retinal images provides the
observer’s brain with the stereoscopic depth cue. Depth judgement is therefore relative to the current vergence point, \( F \), and is most useful to make judgements on the relative rather than absolute depth of objects in a scene.

Points in space, other than \( F \), which project zero retinal disparity are perceived to lie at the same depth as the vergence point, all points that project zero retinal disparity are described as being on a surface in space known as the horopter. The shape of the horopter shown in figure 2 is illustrative only it is known in practice to be a complex shape and to have non-linear characteristics [3, 18].

![Horopter Diagram](image)

Figure 3: Angular disparity is defined relative to the current fixation point.

Geometrically we can define angular disparity, \( \alpha \), as the difference between the vergence angle at the point of fixation, \( F \) and the point of interest. Considering figure 3:

- Points behind the fixation point, such as \( A \), have positive disparity.

\[
\alpha_a = f - a
\]

(1)

- Points in front of the fixation point, such as \( B \), have negative disparity.

\[
\alpha_b = f - b
\]

(2)

The smallest perceptible change in angular disparity between two small objects is referred to as stereo acuity, \( \delta \), [67]. The advantage of defining stereo
acuity as an angle is that it can be assumed to be constant regardless of the actual distance to and between the points $A$ and $B$. However, it is also helpful to know how this translates in terms of the smallest perceived distance between objects at the typical viewing range of a desktop 3D display. This will allow us to compare the ability of the eye to perceive depth with the ability of different displays designs to reproduce it.

![Diagram](https://via.placeholder.com/150)

Figure 4: Stereo acuity defines smallest depth difference an observer can perceive.

Considering figure 4 when points $A$ and $C$ can just be perceived to be at a different depth then stereo acuity will be:

$$\delta = a - c$$

Various studies [67, 28, 31] show the eye is able to distinguish very small values of $\delta$, as little as 1.8" (seconds of arc). As the exact limits vary between people Diner and Fender [8] suggest that a practical working limit is to use a value of stereo acuity $\delta = 20"$. Using this value we can calculate the size of the smallest distinguishable depth difference at a given distance from the observer. We choose $m = 750mm$ as the distance from the observer as a common viewing distance for desktop stereoscopic displays and use an average eye separation, $e = 65mm$.

Calculating along the centre line between the visual axes we can find the minimum distinguishable depth, $n$, at distance $m$ by considering points $A$ and $C$. The angle $a$ can be calculated as:

$$a = 2 \times \arctan \left( \frac{e/2}{m} \right) = 2 \times \arctan \left( \frac{32.5}{750} \right)$$

$$\delta = a - c$$ (3)

$$\delta = 20"$$ (4)
by the definition of stereo acuity we know that:

\[ \tan\left(\frac{c}{2}\right) = \tan\left(\frac{a - \delta}{2}\right) = \tan\left(\frac{a - 20''}{2}\right) \]  

(5)

and if \( n \) is the distance between \( A \) and \( C \) we also know that:

\[ \tan\left(\frac{c}{2}\right) = \frac{(e/2)}{m + n} \]  

(6)

rearranging (6) we have:

\[ n = \left(\frac{(e/2)}{\tan(c/2)}\right) - m \]  

(7)

Substituting (4) in (5) and using the result to solve (7) gives \( n = 0.84mm \).

We can conclude that a person with a stereo acuity of 20" and an eye separation of 65mm will be able to perceive depth differences between small objects of just 0.84mm at a distance of 750mm from the eyes.

It is also possible to calculate a geometric value for the furthest possible range of stereo vision which occurs when the vergence angle between the two visual axes is equal to or less than the stereo acuity.

The distance \( m \) from the observer to the point \( A \) when the angle \( a = \delta \) is given by

\[ m = \frac{(e/2)}{\tan(a/2)} \]  

(8)

Again taking \( \delta = 20" \) and \( e = 65mm \) we get \( m = 670m \).

This means that points such as \( C \) at a distance of 670m or more from the observer will not be able to be distinguished in distance from \( A \) using binocular vision alone. Just before this limit is reached the smallest distinguishable depth difference between points will have increased to over 300m and it is clear only gross differences in depth will be perceived at the furthest limits of stereoscopic perception.

To summarise the above, binocular vision uses the stereoscopic depth cue of retinal disparity to perceive an object’s depth relative to the fixation point of the two eyes. At close and near range this provides a high degree of depth discrimination and even at tens of metres from the observer enables relative depth perception for larger objects.

### 2.3 Depth perception in electronic stereoscopic images.

Wheatstone [62] demonstrated that the stereoscopic depth sensation could be recreated by showing each eye a separate 2D image. The left and right eye views should be 2D planar images of the same scene from slightly different viewpoints; the difference in the viewpoints generates disparity in the images. When the images are subsequently viewed the observer perceives depth in the scene because
the image disparity creates a retinal disparity similar, but not identical, to that seen when looking directly at a natural scene.

Wheatstone was able to demonstrate this effect by building the first stereoscope and many devices have since been invented for stereoscopic image presentation each with their own optical configurations. Reviews of these devices and the history of stereoscopic imaging are available in several sources [23, 55, 41, 33, 30].

To help characterise and compare the performance of different electronic 3D display designs we will consider the perception of depth in planar stereo image pairs and how this differs from the stereoscopic perception of depth in the natural world.

A key physiological difference is that although the eyes need to verge off the stereoscopic image plane to fixate points in depth their accommodation state must always keep the image plane itself in focus. This requires the observer to be able to alter the normal link between vergence and accommodation and is one reason why images with large perceived depth are hard to view. This suggests that the perceived depth range in stereoscopic image pairs needs to be limited to ensure the observer will find a stereo image pair comfortable to view.

While there are several studies of the comfortable perceived depth range on electronic 3D displays [67, 17, 66] it can be difficult to factor out variables relating to display performance from the results. Display variables include absolute values, and inter-channel variations, of brightness and contrast in addition to stereoscopic image alignment and crosstalk. All of these can affect the comfortable range of perceived depth on a particular display. For example high crosstalk displays generally do not support deep images as the ghosting effect becomes more and more intrusive to the observer as screen disparity is increased.

An analysis of the geometry of perceived depth assuming a display with ideal properties helps identify the geometric variables affecting perceived depth independently of the display used. Geometric models of perceived depth have been studied by Helmholtz [23] and Valyus [55] and more recently in [24, 66, 8, 27] We present a simplified model in figure 5 for discussion purposes which helps emphasise the key geometric variables affecting the perception of stereoscopic images.

