CHAPTER 2
AUTOSTEREOSCOPIC DISPLAY TYPES AND HUMAN FACTORS

2.1) Preface

In the first part of this chapter, the implementation and the various advantages and disadvantages of non-head tracking autostereoscopic displays, are considered. The particular classification system used is, in the author's opinion, the most appropriate for determining the suitability for television applications. Although experiments on human factors are not within the scope of the present research, a survey of some of the relevant work in this area is covered in the latter part of the chapter.

2.2) Autostereoscopic Display Types.

The three basic autostereoscopic display types are **holographic** where the image is formed by wave-front reconstruction, **volumetric** where the image is formed within a volume of space without the use of light interference and **multiple image** where different two-dimensional images are seen across the viewing field. These basic types, along with sub-divisions, are shown in Fig.2.1.

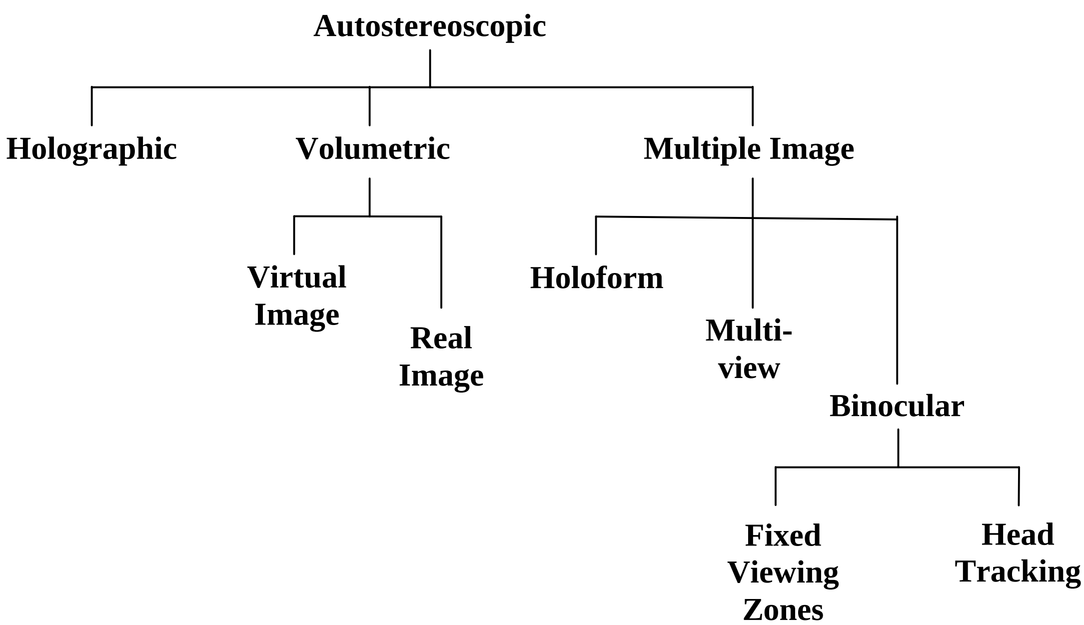


FIG.2.1 CLASSIFICATION OF AUTOSTEREOSCOPIC TYPES

Other workers in this field have used various other classification systems. Siegmund Pastoor of the Heinrich Hertz Institut [PAST97] gives the basic categories as ‘aided viewing’ (stereoscopic), ‘free viewing’ and ‘autostereoscopic’. Displays within the category of ‘free viewing’ are called ‘multi-view’ in the author’s terminology, and these do not require the wearing of special glasses. There are several other classification systems [VALY66b] [FARI94] [BARD95a], but none of these include head tracking and are therefore not particularly useful.

2.3) Holographic

The ‘Holy Grail’ of all stereoscopic displays would be the production in real time of images that exhibit *all* the characteristics of the original scene. This would require the reconstructed wavefront to be identical and could only be achieved using holographic techniques. The difficulties of this approach are the huge amounts of computation necessary to calculate the fringe pattern, and the high resolution of the display, which has to be of the order of a wavelength of light (around 0.5 micron). Approximately ten million discretized samples per square millimetre are required to match the resolution of an optically produced hologram. This means that large amounts of redundant information have to be displayed.

2.3.1) MIT Electroholography

A display was first demonstrated by the Spatial Imaging Group at MIT in 1989. They created an image the size of a golf ball by using an acousto-optic modulator (AOM) and moving mirrors [LUCE95]. Computation of the fringe pattern took several minutes using traditional methods. The speed of this was limited by the large number of samples in the discretized fringe pattern, and by the complexity of the physical simulation of the light propagation used to calculate each sample value.

In 1990 faster computational algorithms were developed that enabled the first interactive Holovideo display system to be implemented. A new method known as diffraction-specific computation was used [LUCE94]. It was more appropriate to the diffraction that occurs during the reconstruction of a holographic image.

Another strategy employed to reduce the information content in the fringe pattern was to dispense with vertical parallax. This reduced the spatial resolution required in the vertical direction from around 1000 lines per millimetre to approximately 10 lines per millimetre, therefore giving a reduction factor of roughly 100 in the information content. A horizontal parallax only hologram can be considered as being an array of one-dimensional holograms known as hololines. Each of these hololines diffracts light into a single horizontal slice of the image.

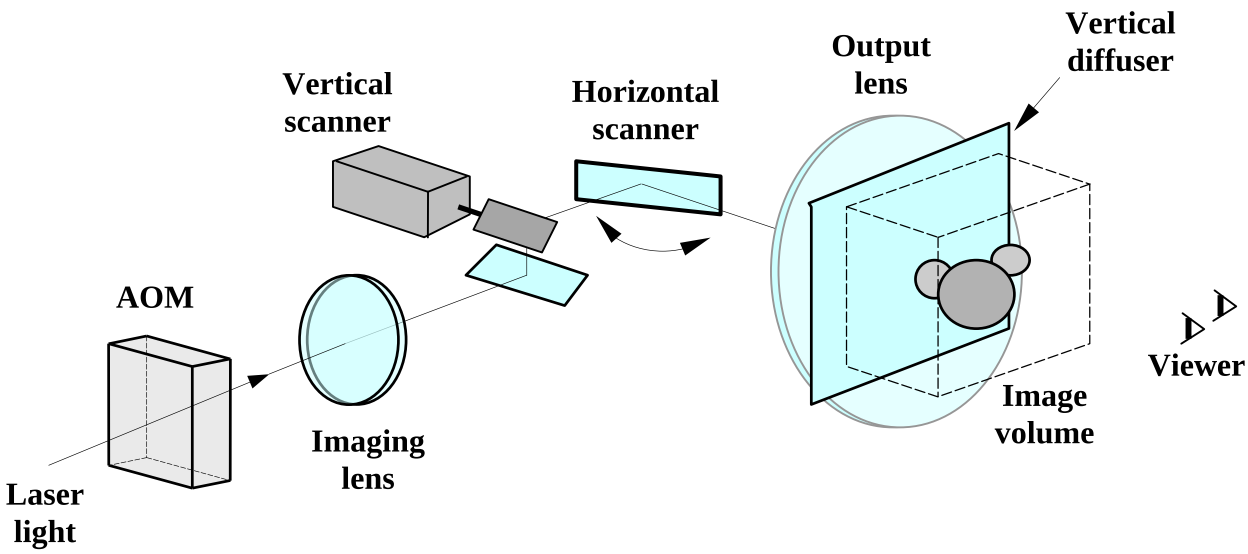


FIG.2.2 SIMPLIFIED SCHEMATIC DIAGRAM OF MIT DISPLAY

The use of an AOM time-multiplexed spatial light modulator makes the display configuration similar to the Scophony television system of the thirties. The AOMs are crossfired (run alternately in each direction) to provide a bidirectional Scophony geometry that utilises the mirror scan in both directions.

The hardware of the display is very large in relation to the size of the image (150 x 75 x 150 millimetres). The most recently published work by MIT describes a large he-ne laser, an 18 channel AOM, a vertical scanning mirror, a beamsplitter, six tiled horizontal scanning mirrors, a screen-sized output lens and a vertical diffuser [LUCE97]. This is shown in the simplified schematic diagram in Fig.2.2.

2.3.2) Japanese and Korean Holographic Displays

Moving parts can be eliminated by replacing the AOM with an LCD. One of the projects within a five year initiative by the Telecommunications Advancement Organization of Japan (TAO) utilises a fifteen-million pixel LCD that consists of five separate LCD panels [HOND95] [MAEN96]. The configuration of this display is illustrated in Fig.2.3. This produces an image that is 50 millimetres wide, 150 millimetres high and 50 millimetres deep. The viewing zone is 65 millimetres wide at around one metre distance. As in the MIT display, vertical parallax is dispensed with.

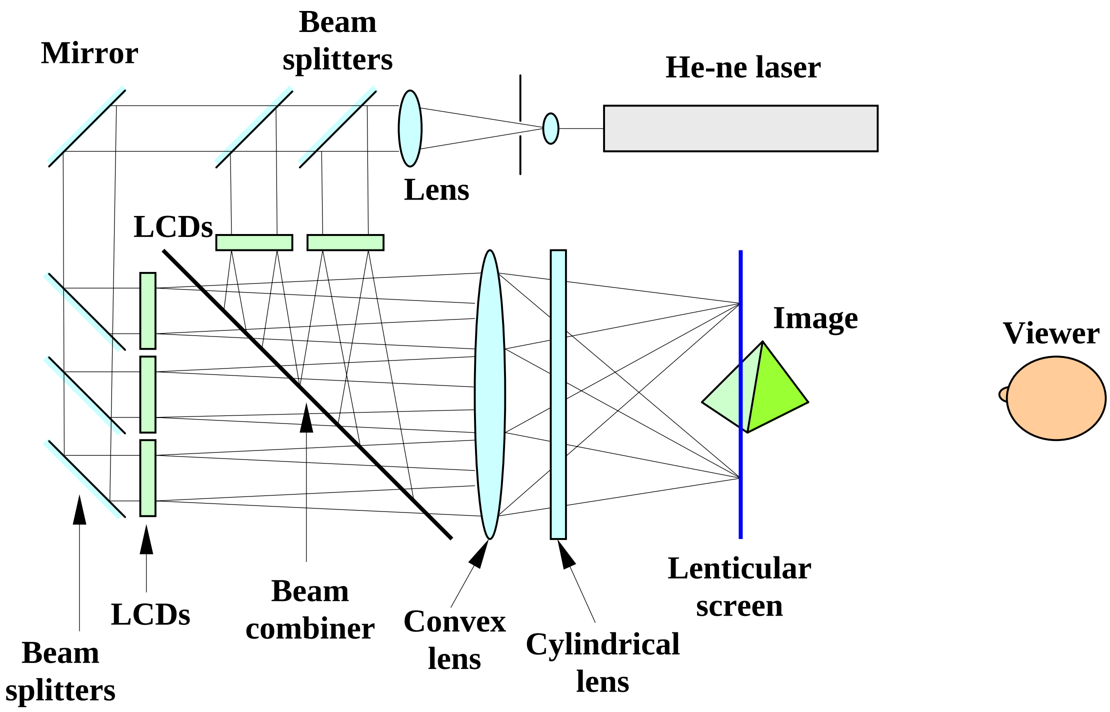


FIG.2.3 TAO 15-MILLION PIXEL DISPLAY

A pulsed laser light source can be used to eliminate the rotating polygon mirrors that are generally used to ‘freeze’ the motion of the acoustic waves on the AOM. A combined Korean/Russian team is working on a system that gives a 74 x 50 x 50 millimetres image with a 60 Hz frame rate [SON96].

A holographic display using a CCD camera to record fringe patterns, and an active-matrix LCD has been described [HASH91]. A he-ne laser is used to generate the hologram. A semi-silvered mirror splits the beam into the object beam and the reference beam. The light diffracted by the object interferes with the reference beam at the CCD where the image is recorded. This hologram is transmitted to the LCD that is illuminated by a second he-ne laser in order to produce the image.

The MIT display has been improved in a project undertaken by the Telecommunications Advancement Organization of Japan (TAO) [KAJI96]. In this display the AOM is replaced with a focused light array consisting of laser diodes, or LEDs, and microlenses. The final monochrome image is produced by 32 discrete images that change semi-continuously across the viewing field. Apart from the replacement of the AOM, the optics of the display are virtually identical to those of the MIT display.

2.3.3) QinetiQ Holographic Display

The problem of obtaining a giga-pixel computer-generated hologram (CGH) has been addressed by QinetiQ (formerly DERA Malvern). This utilises the high speed of some electrically addressed spatial light modulators (EASLMs), and the high spatial resolution afforded by optically-addressed spatial modulators (OASLMs) [STAN00]. EASLMs include digital micromirror devices (DMDs) [YOUN93] [GOVE94], liquid crystal on silicon (LCOS) and a ferroelectric liquid crystal (FLC) on silicon, developed at QinetiQ. EASLMs can have more than 10^6 pixels and operate at speeds in excess of 1KHz.

The OASLM consists of an essentially continuous layer that does not require expensive lithography. It is addressed by applying a voltage to a transparent layer that is in contact with a photoconductor layer, and then allowing the addressing light to fall on the surface. When the control voltage is removed, the photoconductive layer causes an adjacent liquid crystal layer to pass light in the regions where addressing light has fallen. The OASLM is addressed with incoherent light in order to minimise speckle, but is illuminated with coherent light to form the hologram. The output of the OASLM *could* be resolved into a hologram by a simple Fourier transform lens, but the paper suggests that a more efficient replay mechanism is used.

The trade-off between the speed of the EASLM and the resolution of the OASLM can be achieved by transferring the information to the OASLM via replication optics, as shown in simplified form in Fig.2.4. This consists of a 5 x 5 array of lenses that de-magnify the EASLM image. The appropriate regions of the OASLM can be selected by either allowing individual regions of the shutter array to successively pass light, or by enabling separate regions of the OASLM to be written by applying a control voltage to them.

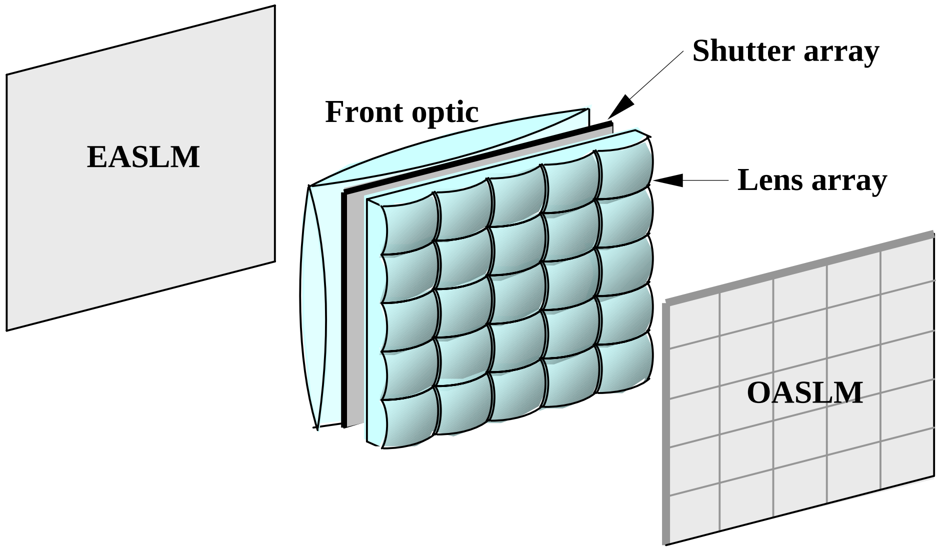


FIG.2,4 FUNCTIONAL DIAGRAM OF QINETIQ ACTIVE TILING

The QinetiQ approach is interesting as it has the potential to provide an SLM with a sufficiently large number of pixels for replicating holographic images in real time. Their estimation is that 10^9 pixels will be needed to produce a hologram in a 0.5 metre^2 volume with a field of view of ± 30º. Consider, for example, a 2,000 x 2,000 EASLM being magnified by 5 x 5. This gives a figure of 10^8 pixels, which is not that far away from the 10^9 that is needed. If the EASLM runs at 1 KHz, the magnification of 25 times will presumably make the refresh rate of the OASLM around 40 Hz.