Figure 5 shows the geometry of perceived depth for a planar stereoscopic display, for simplicity we consider the geometry along the centre line of the display only, more general expressions are available [23, 66]. The viewers eyes, $L$ and $R$, are separated by the interocular distance, $e$, and are at a viewing distance, $z$, from the display plane. The screen disparity between corresponding points in the left and right images, $d$, is a physical distance resulting from the image disparity which is a logical value measured in pixels. Image disparity is constant for a given stereo pair, however screen disparity will vary depending on the characteristics of the physical display. Screen disparity in a pair of aligned stereo images is simply the difference of the physical x coordinates of corresponding points in the right
Figure 5: Perceived depth behind (1) and in front (2) of the display plane.

$x_r$ and left $x_l$ images:

$$d = x_r - x_l$$  (9)

Two key expressions relating screen disparity to perceived depth can be derived from the similar triangles in figure 5. Perceived depth behind the screen plane, i.e. positive values of $d$, is given by:

$$p = \frac{z}{\left(\frac{e}{|d|}\right) - 1}$$  (10)

Perceived depth in front of the screen plane, i.e. negative values of $d$, is given by:

$$p = \frac{z}{\left(\frac{e}{|d|}\right) + 1}$$  (11)

Equations (10) and (11) provide several insights into the geometric factors affecting perceived depth:

- $z$, the viewing distance to the display. Perceived depth is directly proportional to the viewing distance, $z$. Therefore a viewer looking at the same stereoscopic image from different distances perceives different depth. How important this is, is application dependent, but applications such as CAD, medical imaging and scientific imaging may critically depend on accurate and consistent depth judgements.
• *d*, the screen disparity. Perceived depth is also directly proportional to screen disparity, *d*. The screen disparity for any given stereoscopic image varies if the image is displayed at different sizes, either in different size windows on the same screen or on different size screens. Again this is important to note in applications where depth judgement is a critical factor. It means stereoscopic images are display dependent and an image displayed on a larger display than originally intended could exceed comfortable perceived depth limits or give a false impression of depth.

• *e*, individual eye separation. Perceived depth is inversely proportional to individual eye separation which varies over a range of approximately 55mm to 75mm with an average value often taken as 65mm. Children can have smaller values of eye separation and therefore see significantly more perceived depth in a stereoscopic image than the average adult. It may be particularly important to control perceived depth in systems intended for use by children, as they will reach the limits of their vergence/accommodation capabilities sooner than most adults.

For display design controlling these variables so that the viewer sees a consistent representation of depth ideally requires tracking head position, identifying eye separation and controlling screen disparity. These are challenging goals in addition to designing a display with as good imaging performance as a 2D display.

### 2.4 Benefits of binocular vision

An important question is what advantages does binocular vision provide in the real world? As a visual effect it clearly fascinates the majority of people when they see a 3D picture. Beyond the attractive nature of stereoscopic 3D images they provide the following benefits over monocular vision:

• Relative depth judgement. The spatial relationship of objects in depth from the viewer can be judged directly using binocular vision.

• Spatial localisation. The brain is able to concentrate on objects placed at a certain depth and ignore those at other depths using binocular vision.

• Breaking camouflage. The ability to pick out camouflaged objects in a scene is probably one of the key evolutionary reasons for having binocular vision [49].

• Surface material perception. For example, lustre [23], sparkling gems and glittering metals are in part seen as such because of the different specular reflections detected by the left and right eyes.
• Judgement of surface curvature. Evidence suggests that curved surfaces can be interpreted more effectively with binocular vision.

These benefits make stereo image display of considerable benefit in certain professional applications where depth judgement is important to achieving successful results. In addition the effect of stereopsis is compelling enough that stereoscopic images have formed the basis of many entertainment systems.
3D Display Designs using Micro-optics

The possible combinations of LCD and micro-optics provide many degrees of freedom for display design; the ideal 3D display design will depend on specific application requirements. However, there are characteristics that all display designs should give consideration to and we briefly review these here.

There is a need to compare the basic image quality of a 3D design to that achieved by current 2D displays i.e. the 2D characteristics of a 3D display should match the performance of 2D displays as closely as possible. Key characteristics are:

- Brightness, typical of a current LCD display is $150 \text{Cd/m}^2$
- Contrast, typical of a current LCD display is 300 : 1
- Colour reproduction, measured white points and measured CIE coordinates of primaries.

These values are typical of current 2D displays but are clearly be a moving target as 2D displays improve.

In addition there are a number of important characteristics unique to 3D displays. The first is the 2D characteristics need to be matched between all the viewing windows of the 3D display. Each viewing window should also be matched spatially and temporally so that there is no noticeable position or time differences between corresponding images.

Inter-channel crosstalk appears to an observer as a ghost image, which will be particularly visible at high contrast edges in images. It is an unwanted feature in most display designs because high values of crosstalk are known to be detrimental to 3D effect, particularly on high contrast displays showing large values of perceived depth [43]. Ideally crosstalk measurements need to be no more than 0.3 percent if the ghosting effect is to be imperceptible to an observer. Crosstalk, although often due to optical effects in the display, can also result from poor separation of the two image channels in the display driving electronics, image compression formats or the camera system generating the images.

An observer of a 2D display will usually expect to be able to see a good quality image at a wide range of positions in front of the display. Because of the need to direct images separately to the two eyes many 3D displays have a more limited viewing freedom. Consideration needs to be given to the targets for lateral, vertical and perpendicular freedom in a display design. 3D display systems capable of supporting multiple observers will often do so at the expense of viewing freedom. Improved viewing freedom can be found in designs with multiple viewing windows or using head tracking to steer viewing windows to follow the observers head movements. When head tracking is used a design needs to consider targets for the maximum supported head speed as this directly determines key tolerances.
Some displays have the capability to operate in either 3D or 2D modes switching electronically or mechanically between the two. In this case the image quality in each mode needs to be considered against the performance of a standard 2D display, as a display in 3D mode will often have different optical performance to the same display in 2D mode.

The capability of a 3D display to represent perceived depth is probably the single most important design target however we will return to how to quantify and compare this between displays after presenting details of representative 3D display designs.

We would like 3D displays to provide the ability for the observer to accommodate naturally at the fixation point. However, this is not a feature supported in stereoscopic images and has been attempted in very few display designs.

### 3.1 Stereoscopic Systems

Stereoscopic displays require users to wear a device, such as analysing glasses, that ensures left and right views are seen by the correct eye. Many stereoscopic display designs have been proposed and there are reviews of these in several sources [55, 41, 33, 30, 35]. Most of these are mature systems and have become established in several professional markets but suffer from the drawback that the viewer has to wear, or be very close to, some device to separate the left and right eye views. This has limited the widespread appeal of stereoscopic systems as personal displays for home and office use even when the 3D effect is appealing. However, stereoscopic displays are particularly suited to multiple observer applications such as cinema and group presentation where directing individual images to each observer becomes difficult compared to providing each observer with a pair of analysing glasses.