The usefulness of the OASLM / EASLM approach for providing high pixel density in 3D display types other than holographic is being investigated. A joint Cambridge University / KIST group is developing a device of this type for multi-view display applications [JEON00].

2.3.4) The Future of Holographic Displays

Even given the fact that there is a possibility that holography might be used eventually for television, it seems unlikely that the hardware will be sufficiently simple for it to be used in the next generation of television which will hopefully be available within the next ten years. Image capture and transmission are also going to be very challenging.

Another problem with holography that might prove very difficult, if not impossible, to easily overcome, is that of the reproduction of naturally lit scenes. The principal author of the QinetiQ paper has stated that *simulation* of external lighting is possible with CGH: however, this might not be of great use for natural scenes.

The future of electro-holography depends on more computing power, higher bandwidth optical modulation, and improvements in holographic information processing. Computing power is likely to increase sufficiently quickly to support electro-holography within the next few years.

2.4) Volumetric

The second class of display is volumetric, where the surface of the image is actually produced within a volume of space. The elements of the surface are referred to as ‘voxels’ – as opposed to ‘pixels’ - on a two-dimensional surface. Volumetric displays can be of two basic types: these are **virtual image** where the voxels are formed by a moving or deformable lens or mirror, and **real image** where the voxels are on a moving screen or are produced on static regions.

A problem with volumetric displays is that they usually suffer from image transparency. This is where parts of an image that are normally occluded are seen through the foreground object. Whilst this might not be a disadvantage with some computer generated images, it is unacceptable for video. Another difficulty that is possibly less important than transparency, but could give an unrealistic appearance to natural images, is that of the inability to display surfaces with a non-Lambertian intensity distribution

2.4.1) Virtual Image

One of the earliest virtual image methods described is that of Traub [TRAU66] [TRAU67] where a mirror of varying focal length (varifocal) is used to produce a series of images at differing apparent distances. The variable surface curvature of the mirror entails smaller movement than would be required from a moving flat surface for the same effect. The mirror consists of a thin silvered Mylar film that is attached to the front of a loudspeaker. The loudspeaker can be driven between twenty and several hundred Hz. and sound levels are reported to be tolerable. Three dimensional Lissajous figures, simulations of air traffic control display and the presentation of a series of slides to give ten depth planes are described.

The University of Strathclyde is developing a version of this using a stretchable membrane mirror (SMM) [MCKA99] [MCKA00]. The mirror is 1.2 metres diameter and can vary over a large range of F-numbers. The image can be produced both in front of, and behind the plane of the mirror.

Lenses can also be used to produce the same effect. In the xyzscope [FAJA92] a rotating lens is used to effectively vary the distance between the object and the lens centre. The method is not described in great detail, but this will presumably be a very cumbersome means of achieving the same effect as the varifocal mirror. A lens the size of the screen rotating at 1200 rpm or more is likely to create considerable windage problems.

A combination of variable focus lenses and integral photography has been proposed [YANA97]. The paper describes a lens array that would be difficult to make, due to a lenslets that have a varying radius of curvature.

2.4.2) Moving Screen

A solid image can be produced in a volume of space by displaying ‘slices’ of the image on a moving screen. If, for example, a sphere has to be displayed, this can be achieved by displaying a series of circles of varying size on to a moving surface.

The US Navy has developed a system where the image is produced on a 36" diameter, 18 high double helix. An acousto-optic system is used to scan the light from a he-ne laser in order to produce an image of 40,000 voxels. The image is viewable from 360º so that viewers can walk around the display and look down from above [LYTL95]. A display with a volume of 120 x 120 x 100 millimetres has been produced by the Korea Institute of Science and Technology (KIST) [SON99a]. The images are displayed at a frame rate of 15 to 25 Hz. and consist of 250,000 voxels.

A system that has a voxel resolution sufficient for video display has been described [FAVA01]. The 90 million voxel resolution is obtained by presenting 200 radially disposed slices consisting of 768 x 768 pixel images. These are provided from a modified Texas Instruments projector that can supply eight-colour images at around 4kHz. Images are projected on to a disc that rotates at 600 r.p.m., and frames are updated at 20Hz.

2.4.3) Static Images

In this type of display voxels are produced on stationary regions in the image space. An interesting point with these displays is that some of them have the potential to overcome the problem of image transparency.

In the voxel-based display of the University of Texas [MACF94] ultraviolet light is piped to the individual voxels via fibre optics. This causes the dye to fluoresce. Although the fluorescing region is not entirely opaque, it is not be completely transparent as in virtual image or moving screen methods. The device described consists of a stack of transparent spacers, with layers of fluorescent dye in between them. The device was small at 11 x 11 x 5 voxels, but it was envisaged this would be capable of being scaled up to 10^3 x 10^3 x 10^3 voxels. However, it is unclear whether this research was continued as no further references have been found since.

A simple two-plane method by Floating Images Inc. [DOLG97] uses a partially reflecting mirror to combine the real foreground image behind it with the reflected background image. The foreground image is brighter in order for it to appear opaque. This type of display is not suitable for video, but it does provide a simple a simple and inexpensive display that can be very effective in applications such as advertising.

An attempt to overcome the transparency problem has been made by a group at KIST [SON97]. This proposes the use of an SLM in front of a translucent volumetric image in order to block light in directions that would normally be occluded. The paper is not very clear, but appears to conclude that the speed and spatial resolution of the SLM will be insufficient for this method to be effective.

2.5. Multiple Image Displays

Multiple image displays, where two or more images are seen across the width of the viewing field, can take three basic forms. In the first category, a large number of views are produced in order to give the appearance of smooth motion parallax. As these give a hologram-like appearance, they are referred to here as **holoform**. Displays where a smaller number of discrete views are presented across the viewing field are termed **multi-view**. The simplest multiple image displays are **binocular** where only a single stereo pair is displayed. Head tracked displays come under the category of multiple-image, and will be considered in Chapter 3.

2.5.1) Holoform

The object of holoform displays is to provide smooth motion parallax as the viewer traverses the viewing field laterally. This is achieved by producing a large number of closely spaced discrete views that give an image with a hologram-like appearance.

In the 1980’s, a method called the Stereoptiplexer was developed by Robert Collender [COLL86]. This used picture information from rapidly moving cine film to produce a moving ’aerial exit pupil’ from scanning mirrors. The exit pupil is effectively a vertical narrow aperture that traverses the region between the viewer and the virtual 3D scene. The paper describes the apparatus and shows a photograph of it, so presumably this system actually worked. In a later paper a system with no moving parts is described [COLL87], but it is unlikely this was ever built as it required devices that did not exist. Even today, it is very difficult to find hardware that can display sufficient information to exploit this type of solution.

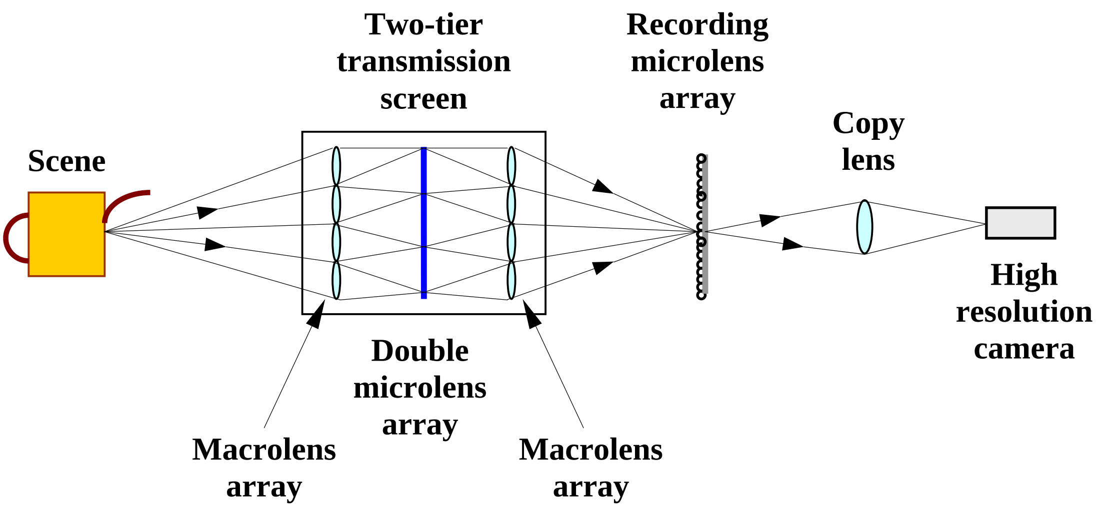
Another variation on this approach is to replace the 'aerial exit pupil' with a physical slit. The earliest work on this appears to be the Parallactiscope of Homer Tilton [TILT85]. In this display a slit is moved rapidly in front of a CRT screen. At any instant, the view of the 3D image that would be seen through the slit is displayed on the CRT. This is updated as the slit traverses the viewed region. In this way a complete 3D image can be built up. This method suffers from the disadvantage of not being suitable for the display of video information, due to the extremely fast frame rate that would be required – a new frame would have to be displayed on the CRT every time the slit had traversed only a small lateral distance. Also, the luminous efficiency will be very low due to the slit capturing light from a small angle from the CRT. Another problem that could possibly occur, but only at quite large viewing distances, is that of diffraction at the slit. However, if the slit is sufficiently narrow for diffraction to be appreciable, the light throughput is likely to be extremely poor.

A version of this display with no moving parts has been developed in the Imaging and Displays Group at De Montfort University [SEXT92]. In this display the moving slit is replaced by a 150-millimetre square 400-element ferroelectric array.

Research is also being carried out by another group at De Montfort University into the use of integral imaging to produce an autostereoscopic display with full motion parallax [MCCO92]. Integral imaging is a technique using an array of small lenses that are either spherical or cylindrical. Integral photography is used to produce the familiar stereoscopic photographs, where a lenticular sheet of vertically aligned cylindrical lenses provide pictures with horizontal parallax-only 3D image. If a photographic emulsion is located in the focal plane of an array of small lenses, parallax information is recorded. If this information is used to reconstruct an image after being developed, the image produced will be pseudoscopic - that is it will be stereoscopically inverted. As long ago as 1908 it was proposed by Lipmann [LIPM08] that a two-stage process should be carried out to restore the image to its original orthoscopic form.

The implementation of the De Montfort display using integral imaging is shown in the schematic diagram in Fig.2.5. The optical transfer required to produce orthoscopic images *could* be achieved by using a semi-silvered mirror and a retro-reflecting screen. The disadvantages of this arrangement are the light loss at the semi-silvered mirror, and the relatively low modulation transfer function of the retro-reflecting screen. For these reasons, a two-tier transmission screen has been adopted for the first stage of the capture system.

This screen consists of three stages. The first stage is an input macro lens array that produces a series of pseudoscopic real images. Within the volume of these images lie two back-to-back microlens arrays that have a common focal plane. Light leaving these arrays is focused by an output macrolens array into a single pseudoscopic image. The recording microlens array is situated within the volume of this pseudoscopic image. It is the image on the focal plane of this array that is transmitted to the display.



<u>Fig.2.5 INTEGRAL IMAGE CAPTURE</u>

The construction of the display is simple as it consists of a high resolution TFT LCD and a microlens array only.

The resolution required is higher than is required for two-dimensional imaging, but the team working on the project anticipate that an increase in the information content by a small factor will enable the transmission of full parallax images. Work is also being carried out into compression algorithms that are appropriate to the nature of the image formed by the recording microlens array.

A research group in the 3D project at TAO have identified the need for a large number of views in order to overcome problems caused by the difference between accommodation and convergence [KAJI97]. Their approach is to provide what they term ‘super multi-view’ (SMV). Under these conditions, the pupil receives two or more parallax images. The authors claim this will cause the eye to focus at the same distance as the convergence. This is a very significant finding regarding the minimum amount of information that has to be displayed in order for the accommodation and convergence of the eyes to be the same. The paper does not state where this finding originates – a rigorous examination would allow for variations in pupil diameter with light levels, and also the fact that the pupil is circular. This consideration is similar to the way in which the pupil function is allowed for in determining crosstalk in Section **12.2.2)**.

The display itself is implemented by using a focused light array (FLA) in order to obtain the necessary horizontal spatial resolution required for the production of 45 views. Effective resolution is obtained by modulating the output of an array of LEDs or laser diodes, and mechanically scanning the light in a similar manner to the TAO 32-image holographically-derived display, which is in turn inspired by the MIT electroholographic system.

Although not mentioned in the references in this paper, holographic stereograms, i.e. where multiple views across the viewing field are produced holographically, are analysed in a paper by Pierre St Hilaire [HILA95]. In this paper, the effect of the image appearing to ‘jump’ between adjacent views is considered. This phenomenon is similar to aliasing when a waveform is undersampled, i.e. when the sampling rate is less than half the maximum frequency in the original signal. This optimum is in the same order as the figure obtained from research at the Heinrich Hertz Institut where it has been determined that typically, 20 views per interocular distance are required for the appearance of smooth motion parallax [PAST92].

2.5.2) Multi-view Displays

In multi-view displays a series of discrete views are presented across the viewing field. One eye will lie in a region where one perspective is seen, and the other eye in a position where the adjacent perspective is seen. The number of views is too small for continuous motion parallax, but strategies, such as merging one image into the adjacent image, and limiting the disparity in order to keep the apparent image content close to the plane of the screen, can minimise the apparent ‘jumping’ between views. This section is not an exhaustive selection of work carried out in this area but it is a fair representation of the various methods being researched in the past few years.

The methods fall within four broad categories. These are: lenses, either in the form of Fresnel lenses or sheets of cylindrical lenses, parallax with ‘point’ light sources: holographic viewing zone formation and ‘Cambridge’ type displays with fast light shutters giving spatio-temporal formation of zones.

A method that is simple in principle, but rather cumbersome to implement, is described in a paper by Stephen Hines [HINE97]. This uses an arrangement of projection lenses, a Fresnel field lens and vertical diffuser (horizontally aligned lenticular sheet) to produce a series of viewing zones across the viewing field. Various configurations of the optics are used to provide 4,7,13 or 21 zones. This gives an inevitable trade-off between the number of views and resolution. The drawings of the apparatus indicate that the housing size is extremely large in relation to the restricted viewing field. This rather limits this approach to being suitable only for arcade games.