As stereoscopic display systems are well described elsewhere we limit ourselves here to a summary of the major types using electronic displays:

- Wheatstone mirror stereoscopes using CRT displays or LCD displays.
- Polarised glasses in combination with a method of polarising the two views.
- Shutter glasses working in synchronisation with a view switching display.
- Analgylph glasses analysing different colour channels to obtain the images.
- Brewster stereoscopes, of which head mounted displays are up to date examples.

A series of stereoscopic display designs that use polarising micro-optics have been produced by the VREX company [14], as shown in figure 6. The micro-optics split a single display into two differently polarised views, which are viewed correctly by left and right eyes when the observer wears a pair of analysing
When viewed with polarised glasses the P1 polarised pixels are seen only in the left eye and P2 polarised in the right.

Figure 6: The VREX micro-polariser stereoscopic display principle.

polarised glasses. This requires two half resolution views and may be achieved using a checkerboard pattern of image multiplexing and polarisation as shown in figure 6 as the spatially multiplexed image (SMI) and patterned micro-polariser (uPol).

A drawback of the design, particularly for direct view LCD based displays, is the parallax between the display pixels and the micro-polariser when the micro-polariser is mounted over the LCD due to the layer of substrate between the two elements forming the gap $g$ in figure 6. If the head moves from the nominal viewing position part of the adjacent view’s pixel becomes visible resulting in crosstalk. One way to reduce this is to use interlace the images in alternate rows so at least lateral head movement is not affected by parallax. As noted by Harrold [20] this problem can only be fully solved in the long term by manufacturing the micro-polariser element within the LCD pixel cells reducing the parallax between polariser and pixel.

### 3.2 Autostereoscopic Systems

Autostereoscopic displays are those that do no require the observer to wear any device to separate the left and right views and instead send them directly to the correct eye. This removes a key barrier to acceptance of 3D displays for everyday use but requires a significant change in approach to 3D display design. Autostereoscopic displays using micro-optics in combination with an LCD ele-
ment have become attractive to display designers and several new 3D display types are now available commercially. The key optical reasons [64] for combining micro-optics with LCD elements are:

- LCD offers pixel position tolerances better than 0.1μm
- LCD pixels, unlike CRT pixels, have high positional stability.
- LCD elements have carefully controlled glass thickness.

Autostereoscopic displays have been demonstrated using a range of optical elements in combination with an LCD including:

- Parallax barriers, optical apertures aligned with columns of LCD pixels.
- Lenticular optics, cylindrical lenses aligned with columns of LCD pixels.
- Micropolarisers are found in several autostereoscopic 3D display designs.
- Holographic elements have been used to create real images of a diffuse light source.

In the following we introduce how these elements are used in autostereoscopic 3D display designs including two-view and multi-view designs. We begin by looking at autostereoscopic two-view designs using twin-LCD elements.

### 3.3 Two view twin-LCD systems.

A successful approach to building high quality auto-stereoscopic displays has been to use two LCD elements and direct the image from one to the left eye and from the other to the right eye, the principle is illustrated in figure 7. Several designs adopted this approach including [12, 13, 22].

Ezra [12, 13] describes one of the Sharp designs which, produces bright, high quality, full colour moving 3D images over a wide horizontal viewing range. As shown in figure 8 the display produces two viewing windows using a single illuminator. The arrangement of optical elements generates horizontally offset images of the illuminator at a nominal viewing distance to form the viewing windows. An observer’s eye placed in one of the viewing windows will see an image from just one of the LCD elements.

If a stereo pair of images is placed on the left and right LCD elements respectively then an observer will see a stereoscopic 3D image. The image appears in the plane of the left LCD as the observer looks at the display and depth is perceived in front and behind this plane. As the two LCD’s are seen separately each eye has a full resolution image and the interface is simply two synchronised channels of digital or analogue video which can be generated at low cost on a desktop PC system.
Each eye is able to see the appropriate image on the display through a viewing “window”.

Left and right images are displayed in different sets of pixels on the display.

Figure 7: Two-view displays create two viewing windows.

Figure 8: The Sharp twin-LCD display, [12].
This basic configuration can be enhanced in several ways, if the light source is moved then the viewing windows can be steered to follow the observer’s head position. In order to implement window steering new technologies for tracking head position have also been developed [25] The effect of implementing head tracking linked to window steering is to increase the viewing freedom of the display and if the images are updated the design has been demonstrated to provide a full look-around effect. This allows the observer to look-around the display and see different views of the scene as they would in the natural world. Image generation for look-around can be implemented by using a 3D computer graphics system to generate the new views when given head tracking position information.

Another possible development of the Sharp system [13] is to have multiple light sources providing multiple stereo views to multiple viewers. This could be implemented either by sending the same image pair to each viewer, or by time slicing the light source and the displays to send a different image to each viewer in rapid succession.

The system uses bulk optics and therefore has a large footprint, particularly as the LCD display diagonal size increased. This led Sharp to develop the micro-optic twin-LCD display [63] which provides the same effect in a smaller footprint and is more practical for scaling to larger display sizes.

![Figure 9: The Sharp micro-optic twin-LCD display, [63].](image)

The Sharp micro-optic twin-LCD display is illustrated in figure 9. The two LCD elements remain in the design with a half mirror acting as a beam combiner between them. The arrangement of optical elements behind one LCD panel...
directs light so that it forms one viewing window at a nominal viewing distance from the display, another is formed adjacent to this from the backlight of the other LCD panel. As with the bulk optic display the observer placing their eyes in the viewing windows will see the appropriate image in each eye and experience a stereoscopic 3D effect.

As discussed in [63] the micro-optic display produces a better viewing window profile than the bulk-optic display. This is because the micro-optics form a wider and more even illumination distribution for each viewing window so that, when steered, the windows can be moved further laterally before aberrations reduce their quality. This also results in side lobes of better quality, which in untracked displays can be used by additional observers.

3.4 A Note on Viewing Windows

One of the key influences on the perceived performance of auto-stereoscopic displays is the quality of the viewing windows that can be produced at the nominal viewing position. Degradation of the windows due to unresolved issues in the optical design can lead to flickering in the image, reduced viewing freedom and increased inter-channel cross-talk. All of these reduce the quality of viewing experience for observers in comparison to the 2D displays they are used to using. In addition in head tracked systems degraded window quality can lead to harder constraints on the accuracy and response speed of the tracking and window steering systems, increasing system costs [25].

The auto-stereoscopic displays considered so far produce two viewing windows in space typically at a nominal distance from the display in a plane parallel to the display surface, as shown in figure 7. Although often illustrated in 2D the viewing windows have a 3D shape and from above appear as diamonds tapering away from the nominal viewing plane as shown in figure 10. As long as an observer’s pupils stay within these diamonds, and the display is showing a stereo image, the observer will see a 3D image across the whole of the display.

Experimentally the window intensity profile can be determined by measurements using a 1mm pinhole, a photometric filter and a detector. To fully characterise a displays performance the profile measurements should be repeated at a range of positions vertically and longitudinally offset from the nominal window position. The variables characterising the quality of the viewing windows are discussed in [63] and are summarised here in figure 11.

The useful width of the window determines how far an observer can move before the image quality degrades. Larger useful width, up to the interocular separation typically 65mm, provides more comfortable viewing in fixed position displays as there will be a small but useful lateral range of head positions at which a good 3D image can be seen.

A systems benefit of wider viewing windows is that it helps relax the tolerances required for window steering and tracking mechanisms in head tracked displays.
The best lateral viewing freedom is found at the nominal window plane. Additionally longitudinal freedom is possible as long as the observer's eyes stay within the viewing diamonds.

Figure 10: Viewing freedom in an autostereoscopic display, [63].

The characteristics of a viewing window, [63].
such as [12, 63]. This is because a wider viewing window allows more time and/or distance before the steering and tracking mechanisms have to respond to user head movement in order to prevent the user moving out of the useful width and seeing a degraded image on the display.

3.5 Two-view single LCD systems

Even with the advantages of a micro-optic design twin-LCD 3D displays have a component cost that must include two LCD elements. This cost is acceptable in some applications when image quality is the key requirement however for the mass market, i.e. personal office and home use, it is desirable to find display designs based on a standard single LCD element.

We will group the single LCD autostereoscopic designs by the type of optical element used to generate the viewing windows, beginning with the parallax barrier.

3.5.1 Parallax barrier designs

![Diagram of parallax barrier](https://via.placeholder.com/150)

Figure 12: The principle of the front parallax barrier.

Typical emissive displays have pixels with diffuse radiance, that is they radiate light equally in all directions. To create a twin-view auto-stereoscopic display half the pixels must only radiate light in directions seen by the left eye and half the
pixels in directions seen by the right eye. The parallax barrier is perhaps the simplest way to do this and works by blocking light using strips of black mask.

The principle of the two view parallax barrier is illustrated in figure 12. The left and right images are interlaced in columns on the display and the parallax barrier positioned so that left and right image pixels are blocked from view except in the region of the left and right viewing window respectively. Although not illustrated the viewing windows repeat in side lobes to each side of the central viewing position and can be used by more than one observer if the optical quality remains high enough.

The pixels and barrier are arranged so the centre of each pair of left and right view pixels is visible at the centre of the viewing windows. The geometry defining the design of the parallax barrier pitch, \( b \), can then be determined from considering similar triangles in figure 12.

\[
\frac{b}{z - g} = \frac{2i}{z}
\]

which can be rearranged to give:

\[
b = 2i \left( \frac{z - g}{z} \right)
\]

The result (13) is that the barrier pitch for a two viewing window display is just less than twice the pixel pitch on the display. This small difference between the pixels and the barrier pitch accounts for the variation in viewing angle between the eyes and the pixels across the display and is often referred to as viewpoint correction.

Viewing distance, \( z \), for the best quality viewing windows is another design factor and again from similar triangles in figure 12 we can deduce a geometric relationship for this.

\[
\frac{i}{g} = \frac{e}{z - g}
\]

which can be rearranged to give:

\[
z = g \left( \frac{e + i}{i} \right)
\]

The window width is typically set to the average eye separation, \( e = 65mm \), the pixel pitch, \( i \) is defined by the display and the gap, \( g \), between display and barrier is defined by the thickness of the front substrate on the LCD. For example pixel width might be of the order \( i = 0.1mm \) and the gap, including front substrate and polariser, \( g = 1.15mm \). The result is relatively little control of the closest possible viewing distance and given current LCD substrate thickness many current parallax barrier based displays have optimal viewing distances of \( z = 750mm \).
More recent 2D displays could use a substrate such as Corning Eagle\textsuperscript{2000} with thickness from 0.4mm to 0.63mm and given a polariser of thickness 0.2mm may then be able to reduce viewing distance for a front parallax barrier to $z = 390\text{mm}$. This compares favourably with the typical viewing distance of 2D displays of 300-350mm although care would be needed to avoid artefacts at the edges of the screen plane where the viewing angle increases with reduce viewing distance.

Variations on the basic twin-view parallax barrier design and further practical issues are described by Kaplan [29] including a discussion of multi-view parallax barrier displays and aperture design.

Okoshi [41] notes that problems with parallax barriers include the reduced brightness due to blocking the light from pixels, reflection from the glass surface of the parallax barrier and the design of the parallax apertures to avoid diffraction problems. However these disadvantages have been addressed and recent LCD based designs overcome the first two problems by using bright light sources and anti-reflection coated optics. The result is parallax barriers are now widely used for two view displays such as described by [64, 65] and illustrated in figure 13.

Figure 13: Detail of a single LCD front parallax barrier design, [64].

The diffraction problem is more serious but has also recently been addressed. An ideal display would have viewing windows described by a top hat function however in practice they have the characteristics shown in figure 11. A number of factors determine this and an important one is the detailed design of the parallax barrier apertures, $w$, shown in figure 13. A wider aperture results in a brighter
image but reduces the geometric performance of the aperture and creates less well-defined windows. A narrow aperture results in a less bright image with better window definition however too narrow an aperture suffers from diffraction effects which in turn results in less well-defined windows. In both cases the crosstalk performance, useful width and uniformity of intensity at the viewing window are affected.

A detailed study of the barrier position, aperture design and related diffractive effects is presented by Sharp in [64, 36]. In [64] a comparison was made between placing the parallax barrier behind and in-front of the LCD element. The analysis uses a model of the parallax barrier accounting for Fresnel diffraction and compares this to a set of experimental measurements. Placing the parallax barrier behind the display results in lower crosstalk while placing it in front of the display has very much better intensity uniformity and useful width at the window plane. These factors are decisive for tracking displays and hence the front position was adopted by Sharp to build a single-LCD observer tracking display [64].

In [36] several apodization modifications to the parallax barrier are analysed, these include soft aperture edges, multiple sub-apertures at aperture edges and combinations of the two techniques. The analysis concluded that choosing the correct apodization can make a substantial improvement to the window profile improving both the crosstalk performance and viewing freedom of the display. In particular crosstalk of less than 1 percent is theoretically achievable using an improved parallax element this is a significant improvement over the value of 3.5 percent achieved using unmodified apertures. These new studies show it is now possible to overcome the limitations of parallax barriers identified by Okoshi.