Lenticular screens, with the lenses running vertically can be used to direct the light from columns of pixels on an LCD into viewing zones across the viewing field. The principle of operation is shown in Fig.2.6. The liquid crystal layer lies in the focal plane of the lenses, and the lens pitch is slightly less than the horizontal pitch of the pixels in order to give viewing zones at the chosen optimum distance from the screen. In this case, three columns of pixels contribute to three viewing zones. Early multi-view displays with four zones were produced at NHK [ISON90]. There were two versions, one using a 12" plasma display panel (PDP) and one with 9" electroluminescent (EL) panel.

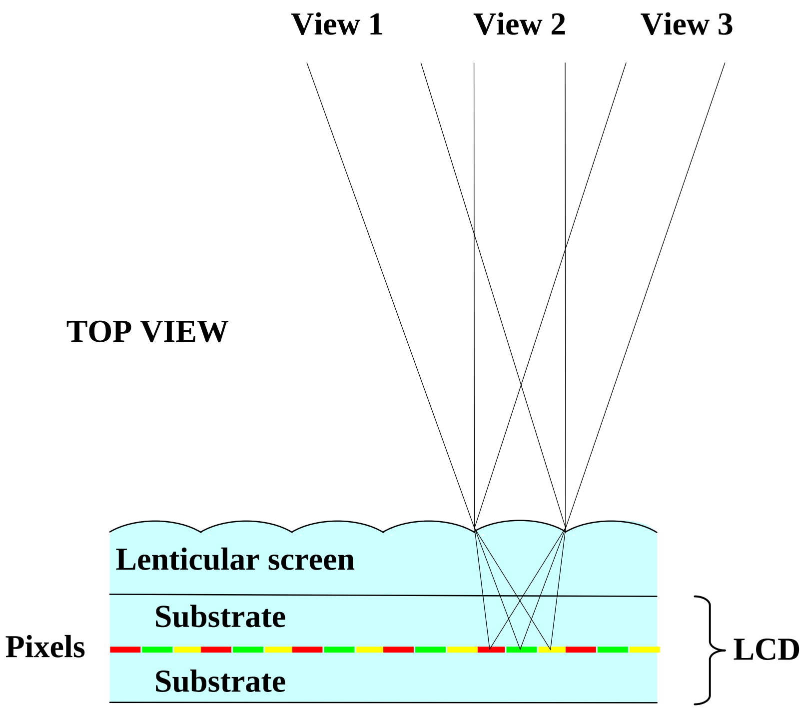


FIG.2.6 PRINCIPLE OF LCD MULTIVIEW OPERATION

A simple multiview display with the above construction suffers from two quite serious drawbacks. Firstly, the mask between the columns of pixels in the LCD gives rise to the appearance of vertical banding on the image known as the ‘picket fence’ effect. Secondly, when a viewer’s eye traverses the region between two viewing zones, the image appears to ‘flip’ between views.

These problems have been addressed by the Philips Research Laboratories in the UK by the simple expedient of slanting the lenticular sheet in relation to the LCD [BERK96], [BERK97] [BERK99]. An observer moving sideways in front of the display always sees a constant amount of black mask, therefore rendering it invisible and eliminating the appearance of the ‘picket fence’ effect. The transition between adjacent views is also softened so that the appearance to the viewer is closer to the continuous motion parallax of natural images rather than a succession of flipping views.

Fig.2.7 shows the relationship between the pixels and the slanted lenticular sheet for a seven-view display. As the LCD is located in the focal plane of the lenticular sheet, the horizontal position on the LCD corresponds to the viewing angle. Therefore all points on the line XX direct view 3 in a given direction, and all points on line YY direct view 4 in another direction. The way in which the effect of flipping is reduced is evident by examining line XX where view 3 predominates, but with some contribution from view 2. Similarly, for the angle corresponding to line YY, view 4, with some contribution from view 3 is seen.

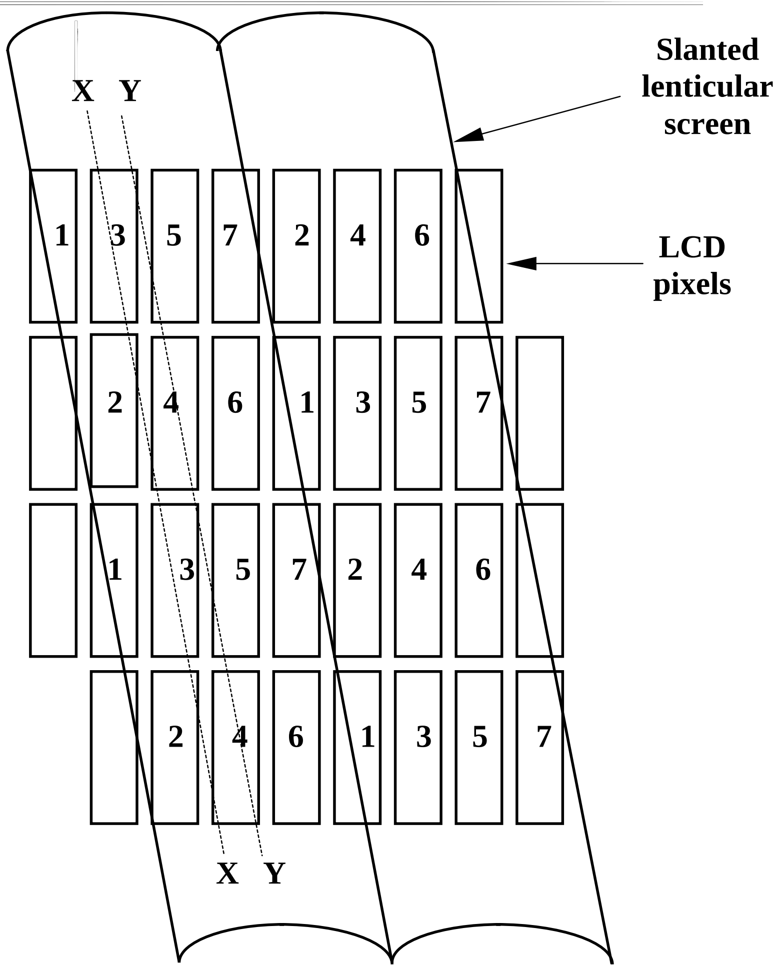


FIG.2.7 ARRANGEMENT OF PIXELS IN PHILIPS DISPLAY

Although by their very nature, multi-view displays are limited in the quality of the stereo effect, the size of the usable viewing region and the restricted depth of image field, the actual appearance of the Philips display is remarkably good, especially bearing in mind its simplicity.

'Point' light sources behind an LCD are used by a Korean group to direct images to the viewing zones [KIM01]. A simple 32 x 32 pixel display is described, where the light sources are obtained from a collimated blue laser beam passing through a microlens array. Each light source lies behind a 6 x 6 array of pixels, therefore providing both horizontal and vertical parallax. The paper acknowledges that the display suffers from the loss of resolution – this is particularly severe where both parallaxes are available.

A holographic optical element (HOE) is used by Osaka City University to form viewing zones [SAKA95] [TAKA96]. In this display an HOE mounted behind an LCD forms four viewing zones in the viewing field as illustrated in Fig.2.8.