A practical problem encountered by users of two view parallax barrier displays without head tracking is how to find the best viewing position. One reason is the parallax barrier produces not just the central two viewing windows but also repeated lobes to each side of these as illustrated in figure 14(a). An observer in position $A$ will see an orthoscopic image (left image to left eye and right image to right eye image) as will an observer in position $D$. However an observer in the intermediate position $C$ sees a pseudoscopic image (the left image in the right eye and the right image in the left eye). This causes problems as typically pseudoscopic images show false depth effect and it can be hard for novice observers to determine if they are seeing a correct 3D image or not. A number of devices have been proposed to help observers determine when they are in the correct viewing position, the VPI (Viewing Position Indicator) display described in [64, 65] achieves this by integrating an indicator into the parallax element.

The parallax barrier in the VPI display is divided into two regions the image region, which is most of the display, and the indicator region, which may cover just the bottom few rows of pixels on the display. The result is shown in Figure 14(a) and (b) respectively. In the image region the conventional barrier design allows the left and right views to be seen at the nominal viewing position $A$. In the indicator region the display shows a pattern of red and black stripes and the
The VPI display operation (a) in image region and (b) in indicator region, [64].

The indicator region is implemented by using a barrier pitch in the indicator region double that used in the image region. As a result the VPI display requires little additional design or manufacturing cost and uses only a few lines of pixels to display the appropriate indicator pattern. It has the benefit that once the parallax barrier is aligned for image viewing the indicator mechanism is automatically aligned. The VPI also works to help guide observers find the best longitudinal viewing position if the aperture width, $w$, is kept the same in both the image and indicator regions of the parallax element.

A range of designs using parallax barrier optics in combination with LCD elements has been proposed, prototyped and commercialised.

Sanyo developed a large range of display designs using parallax barriers [19]. One example uses both a rear and a front parallax barrier with the aim of re-
ducing crosstalk, although no window profile measurements are given to say how successful this was. Because the combination of two parallax barriers reduces display brightness the rear barrier was mirror coated on the side facing the illuminator to recirculate light. A further design using just a rear parallax barrier places an electronically switchable diffuser between the parallax barrier and the LCD element. This allows instantaneous switching between 2D and 3D modes and if the diffuser is programmable also allows 3D windows to appear on a 2D display. Several Sanyo designs also combine a window steering mechanism and head tracker to increase lateral viewing freedom, one of these [26] uses an electronically programmable LC parallax barrier.

A design from NYU also based on an electronically programmable parallax barrier is described by Perlin [45, 46, 47]. A key goal for the NYU design is to steer the viewing windows to track the viewer in three dimensions by varying the pitch and aperture of the parallax barrier in real time. The aim is to generate real time viewpoint correction so the viewer can vary their position and still see a 3D image across the whole display surface. The potential benefit of the design is in extending longitudinal movement with respect to the display and it is also capable of accounting for head rotation, which effectively varies the observer’s eye separation. The design is relatively complex and before choosing this approach it would be wise to make a comparison with the longitudinal freedom already available from a fixed aperture display with good quality viewing windows. In practice realising the NYU display presents a number of challenges including the optical quality achievable from the programmable parallax element and the speed and latency targets with which the tracking and steering mechanisms need to work.

3.5.2 Lenticular element designs

Lenticular elements used in 3D displays are typically cylindrical lenses arranged vertically with respect to a 2D display such as an LCD. The cylindrical lenses direct the diffuse light from a pixel so it can only be seen in a limited angle in front of the display. This then allows different pixels to be directed to either the left or right viewing windows.

The principle for a two view lenticular element stereoscopic display is illustrated in figure 15 and described in [52]. This shows the geometry for a viewpoint corrected display where the pitch of the lenticular is slightly less than the pitch of the pixel pairs. As with parallax barrier displays the effect of viewpoint correction is to ensure pixels at the edge of the display are seen correctly in the left and right viewing windows. The lenticular pitch needs to be set so that the centre of each pair of pixels is projected to the centre of the viewing windows and this can be found by considering similar triangles where:

\[
\frac{2i}{z} = \frac{l}{z - f}
\]  

(16)
Typically the pixel pitch \( i \) is set by the choice of 2D display and the minimum focal length, \( f \), determined in large part by the substrate thickness on the front of the display.

The viewing distance can again be derived from similar triangles:

\[
l = 2i \left( \frac{z - f}{z} \right)
\]

(17)

Typically the window width for a two view system is taken to be the average eye separation, \( e = 65\text{mm} \), to give some freedom of movement (up to \( e / 2 \)) around the nominal viewing position. Combining this factor with the display related values of \( i \) and \( f \) it may be that there is again little choice over the closest possible viewing distance.

Lenticular elements have been used less often than parallax barriers in recent two view displays designs; one exception is the range of displays designed by the DTI corporation.
Figure 16: The geometry of rear parallax illumination by light lines.

The DTI display design described by Eichenlaub [10, 11] uses light guide and lenticular elements behind an LCD display to generate light lines that are functionally equivalent to having a rear parallax barrier. The principle of creating viewing windows using the light lines is shown in figure 16. The pitch required for the light lines can be calculated using similar triangles as for parallax barrier example discussed earlier.

\[
\frac{b}{z + g} = \frac{2i}{z}
\]

which can be rearranged to give:

\[
b = 2i \left( \frac{z + g}{z} \right)
\]

In this case the pitch of the light lines, \( b \), is slightly larger than twice the pixel pitch to achieve viewpoint correction. Again the gap, \( g \), will determine viewing distance and is likely to be constrained by the substrate glass thickness when using an LCD.

The backlight construction that creates the light lines is shown in figure 17. A modified light guide uses a series of grooves to generate an initial set of light lines, which are then re-imaged by the lenticular element to form a larger number of evenly spaced light lines in front of the light guide.

A 2D/3D switching diffuser in front of the lenticular element is made of polymer dispersed liquid crystal (PDLC) which when on is transparent allowing the
display to operate in 3D mode. When the PDLC is off it becomes a diffuser, scattering light and preventing the initial set of light lines reaching the lenticular lens. The result is a diffuse illumination for the display, which will operate with similar performance to a normal 2D display. Various size displays have been constructed with 5.6 inch and 12.1 inch displays having crosstalk of 3 and 6 percent and uniformity of 20 and 24 percent respectively.

The DTI design has the advantage of being able to electronically switch between 2D and 3D illumination modes as well as being small enough to be used in portable display devices. In addition there are no optical elements in front of the display surface allowing the observer to directly view the LCD display. Against this are some tradeoffs and the 3D mode has higher crosstalk than a well-designed parallax barrier system.

Other designs for single-LCD 3D displays using lenticular optics include Sharp Laboratories of Europe in Oxford [63], the Heinrich Hertz Institute in Berlin [44] and Canon Mixed Reality Systems Centre in Yokohama [39, 38].

A novel design using micro-prism elements was proposed by Dresden University [50, 51]. The D4D display uses an array of vertically oriented micro-prisms as the parallax element and the left and right images, vertically interlaced in columns, are directed to two viewing windows by the micro-prisms. A commercial display based on this principle included a head tracking device and both electronic image shifting and mechanical movement of the micro-prisms were investigated as ways to steer the viewing windows.
3.5.3 Micro-polariser designs

Displays using polarisation to create light steering optical elements have been proposed by several groups. The VREX stereoscopic display design described by Faris [14, 15] can also be configured to have an auto-stereoscopic mode by using a series of stacked micro-polariser elements to create a switchable parallax barrier. However despite this potential for autostereoscopic operation most of the commercial products from VREX have been stereoscopic systems.

![Diagram of LCD panel with polariser and retarder](image)

Figure 18: The Sharp micro-polariser display with 2D/3D switching capability, [20].

Sharp describes display designs using micro-polarisers in [20, 21]. The design exploits the polarised light output from an LCD element over which is created a patterned retarder array. A final polarising layer is placed over the retarder array effectively creating a front parallax barrier and hence an autostereoscopic display. If the final polarising layer is constructed so that it is removable the display can be mechanically switched between a 2D display mode and an autostereoscopic 3D display mode.

Key to the success of this design is the construction of the patterned retarder array to an accuracy of better than 1 part in 2000 for the 13.8 inch XGA display prototype. This was achieved using a process based on standard LCD manufacturing techniques to create a manufacturable patterned retarder array that is
front mounted onto the LCD element.

A stereoscopic display design is also described by Harrold in [20] where the patterned retarder and polariser are constructed inside the LCD element to avoid the parallax problems of the Faris design [14, 15]. A prototype LC cell was constructed by Sharp to demonstrate the feasibility of this approach.

A micro-polariser display described by Benton [1, 2] uses a combination of polarisation and bulk optics to create two viewing windows that can be steered electronically if a suitable head tracker is available. An LCD panel with the analysing polariser removed acts as an electronically programmable polarising light source, light coming from the light source LCD will either rotated at 90 degrees or not rotated. An illumination pattern of two blocks of light is displayed on the light source LCD, each polarised differently. A micropolariser array, manufactured by VREX, arranged as rows behind an image LCD display allows alternate rows of image to be illuminated by differently polarised light and hence appear in the viewing windows for the left and right eyes. A large lens after the LCD produces an image of the viewer-tracking LCD (polarised light source) at the intended viewing distance of about 1 metre creating the two viewing windows.

Benton notes there can be problems with the lens (a fresnel lens) creating moire patterns in association with the image display LCD. In common with many auto-stereoscopic displays the viewer has to be at or close to the nominal viewing distance, which at 1 metre is significantly further than typical 2D display viewing distances. No measurements of crosstalk or window brightness uniformity are given.

3.5.4 Holographic elements

Holographic optical elements (HOE) have been used [53, 54] to create 3D displays in conjunction with LCD elements.

When illuminated the HOE acts to form the viewing windows. The HOE is arranged in horizontal strips to reconstruct a real image of a diffuse illuminator, the strips are arranged so alternate strips reconstruct left and right viewing windows. When placed behind a display with two horizontally interlaced images the observer will see an autostereoscopic image.

A number of practical problems in the optical design are discussed in [53] and in particular colour fringing due to the diffractive nature of the HOE could prove difficult to overcome. Otherwise this design has several advantages and can be modified to track users by moving the light source and also constructed so that it can be switched between 2D and 3D using a modified light source.

3.6 Multi-view systems

The viewing freedom of a 3D display is a key requirement in certain applications, for example public information kiosks, where ease of viewing is needed to attract
and retain the attention of passers-by. Multi-view systems, as in figure 19, provide viewing freedom by generating multiple simultaneous viewing windows of which an observer sees just two at any time. Multi-view systems can also support more than one observer if enough horizontal viewing freedom is available.

Bulk optic multi-view displays have been developed such as the Cambridge display and are reviewed in the literature [37, 7]. The Cambridge display was designed to use temporal multiplexing of the view images and because the basic switching speed and interface bandwidth of LCD displays were not sufficient this led to the use of high speed CRT technology.

Micro-optic multi-view designs using standard 2D displays have been proposed where the images are spatially multiplexed. The Heinrich-Hertz-Institut has a well established programme investigating lenticular 3D displays and Borner [4] describes a number of multi-view designs.

The principle for a multi-view LCD display using a front lenticular element, similar to the two view lenticular design described previously, is illustrated in figure 20. This shows a five view lenticular display, where each pixel in every group of five pixels is directed to a different viewing window. As with the two view displays the system should be view-point corrected so that the viewing windows are aligned with pixels across the whole display.

To use the display five images are sliced vertically into columns and interlaced appropriately. The images will then be visible separately in the five viewing windows $V1 - V5$ in figure 20. The viewing windows can be designed as shown
so pairs of image separated by one image, for example $V_2$ and $V_4$, are seen simultaneously by the left and right eyes and if these form a stereo pair then an observer sees an image with stereoscopic depth. In addition if the observer moves laterally they can see a different pair of images, for example $V_3$ and $V_5$ and therefore a different stereoscopic view of the scene.

Using a similar geometrical argument as for two view lenticular displays the pitch of the lenses can be determined by:

$$l = N_v t \left( \frac{z - f}{z} \right)$$  \hspace{1cm} (22)$$

Where $N_v$ is the number of viewing windows required.

There are several drawbacks to the basic multi-view approach that are particularly apparent when electronic displays are used [57]. The first is there is a black mask between LCD pixels and this is imaged into dark lines between each view window which is distracting to observers when their eye crosses a window boundary. Also images with any significant depth will result in an image-flipping artefact as the observer moves their eye across one view window and into the next. Finally as more views are used the horizontal resolution of the images decreases rapidly. To overcome these problems Philips proposed a new approach to multi-view LCD display [57].

Philips [56, 57, 58] proposed and prototyped several multi-view systems based on lenticular micro-optics and single LCD displays. A significant step forward was
made by positioning the lenticular array at an angle to the LCD pixel array, this mixed adjacent views reducing image flipping problems and spreading the effect of the black mask making it less visible. The other benefit of this design is that each view has a better aspect ratio, rather than splitting the display horizontally into many views both horizontal and vertical directions are split.

Figure 21: The slanted arrangement of the lenticular lens and pixels in the Philips multi-view display, [57].