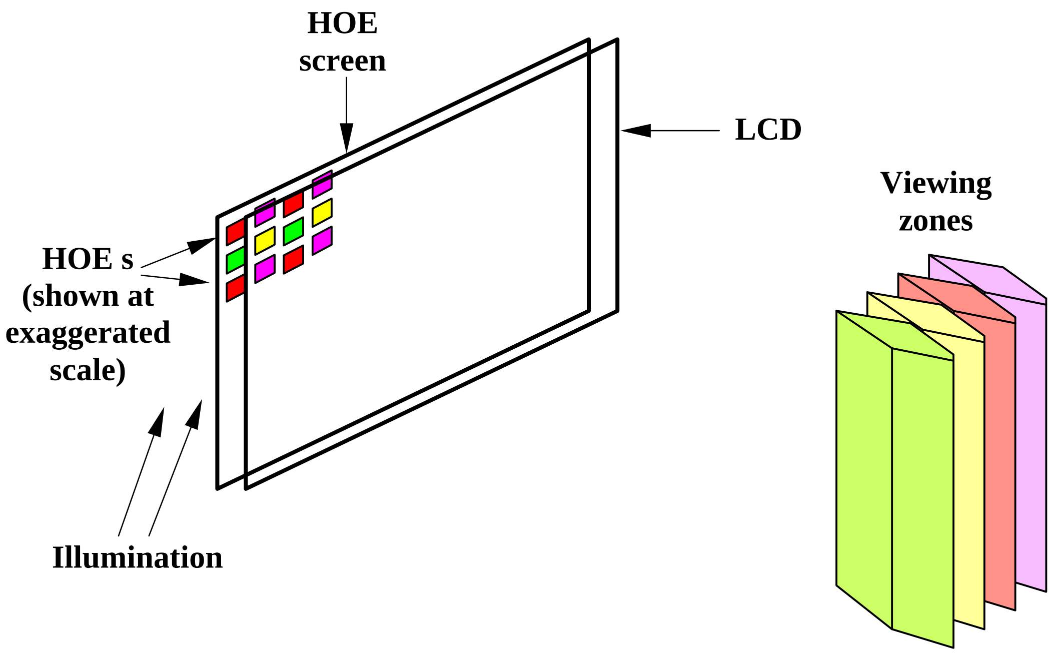


FIG.2.8 OSAKA HOE DISPLAY

A team at Cambridge University has opted for temporal multiplexing where the series of images is presented in sequence [TRAV91] [MOOR 92] [MOOR 96]. Although a sufficiently fast device is not available to perform this function, the operation of the display can be best understood by imagining a transmission LCD as shown in Fig.2.9 (a). If a large Fresnel lens is located adjacent to the LCD, a vertical illumination source behind the lens will form a real image in the viewing field. This image is the exit pupil for the view being displayed on the LCD at that particular time. The illumination will be even over the complete area of the LCD, and the view will only be visible over the area of the exit pupil.

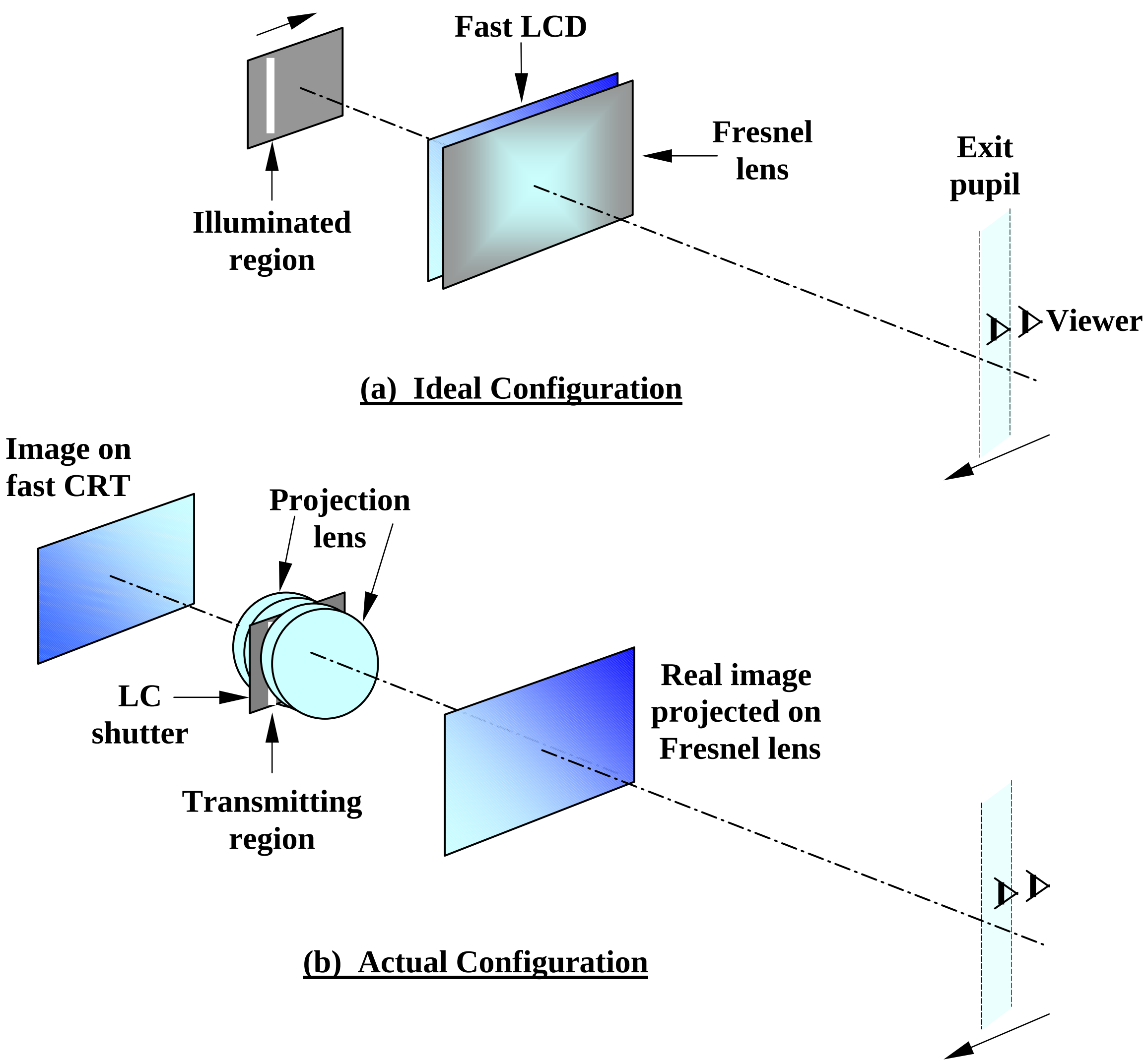


FIG.2.9 CAMBRIDGE MULTI-VIEW DISPLAY

If the adjacent view is next displayed on the LCD, the illumination source moves laterally to form an exit pupil in a position next to the previous one. This process is repeated until the complete series of views is presented across the viewing field. Operation in this mode would require the LCD to be running at N times the normal video rate, where N is the number of views.

The display is implemented using a CRT that is able to operate at a sufficiently fast frame rate. Instead of a view being displayed on an LCD, it is projected on to the Fresnel lens by a projection lens located where the illumination sources were, as shown in Fig 2.9 (b). A ferroelectric liquid crystal shutter replaces the illumination sources. This shutter is in the Fourier transform plane of the projection lens, and its real image forms the exit pupil. However, this is not seen on the image perceived by the viewer.

Various versions of the display have been built with up to 16 views, and with colour and monochrome images. Colour is obtained by using a Tektronix sequential liquid crystal shutter. A recent version of this display uses a 50" concave spherical mirror [DODG00]. This overcomes the problem of scattering ambient light from which Fresnel lenses suffer. Images are derived from three primary-colour CRTs whose outputs are combined by dichroic mirrors for maximum efficiency. A further development provides two sets of viewing zones that are derived from two sets of CRT subsystems. This makes the display particularly suitable for two-player arcade games.