The arrangement of one lenticule and the underlying pixels in the Philips slanted lenticular design is shown in figure 21. The slanted lenticular arrangement means that all pixels along a line such as \(a\) will be imaged in the same direction. In this case all view 3 pixels are seen in the same direction. The arrangement shown allows seven views to be interlaced on the display and imaged in different directions by the lenticule. As the eye moves from position \(a\) to \(b\) the eye sees a gradual transition from view 3 to view 4. At most viewing positions the eyes will see a combination of more than one view; while this inherent crosstalk limits the depth that can be shown on the display it does hide the transition between views at boundaries and blurs the appearance of the black mask so that it is no longer an obvious visual artefact. For the seven view display described in [58] the magnification of the lenticules is designed so that a viewer at a distance of approximately 700mm from the display sees views 3 and 5 in left and right eyes respectively, i.e. views separated by one view form a stereo pair.

An alternative design where the pixels are slanted instead of the lenticular element is described in [59]. However such a major change to LC display design is
unlikely to happen unless there is a substantial worldwide market for 3D displays or an advantage of slanted pixels for 2D LCD operation is found.

The multi-view display design by Stereographics adopts a similar solution, citing an earlier reference [61] as the source of the idea for using a lenticular slanted with respect to the vertical image axis. This display generates nine viewing regions, through which the user can see nine equal resolution images. Based on an SXGA (1280x1024) LCD display this results in each viewing window image having a 2D resolution of 426 by 341 pixels.

Experience with lenticular optics [63] suggests displays based on lenticular optics have to make additional design tradeoffs. An important one is the difficulty of anti-reflection coating the lenses, which can lead to distracting reflections on the display surface. Another is the scattering of light in the lenses generates a visible artefact looking to the user like a light grey mist present throughout the 3D scene.

To summarise multi-view displays:

- Temporally multiplexed displays with high resolution per view suffer a number of drawbacks, they need high speed display elements and high bandwidth image generation and interface circuits. This seems likely to delay their widespread adoption in personal 3D display applications.

- Spatially multiplexed designs have lower resolution per view than twin-view displays and recent designs build in crosstalk limiting the 3D depth. Despite this they are attractive commercially because of the benefit of viewing freedom they provide and their relatively low cost and manufacturability.

A solution for the future is to build a system with an intermediate number of views, say three, not requiring mechanical view steering and use a head tracking device to keep the images up to date with the observer’s head position. One such system, known as PixCon, is described by Sharp in [63] and another design from Dresden is presented in [50]. A similar idea for using view switching in a twin-view system was proposed by NTT in [52]. A prerequisite for this is low cost, accurate, observer head tracking and some good progress is being made in this area [25].
4 3D Display Performance and Use

4.1 Comparing perceived depth reproduction

Perceived depth reproduction is the single most important reason for building 3D displays but system characteristics in this respect are rarely reported in the literature. In this section we consider three generic designs the twin-LCD and single LCD two-view systems and a single LCD multi-view system and analyse their ability to reproduce perceived depth. Similar real examples of these designs are the Sharp twin-LCD display [63], the Sharp single-LCD VPI display [64] and the Stereographics nine view multi-view display, but our discussion abstracts from the details of specific display implementations for clarity. We compare the ability of the three generic designs to reproduce depth to each other and to the performance of the human eye, we also consider the demands on the graphics and imaging systems supplying the displays with content.

The generic 3D display designs are assumed to be based on the same underlying LCD element, a 1280 by 1024 pixel display with a horizontal pixel width of $i = 0.3\, mm$ approximating an 18.8 inch diagonal SXGA display. The 3D displays can then be characterised by the effective pixel width in the image seen by one eye:

- The twin-LCD twin view display has two overlaid images and the pixel width in each view is the same as the base panel at $i = 0.3\, mm$.

- The single-LCD twin view display has two horizontally interlaced images and the pixel width in each view is double the base panel at $i = 0.6\, mm$.

- The single-LCD multi-view display has nine views, interlaced horizontally and vertically and the pixel width in each view is triple the base panel at $i = 0.9\, mm$.

We assume the latter two displays overlay the left and right eye images to simplify discussion, but note in practice it will be necessary to consider the exact interlacing of RGB components.

The following set of characteristics provides a basis for comparing display designs. Our aim is to capture the characteristics that are important in the human perception of 3D displays.

**Total display resolution:** However a stereoscopic display is designed to provide views to each eye the total display resolution, i.e. the sum of all pixels in all views, largely determines the computational effort required to generate the images for display and the bandwidth required in interface circuits. Displays, which require image interlacing, will also require additional functionality in interface circuits as pixels from different views typically need to be interlaced at the RGB component level. Bandwidth requirements can be determined from total display resolution and the desired frame rate.
Resolution per view: The resolution per view is a key characteristic of a 3D display. Having stereo 3D does not replace the need for high spatial resolution and anyone used to 1280x1024 monoscopic displays will notice the step down when dividing these pixels between two or nine views. A 3D display can often look better than a monoscopic display with the same resolution as a single view on the 3D display because the brain integrates the information received from the two views into a single image.

![Diagram](image)

Figure 22: The perceived depth represented by corresponding pixels of 0 and 2 pixels screen disparity.

Perceived depth voxels: As shown in figure 22 a pair of corresponding pixels in the left and right images represent a volume of perceived depth, we will call this a stereoscopic voxel or voxel as in [24]. Of particular interest is the depth of a voxel that a display can represent for a given screen disparity between corresponding pixels. We can use this to compare the depth representation abilities of different displays in depth and to compare displays with the ability of the eye to perceive depth. The perceived voxels are arranged in planes from in front to behind the display as they recede from the viewer the cells increase in depth[8, 24].

The depth span of a voxel can be found by using equations (10) and (11) as...
appropriate to calculate difference in depth of points 1 and 2 in figure 22.

Considering zero pixels disparity as in figure 22(a). For point 1, a pixel width $i = 0.3mm$ implies screen disparity of $d = -0.3mm$ and assuming $z = 750mm$ and $e = 65mm$ then the perceived depth in front of the screen plane is:

$$p = \frac{750}{\left(\frac{65}{-0.3}\right) + 1} = 3.45mm$$  \hspace{1cm} (23)

For point 2 the screen disparity is $d = 0.3mm$ and the perceived depth behind the screen plane is:

$$p = \frac{750}{\left(\frac{65}{0.3}\right) - 1} = 3.48mm$$  \hspace{1cm} (24)

Therefore the total perceived voxel depth in this case is 6.93mm. This is the perceived depth represented by corresponding pixels with zero disparity at the screen plane. In practice it tells us this display cannot reproduce a depth difference between objects at the screen plane of less the 6.93mm. Results of similar calculations for all three generic displays are given in figure 24.

**Perceived depth range:** The perceived depth range, that is the nearest and furthest points a display can reproduce, is of interest. Geometrically this can be calculated from the maximum screen disparity available, however for most displays of any size the geometric range is much more than can be viewed comfortably by the majority of observers. Instead it is important to determine the comfortable perceived depth range experimentally and for our discussion we adopt results reported in [27]. This suggests a comfortable working range for the majority of people is from 100mm in front to 100mm behind the display surface and this range could probably be extended to 200mm in front and 500mm behind and still be comfortable to view for the majority of observers. We take the +/-100mm range for our calculations here without affecting the generality of the discussion.

**Stereoscopic resolution:** Identifying the comfortable working range of perceived depth on a display also allows us to define the resolution of perceived depth within this range. Perceived depth voxels of equal screen disparity form planes of voxels parallel to the display surface as illustrated in figure 23. We will define stereoscopic resolution to be the number of planes of voxels within the range of +/-100mm.

Stereoscopic resolution can be calculated identically for each of the generic displays, which have the same viewing distance, by finding the screen disparity, $d$, that generates voxels at +/-100mm. The sum of these values is then divided by the width of a stereoscopic pixel, $i$, on the display in question.

The table in figure 24 shows values of the characteristics discussed here for the three generic displays. Not surprisingly the twin-LCD display with the most pixels per view has the best results for depth reproduction with an ability to reproduce depth differences of 7mm at the screen plane and a stereoscopic resolution of 60 planes of depth in the working depth range +/-100mm. However
Figure 23: Stereoscopic resolution is defined by planes of stereoscopic voxels.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Twin-LCD Twin View</th>
<th>Single-LCD Twin View</th>
<th>Single-LCD Multi (9) View</th>
<th>Human Vision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total resolution</td>
<td>2x</td>
<td>1280(h)x1024(v)</td>
<td>1280(h)x1024(v)</td>
<td></td>
</tr>
<tr>
<td>View resolution</td>
<td>1280(h)x1024(v)</td>
<td>640(h)x1024(v)</td>
<td>426(h)x341(v)</td>
<td></td>
</tr>
<tr>
<td>View pixel width</td>
<td>0.3mm</td>
<td>0.6mm</td>
<td>0.9mm</td>
<td></td>
</tr>
<tr>
<td>Viewing distance</td>
<td>750mm</td>
<td>750mm</td>
<td>750mm</td>
<td></td>
</tr>
<tr>
<td>Voxel depth: 9 pixels disparity</td>
<td>7mm</td>
<td>14mm</td>
<td>21mm</td>
<td>0.84mm</td>
</tr>
<tr>
<td>Stereo resolution (in +/-100mm)</td>
<td>60 voxels</td>
<td>31 voxels</td>
<td>20 voxels</td>
<td>~240 voxels</td>
</tr>
</tbody>
</table>

The calculations for this table assume an observer eye separation of 65mm.

Figure 24: Table comparing characteristics of the generic displays and the eye.
the eye is much better at perceiving depth than the best display is at reproducing it with a minimum detectable depth difference of 0.37mm and an equivalent stereoscopic resolution of 540 planes of depth in the working range +/- 100mm. This difference suggests significant improvements are still possible to the depth reproduction characteristics of stereoscopic displays. It is also important to keep in mind when using the displays if depth judgement is critical to task performance. In the next section we briefly review how to create images that account for the available working depth range and resolution of 3D displays.

4.2 Perceived depth control and image generation

As discussed 3D displays have limits on the comfortable perceived depth range they can reproduce. This results in a working volume of space around the display plane that content producers can use to present a scene in. The working volume available on the display is unlikely to match the volume in the scene being captured. As a result several approaches to mapping depth from a scene onto the available depth range of the target display have been proposed.

Traditionally this has involved a discussion of whether to set cameras at eye separation or not and whether camera axis should be parallel or verging. However recent methods approach the problem as a mapping of a volume of scene space onto the available working volume on the target display. These methods automatically calculate stereoscopic camera parameters given a camera position, scene volume to capture and target display specifications. Wartell describes one approach in [60] while a simpler and more general method is given in Jones [27]. These have significant benefits in ease of image generation for content creators and guarantee that depth mappings will be geometrically consistent even on head tracked displays. The result is stereoscopic images should no longer be produced with excessive perceived depth or unwanted distortions.

Despite the long history of stereo image generation it is only recently that new technology, in the form of 3D computer graphics and digital camera technology, has been able to give enough control over the image creation process to use these methods. The methods are particularly important to apply when creating images for testing and improving a display design since poorly created images, or even just images produced correctly for a different 3D display can cause the highest quality display to become uncomfortable to view.
5 Summary

Advances in micro-optics, display technologies and computing systems are combining to produce an exciting range of new opportunities for 3D display designers. To achieve a good 3D display design requires a systems approach combining optical, electrical, mechanical and digital imaging skills along with an understanding of the mechanism of binocular vision.

The characteristics and geometry of binocular vision define limits on the maximum range of binocular vision and the minimum depth differences it is possible to perceive in the natural world. Because the perception of depth is relative to the current fixation point binocular vision is best suited to making relative depth judgements between objects.

Stereoscopic images do not provide the same stimulus to the eyes as the natural world and the implications of this affects 3D display design and use. In particular while the eyes verge to fixate different depths in a stereo image the eye’s accommodation must keep the image plane, rather than the fixation point, in focus. This places measurable limits on how much perceived depth is comfortable to view on a particular 3D display.

As well as the stereoscopic depth cue the brain uses many 2D depth cues to help it understand depth information in a scene. Therefore the first aim for a 3D display design needs to be to keep the same basic image quality as a 2D display including values of brightness, contrast, spatial resolution and viewing freedom.

We have introduced two-view and multi-view autostereoscopic display designs based on micro-optic elements including: parallax barriers, lenticular arrays, micro-polarisers and holographic optical elements. These provide different tradeoffs in cost, system complexity and performance. Key characteristics that define the performance of different displays include:

- Perceived voxel depth at zero disparity, i.e. minimum reproducible depth at the screen plane.
- Stereoscopic resolution, i.e. the number of discrete voxel planes in +/-100mm depth.
- Viewing window characteristics particularly inter-channel crosstalk and uniformity.

As 3D display quality continues to improve it becomes increasingly important to consider the quality of the stereoscopic images used to evaluate displays. This requires the adoption of new methods for image generation based on an improved understanding of the human perception of stereo images to define the mapping of depth from a scene onto the working depth range available on the 3D display.
References


[38] H. Morishima, H. Nose, N. Taniguchi Stereoscopic image display apparatus. US Pat No. 6,160,527