2.5.3) Multi-view Display Limitations

There are two fundamental reasons why multi-view displays are unsuitable for television. In order to perceive stereo correctly, the right eye of a viewer must be located in one exit pupil and the other in the adjacent pupil.

Reference to Fig.2.10 shows that the regions where the eyes may be located is restricted. This is possibly not a very severe problem with a small display, where the pupils are quite deep. However, as the screen becomes wider the pupils become foreshortened as shown in Fig.2.10 (b). The exit pupil depth is approximately inversely proportional to the screen width.

A 28″ diagonal screen with an exit pupil pitch of 6.5 cm. would give exit pupil depths of approximately 400 millimetres when the pupils are formed 2 metres (approximately 5 times picture height) from the screen. This requires viewers to be located close to an optimum-viewing plane, hence restricting their movement.

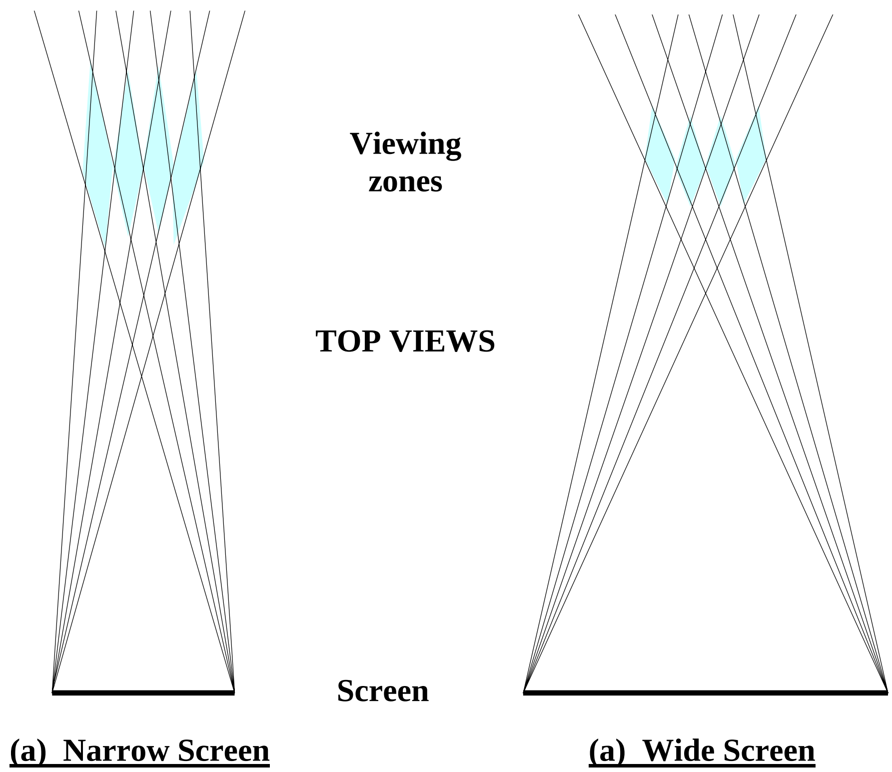
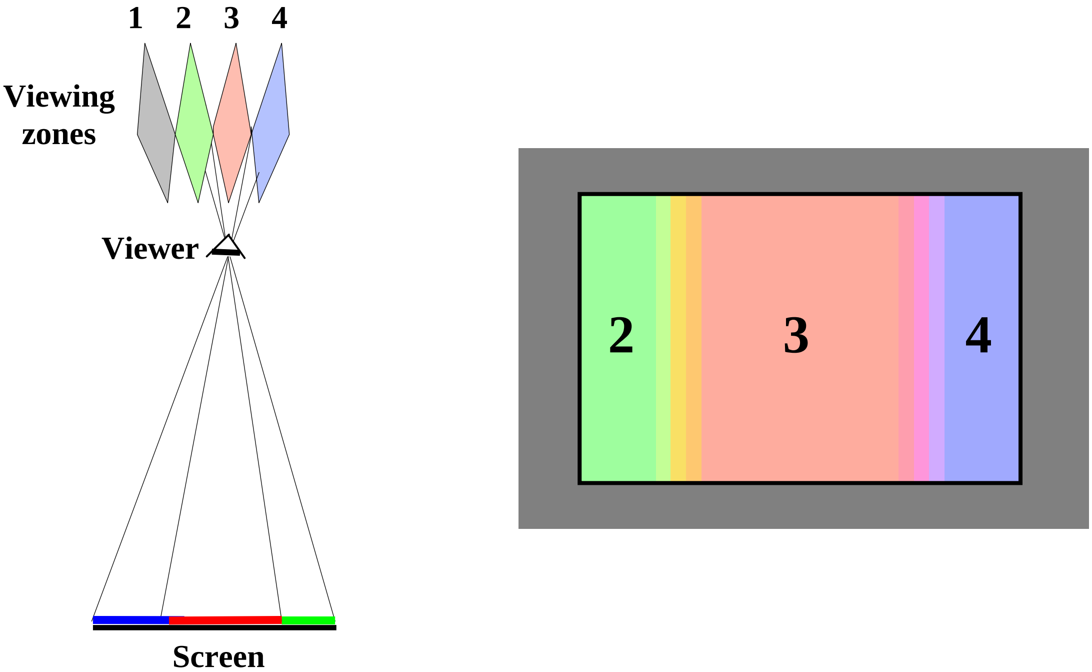


FIG.2.10 MULTI-VIEW: EFFECT OF SCREEN WIDTH

Next, it is necessary to consider the image seen by an eye that is not situated within an exit pupil. An eye located at the position indicated in Fig.2.11 will see parts of images 2, 3 and 4 across the width of the screen. If a region of the image appears to be in the plane of the screen, a continuous image will be observed with no breaks at the boundaries between the different images. However, discontinuities will be seen at the boundaries for areas that do not appear to be in the plane of the screen. Even though the effect will be made less objectionable due to the overlapping of images at the boundaries, unacceptable discontinuities will occur, especially where the *subject* of the scene is away from the plane of the screen



(a) Top View (b) Appearance of Screen

FIG.2.11 MULTI-VIEW DEPTH LIMITATION

2.5.4) Binocular Display Types

The simplest type of display is binocular or two-image, where a single pair of viewing zones is produced. These can be of four basic types; the viewing zones can be formed by lenticular screens, with twin projectors, by parallax methods or by HOEs. In its simplest form of the lenticular screen display operates in the same way as described in section **2.5.2)**. Twin projector methods produce exit pupils that are real images of the projector lenses, with the image formed on a double lenticular screen or a special reflecting screen. Parallax displays use an opaque mask, an array of orthogonally polarised image multiplexing elements or a series of line illumination sources behind an LCD.

The simple lenticular screen display consists of an LCD with a lenticular screen in front of it. The screen consists of a series of vertically aligned cylindrical lenses with a pitch slightly less than double the horizontal LCD pitch. This allows for the fact that the viewer is at a finite distance from the screen and parallax has to be allowed for. As the majority of LCDs have the RGB sub-pixels in the vertical stripe configuration, the LCD has to be operated in the portrait mode in order to avoid coloration and distortion of the colours in the image. Left and right images are displayed on alternate columns (parallel to the lenticular lenses). A display of this type has been built and evaluated in the Imaging and Displays Group at De Montfort University [BARD95b].

An LCD can be operated in the normal landscape mode in a display utilising a chequered mask and orthogonally aligned lenticular screens [MORI98]. The left and right images are multiplexed on alternate pixel rows. The display consists of five layers, these are, in order from the back, the backlight panel, the chequered pattern mask, a vertically aligned lenticular sheet, a horizontally aligned lenticular sheet and the LCD. The horizontal pitch of the mask and the pitch of the vertically aligned lenticular sheet are around double the LCD horizontal pitch. These perform the same *function*, but in a different manner, to the lenticular screen in the previous method. Rows of the chequered pattern are directed to the appropriate rows of pixels by the horizontally aligned lenticular sheet.

Twin projectors are used in conjunction with double lenticular screens to make large screen displays for single viewers [ISON95]. Real images of the projector lenses are formed into vertical exit pupils by the double lenticular screen. With the correct pitches and focal lengths, this screen acts as a two-dimensional version of a Gabor superlens [HEMB97]. This is a type of lens that is normally made from two-dimensional arrays of microlenses, and has unusual imaging properties. The double lenticular screen performs focusing in the horizontal direction, and scattering in the vertical direction, to form vertical viewing zones that allow a degree of vertical viewer movement.

A special reflecting screen, where retroreflection occurs in the horizontal direction, and scattering in the vertical direction, also performs the same purpose [OHSH97]. This is referred to as a ‘curved directional reflecting ‘(CDR) screen. Retroreflection is achieved with micro corner reflectors with vertical alignment, and vertical scattering with a lenticular sheet.

The first of the parallax methods uses thin vertical illumination lines behind the LCD in order to direct the light to the appropriate viewing regions [EICH94] [EICH95] [EICH96] [EICH97]. The lines are produced on a diffusing screen by a lenticular sheet that is mounted behind it. The primary light sources are a series of vertical lamps that are located behind slit apertures and are focused by the lenticular sheet.

The Sanyo display uses masks to produce a simple and effective means of supplying 3D to a single viewer [HAMA95]. In the most advanced version of their optics, parallax barriers, both behind and in front of an LCD, are used to present images with virtually no Moire fringing. These barriers consist of masks that have vertical apertures in them. The operation of the optics was clarified in a communication from Sanyo's laboratories [MASH97]. At first sight, it appeared that the LCD would require RGB sub-pixels to be in the horizontal orientation in order to avoid coloration problems.

The information supplied regarding the configuration of the pixels is as follows –

Table 1.1 Sanyo RGB Sub-pixel Configuration

Colour filter configuration	**Red**	**Green**	**Blue**	**Red**	**Green**	**Blue**
Parallax image configuration	**Right eye**	**Left eye**	**Right eye**	**Left eye**	**Right eye**	**Left eye**

This is very interesting as it implies that individual triads of RGB sub-pixels are used for both left and right images. Modification of the LCD drivers will be necessary but presumably this would not be difficult for Sanyo as an LCD manufacturer. This has a useful implication for lenticular displays, as a lenticular screen with a pitch of 2 / 3 the horizontal LCD pitch would enable the LCD to be used in the landscape mode, provided the drivers were modified.

Polarization can be used to provide what is effectively a vertical slit mask A display that uses a dichroic type polarisation plate is described in a paper by KIST [SON99b]. The image-multiplexing screen consists of an array of vertical strips of dichroic polarizing material of alternating orientation. A Fresnel lens produces exit pupils from a pair of illumination sources that have polarizers in front of them to select the odd and even columns of pixels. The conclusions of the paper state that difficulties were encountered with the manufacture of the multiplexing screen. The optics are very basic as the pupils are produced with a Fresnel lens. Also, the multiplexing barrier would have been more simply obtained by using an off-the-shelf micropolarizer array from Reveo Inc. [FARI01].

HOEs can be used to provide the viewing zones, and RealityVision [TRAY97] has developed a display of this type. As this will be a head tracked display in its final form, it is considered in greater detail in Chapter 3.

2.5.5) Limitations of Binocular Displays

Binocular displays without head tracking impose a greater restriction on viewer movement than any other autostereoscopic display method. When lenticular screens or parallax barriers are used, the viewing field will be as shown in Fig.2.12 (b). In the diamond shaped regions marked **R,** a right image is seen across the complete width of the screen, and a left image in the regions marked **L**. In order to see 3D, the viewers right eye must lie in an **R** zone, and the left eye in an **L** zone. This means that the eye-centre must occupy the shaded region shown in Fig.2.12 (b). The geometry of the displays is designed to give zone regions with a width of around the average inter-ocular distance of 65 millimetres. It can be seen that at the optimum viewing distance from the screen, 3D can only be seen for a maximum of half the width of the viewing field. In practice this will be less due to the edges of the zones not being sharp.

When the eye-centre is located between the shaded regions, pseudoscopic images are seen. This is where the stereo pair is reversed, and unusual stereo effects are observed, As the viewer moves away from the optimum viewing distance, the proportion of the field over which 3D can be seen becomes less. As with multi-view displays, the zones become foreshortened with increasing screen width. If there are sufficient viewing zones across the field, more than one viewer could be accommodated [VALY62b].

In projection displays, only a single pair of viewing regions is formed, thereby restricting the viewing region even more. A larger viewing region is provided by the

RealityVision HOE display. Instead of producing diamond-shaped regions, the right image is directed to the right side of the viewing field, and the left image to the left side. The distance from the screen over which 3D can be seen is considerably increased. Also, when both eyes are the right side of the field, a right image is seen by both of them, and a left image by both eyes when they are in the left side of the field

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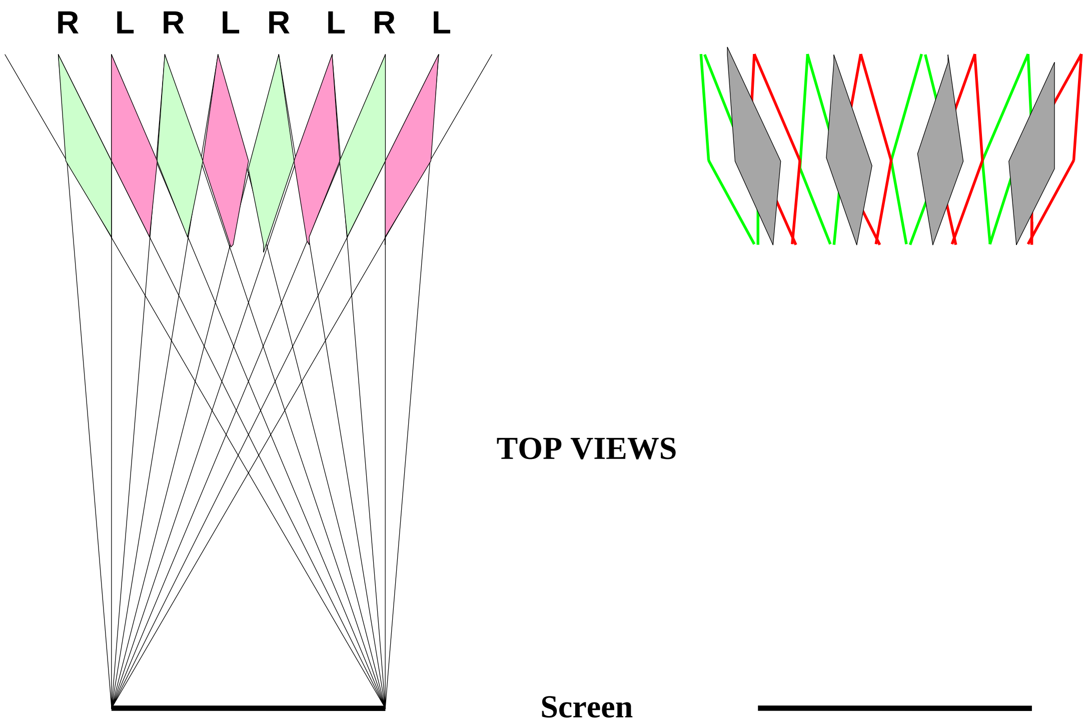

(a) Left and Right Zones **(b) Eye-centre Posiitions**

FIG.2.12 BINOCULAR VIEWING ZONES